ACDIS

Occasional Paper

Is a Naval Nuclear Arms Race with China Inevitable?

Clifford Singer
Director
Program in Arms Control & Domestic and International Security (ACDIS)
University of Illinois at Urbana-Champaign

Is a Naval Nuclear Arms Race with China Inevitable?

Clifford Singer

Director
Program in Arms Control & Domestic and International Security

Is a Naval Nuclear Arms Race with China Inevitable?

Clifford E. Singer

China's intercontinental nuclear-armed rockets used to be immobile and liquid fueled. Those rockets were configured to make a political statement about possession of nuclear weapons capability by creating uncertainty about the possibility of at least one reaching its target, not necessarily to survive a nuclear first strike. Now China is reportedly developing solid fueled road-mobile rockets with multiple independent re-entry vehicles (MIRVs). Of even greater interest for the present discussion, China is reportedly developing submersible ships with ballistic missiles and nuclear propulsion (SSBNs) with twenty-four missiles with about six nuclear warheads per missile. These developments raise serious questions about U.S. military and diplomatic strategy vis-à-vis China.

When China's long-range missiles were liquid fueled and immobile (Cunningham and Fravel 2015), it was technically feasible for the United States to plan for a pre-emptive strike to limit damage from such missiles. Whether or not a U.S. posture of trying to maintain first strike capability vs. China was politically useful, it was inherited from Cold War strategy vs. Russia and thus the de facto situation.

Cold War Damage Limitation Strategy

One outcome of the U.S. damage limitation strategy against the USSR is evident from assembled nuclear explosives counts plotted in Figure 1 (Ploughshares 2016). In 1960, the NATO countries had over ten times as many nuclear explosives as the USSR. After the 1962 Cuban Missile Crisis, the USSR accelerated its production of nuclear weapons and long-range delivery vehicles. By 1972, the USSR had over 10,000 "strategic" nuclear warheads and many more available to target assets of the United States and its allies in Europe.
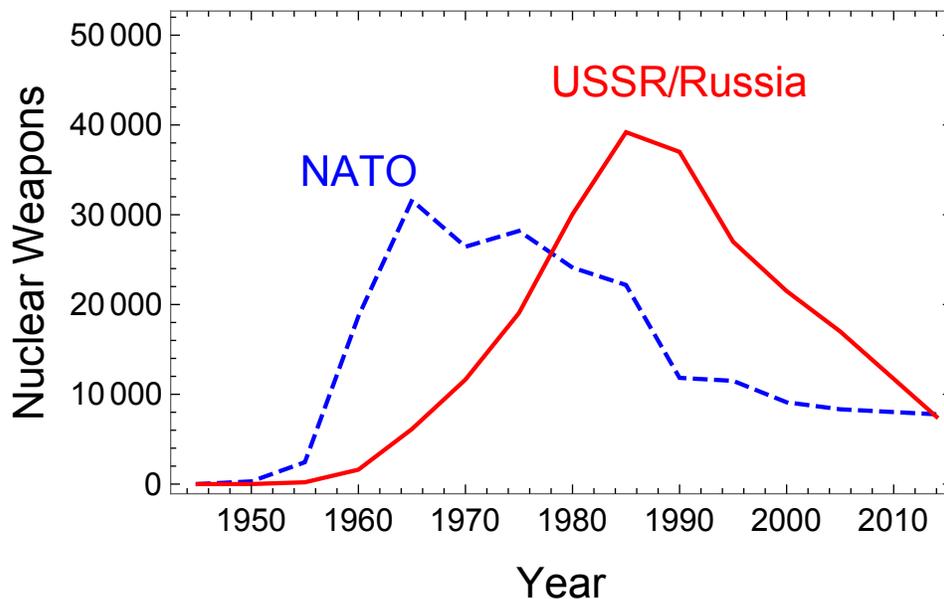
Fig. 1. Evolution of NATO and USSR origin assembled nuclear explosives holdings.

An estimate of the number of Soviet nuclear warheads in 1985 was over 39,000. It seemed implausible that any damage limitation strategy would preclude over ninety-nine percent of this arsenal from reaching targets, the result being so devastating as to nullify any plausible gain to either side from initiating nuclear war. The first response of the Reagan administration in the 1980s

to this situation was to plan for a protracted nuclear war and civil defense enhancements, under the assumption that the USSR would pursue a gradual nuclear escalation strategy. Domestic U.S. political resistance led to a switch to an alternative damage limitation strategy using directed energy weapons, but that proved to be technically infeasible (Bloembergen et al. 1987). The large numbers of nuclear weapons and missiles built in pursuit and frustration of damage limitation during the Cold War were greatly in excess of the numbers needed for the alternative approach of mutually assured destruction. So there followed a series of agreements on delivery systems, a parallel bilateral reduction of the numbers of assembled nuclear explosives, and a nearly universal moratorium on test nuclear explosions. As of 2016 (Ploughshares 2016), Russia and NATO respectively had an estimated 7,300 and 7,495 assembled nuclear explosives (with the United States having ninety-three percent of NATO's). The United States and Russia had an agreement to limit by 2018 nuclear warheads on long-range missiles to no more than 1,550, minus one missile warhead for each long-range bomber that could be configured to carry multiple nuclear weapons (U.S. Department of State 2010). With the notable exception of North Korea's five nuclear explosions through September of 2016, there were no other nuclear explosions after the Indian and Pakistani tests in 1998 (Kimball 2016a).

In 2016, no progress was apparent in negotiations with Russia on further reductions of nuclear weapons delivery systems. There were no agreements in force limiting the number of assembled nuclear explosives. Russia and the United States had respectively an estimated 2,800 and 2,500 nuclear warheads retired or awaiting disassembly, but each had 4,500 or more not in that category, along with over 500 more possessed by the United States' NATO allies (Davenport 2016). Russia and the United States have accused each other of deployment or testing programs incompatible with the Intermediate Nuclear Forces treaty covering Europe (U.S. State Department 2015; Kimball 2016b). In short, there is no agreed upon program for further dismantlement of U.S. and Russian assembled nuclear explosives, and the number of such explosives and their delivery vehicles remain an order of magnitude higher than that estimated to be sufficient for mutual assured destruction in the absence of a highly effective damage limitation capacity (Glaser and Fetter 2016).

Damage Limitation, China, and SSBNs

If U.S. nuclear strategy towards China parallels that directed at the USSR during the early stages of the Cold War, the United States will retain a large arsenal of nuclear-armed missiles capable of striking land-based Chinese missiles. The United States may also use methods including satellite reconnaissance to try to locate mobile land-based Chinese missiles and maintain capabilities to attack China's missiles with non-nuclear-weapons systems.

Trying to maintain a nuclear damage limitation option against China, the United States would also try to track and trail Chinese submarines that are armed with nuclear weapons. For a mixture of reasons addressed below, the United States has already shifted attack submarines to bases in Guam, Hawaii, and California; arranged to have a littoral combat ship (LCS) use port facilities in Singapore; and scheduled anti-submarine warfare (ASW) exercises with allies in the Western Pacific. The U.S. Congress has been pressing for more LCS builds and expanding use of underwater drones, which would enhance ASW capabilities.

During the Cold War, the United States tried to track and trail Soviet SSBNs but have U.S. SSBNs elude Soviet efforts to do the same. By 1985, U.S. gross domestic product in terms of purchasing power parity (PPP) was still about twice that of the USSR. NATO allies also had a shared technology and education base, while that of the Soviet Union was more constrained. After the Cold War, Russia's PPP bottomed out at 15% of that of the USA and only recovered to 21% by 2015 (or about half as much when compared to NATO as a whole). Concerning opportunities for technical education, the number of 35,000 Russian college students studying in the EU and United States combined in the early 2010s (Forsberg and Haukkala 2016,184) was small compared to just over 300,000 Chinese at U.S. colleges and universities in 2015 (Open Doors 2015). At the University of

Illinois at Urbana-Champaign (UIUC) alone, in 2015 there were 5,241 Chinese students, of which 3,884 were in the College of Engineering. Half of the total number Chinese students were in graduate programs, with 359 in Computer Science, 323 in Electrical and Computer Engineering, 270 in Mechanical Science and Engineering, and 129 in Physics (International Student and Scholar Services 2015).

During the lifetime of systems relevant to construction and detection of SSBNs, the situation of the United States vis-à-vis China will be substantially different than that of the United States vis-à-vis the USSR, and particularly vis-à-vis post-Cold-War Russia (Kristensen 2007). Figure 2 shows International Monetary Fund historical short-term estimates and projections of purchasing power parity gross domestic product (PPP GDP) for the United States and the People's Republic of China (PRC) from 2001–2021. Purchasing power parity is a measure of the domestic production capability of a country and is taken here to be relevant for large countries like the China and the United States that can rely primarily on domestic manufacturing for production of nuclear weapons systems.
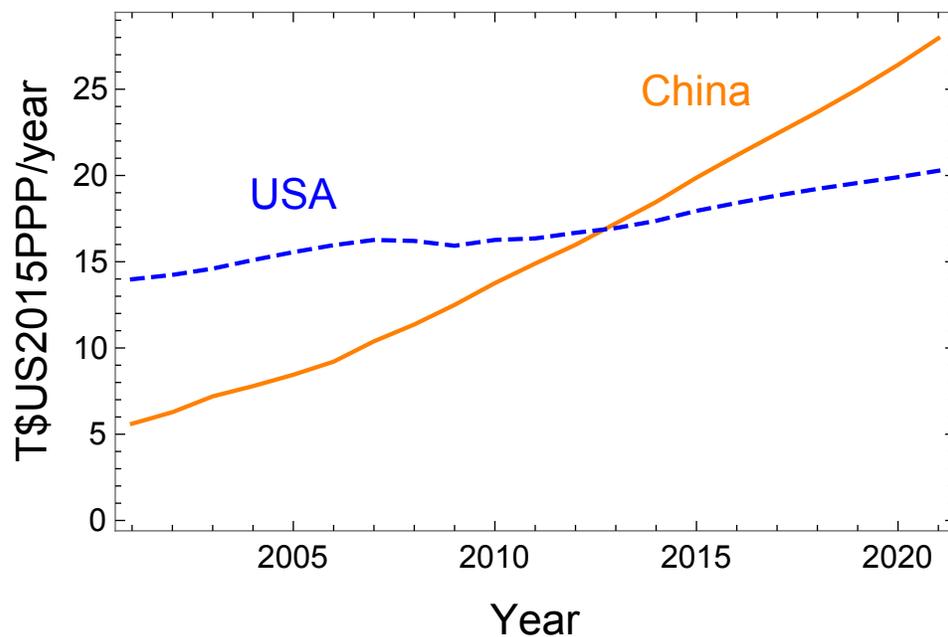

Fig. 2. International Monitary Fund estimates and extrapolations of Chinese and U.S. purchasing power parity GDP, adujsted to year 2015 dollars using a United States price index inflator.

Figure 3 shows longer-term extrapolations of the per capita PPP GDP growth rate for the PRC (with Hong Kong and Macau but excluding Taiwan) and the United States (with Puerto Rico and the U.S. Virgin Islands). When doing longer-term extrapolations, it is important to account for the generic tendency of per capita PPP GDP growth rates to decline with time in industrial countries. For clarity on this, the theory and data calibration method used to produce the results in Figure 3 are described in the Appendix.
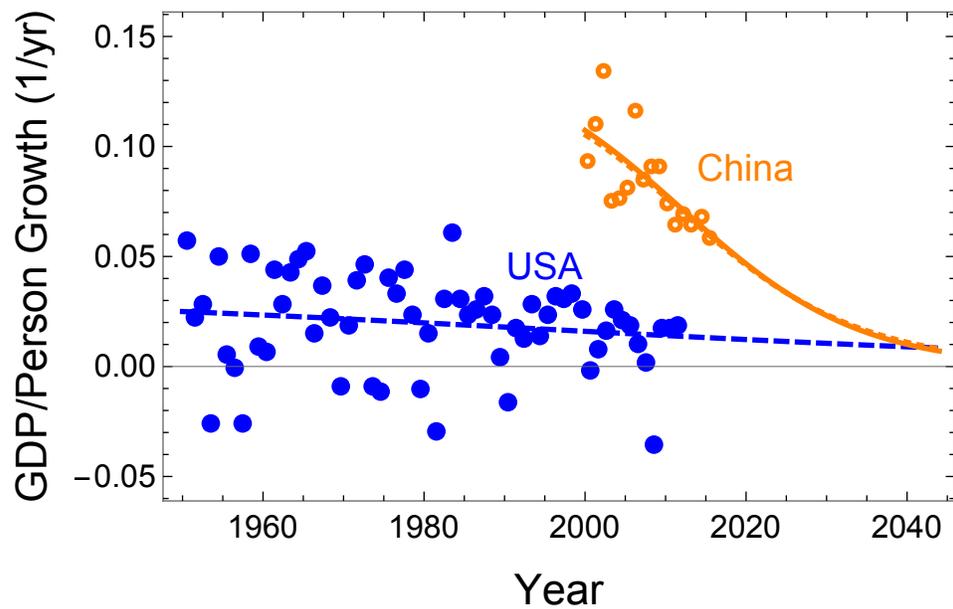
Fig. 3. Data and fits to per capita purchasing power parity for the incremental GDP and population increments over year 1820 values, using the analytic (dashed and solid curves) and numerical procedure (dotted curve) described in the Appendix.
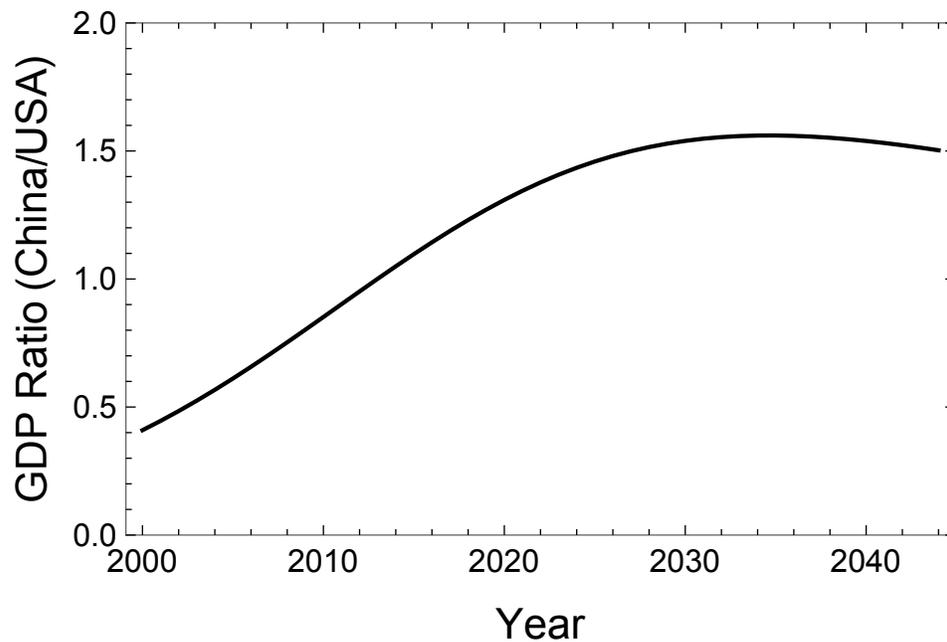
Fig. 4. Ratio of total Chinese to U.S. purchasing power GDP.

The extrapolation method used to produce the results in figure 3 gives a slightly lower GDP for China than the near-term IMF extrapolations shown in figure 2. Nevertheless, using the maximum likelihood method described in the Appendix, the results shown in figure 4 have China developing a GDP fifty percent larger than the United States within a decade of 2016 and maintaining that edge

for nearly two decades. Through 2008, the number of Chinese students returning from abroad was less than half of the number going abroad, but Chinese government incentives and overall improving employment opportunities changed that trend, with the ratio of students returning from China to those leaving reaching 5/6 in 2013 (Xiang 2016). Considering the number of its students receiving state of the art education and experience in engineering and natural sciences, the incentives that China provides for those with advanced degrees to return to China, and China's overall economic production capability, China can be expected to have the technical capacity to match or exceed U.S. capabilities in submarine design and deployment and in ASW capabilities, should China choose to develop and use those capabilities. Claims to the contrary (c.f. Cunningham and Fravel 2015) thus seem very unlikely to hold up over the time period covered in Figure 4. There remain two possible outcomes, both posing conundrums for retaining a damage limitation strategy.

One possibility is that China gains the ability to keep SSBNs undetected while on patrol. China is reportedly developing new Jin 096 SSBN carrying missiles designated as JL-3 (DOD 2016). Thomas Skypek [2010] estimated that, starting before 2020, every 2.5 years China could build a Jin 096, each with 24 MIRVed JL-3 missiles. China has been commissioning its first generation SSBNs at the rate of about one every two years since 2007. If China starts commissioning 096 type submarines before 2020 and continues to do so at a rate of one every two years or faster, then it could have an SSBN arsenal comparable to that of the United States by the end of the next decade. Moreover, Russia continues to deploy SSBNs, and India will likely follow China's lead.

During the Cold War, a missile fired from an SSBN would likely be known to come from either the USSR or one of the NATO allies. Soviet doctrine for counterattack against NATO as a whole mirrored the NATO's deterrence posture. In a world with more than two alliances possessing SSBNs and no limits on where they patrol, however, it could become difficult during or in the immediate aftermath of a nuclear attack to reliably identify the source of that attack. This situation could seriously undermine the rationale for nuclear deterrence, which relies on knowing where to threaten to retaliate.

It might seem outlandish to imagine that an SLBM launch by a third party would deliberately trigger a nuclear weapons exchange involving other countries, or involving one or more other countries and an alliance. However, the possibility of an inadvertent launch may increase as the number of nuclear-armed naval fleets increases. Moreover, when in desperate or even not so desperate straits, countries' leaders have been known to make decisions that lead to hundreds of thousands or millions of avoidable deaths. When their regime and their lives were targeted for extermination as announced by Winston Churchill's (1941) vow to "destroy Hitler and every vestige of the Nazi regime," the leaders of that regime ordered a continuing fight at enormous cost to its own people and others even after there was no plausible hope of avoiding defeat. When Saddam Hussein faced a less clear threat to the financial underpinnings of his regime in 1990, over 100,000 of his draftees soon died, and so eventually did he, because he took the enormous risk of the United States not leading retaliation against the attack on Kuwait that he ordered (Singer 2008). These examples were extreme events, widely separated in time; but it should be kept in mind that, once commissioned, individual nuclear ships can have an operational lifetime of up to half a century, and their mission types can persist longer than that. So even if an authoritarian regime deliberately guiding a region or the world towards catastrophe at enormous human cost remains a rare event, it is not out of the question that a submarine might launch nuclear weapons without the targeted country having adequate time to determine their origin before making a decision on retaliation.

Even if a third party never actually precipitates a nuclear war between other parties, just the ability to do so could preclude effective pressure on such a party to limit its nuclear weapons deployments. In time that, in turn, could lead to increased probability of use of nuclear explosives by a country or non-state actors, either inadvertent or deliberate.

Another possibility is that developments in ASW make it possible to track and tail state of the art SSBNs. During the Cold War, the principle technology for detecting submerged SSBNs was passive and active use of high-frequency sound. In the era of comprehensive computer-based modeling drawing on large databases, other possibilities may open up. Sound with frequencies of 1000 Hertz or lower has reduced location precision, but this may be compensated for by larger scale data collection and analysis and the lower attenuation of lower frequency sound during propagation through seawater. Detection of disturbance of background bioluminescence and other properties of water, including use of lasers or light emitting diode arrays with wavelengths around 480 nanometers, may complement other search methods. Underwater, surface, and airborne drones may allow for larger scale data collection than possible with manned systems. Successful use of a combination of new and older detection methods may require development and continually updating of data-based calibration of comprehensive time-dependent three dimensional models of the physical and biological ocean environment (Clark 2015; Swain, Trinath, and Tatavarti 2012).

If it becomes possible to track SSBNs sufficiently to allow use of a damage limitation strategy against them, then it is likely that this capability will become available to the China as well as to the United States. There is a difference, however, between SSBNs and land-based systems in this regard. This is because the time between detecting that an SSBN is preparing to launch and the last opportunity to prevent its missiles being able to reach their targets can be on the order of a minute. This means that authorization to attack members of an SSBN fleet may need to be delegated to a lower command level that could be lacking an integrated overview of the overall threat situation. Instead of naval commands being allowed more time for situation assessment than land-based missile commands as can currently be the case, SSBN and ASW resources could end up in a potentially more unstable position.

Naval Deployments and Posturing

The rationale for finding an alternative to the above-mentioned problems with SSBN deterrence or damage limitation can be confounded by planning for a conventional naval confrontation near China's coast. China has two principle contentions driving an interest in naval operations near its coast. One of these concerns China's disputed (Phillips, Homes, and Bowcott 2016) claim that 90% of the South China Sea lies in its exclusive economic zone. The other contention is that China has the right to govern Taiwan.

The U.S. Energy Information Agency has estimated natural gas and oil proved and probable reserves in the South China Sea at 190 trillion cubic feet (200 billion gigajoules) and 11 billion barrels of oil (about 70 billion GJ). Extracted over 27 years and sold at a profit of $4/GJ, these reserves would be worth about $40 billion per year. There are likely additional fluid fossil fuel resources under the South China Sea, but these are not estimated to be economically recoverable at present. Some of the estimated economically recoverable proved and probable resources are "in uncontested parts of the sea, close to shorelines of the coastal countries" (EIA 2013), so the part in contested waters is lower than the estimated total in the South China Sea. Even if a U.S. demonstration of ability to deploy substantial naval forces into the South China Sea were able to forestall Chinese recovery of fluid fossil fuels from contested areas, it is likely that China's ability to do the same would preclude other countries from extracting fluid fossil fuels from the same area. The net result would be in increase of China's fluid fossil fuel imports and thus an upward price impact on global markets for fluid fossil fuels. Assuming the applicability of a long-term price elasticity of 0.5, for example, this would imply a cost to other fluid fossil fuel importers of up to $20/billion dollars per year, depending on what fractions of the total estimate economically recoverable reserves lie in the disputed areas. The numbers involved in such an analysis have quite uncertain values. Whatever the appropriate numbers, however, under this type of assumption it is not in the direct economic interest of more geographically distant oil importing countries (including the United States) for U.S. naval

force projection to be effective in precluding China extracting fluid fossil fuels from contested areas of the South China Sea.

The annual value of the South China Sea as a fishery is of the same order of magnitude as the potential fossil fuel value, but there are important differences. A key difference is that there is an established fishery industry employing hundreds of thousands of workers distributed across several countries. Another difference is that coral reefs are in decline and many species are too heavily harvested for sustainability (Greer 2016). There are thus acute needs for more sustainable fishery management in the South China Sea, whether cooperative or hegemonic, and for aid to human populations that may be adversely affected however control of the fishery pans out. As with the South China Sea's potential fossil fuel resources, it is far from clear that U.S. naval power projection into the area near China will have a beneficial effect in correcting the current "everybody is losing" approach to fishery management in that area. Alone and in concert with other countries and global organizations, the United States might more usefully use economic rather than military approaches avoiding China's actions unduly disadvantaging other countries' interests in the South China Sea, even if China declines to comply with international court rulings (c.f. Phillips, Holmes, and Bowcott 2016).

Options for dealing with Taiwan have been summarized in Glaser (2015) and references therein. The question addressed here is what options are available that do not require U.S. ASW assets that might be deployed or deployable in a way that compromises a submarine Chinese nuclear second-strike capacity. It is possible, albeit not necessarily optimum, to choose such an option that is compatible with the Taiwan Relations Act (1979, Public Law 96-8, *U.S. Code 22* § 3301). Helping Taiwan to acquire and deploy, if and as needed, sufficient hardened land-based defenses against a Chinese naval and air assault is a possible albeit potentially expensive approach. This could be backed up with a commitment to use remotely stationed U.S. conventional or even nuclear weapons as a last resort to attack China's naval forces, should an unprovoked attack on Taiwan from the mainland look likely to succeed.

Glaser (2015) suggested attempting a negotiated settlement with China that would involve repealing or drastically modifying the Taiwan Relations Act in exchange for Chinese accommodation of interests of other countries in the region. This approach assumes China is actually interested in controlling the Taiwanese government to a greater degree than keeping that government from symbolic or legal moves connected with independence, and would thus make other concessions in exchange for changes in the relationship between the United States and Taiwan. If that assumption is incorrect, then this approach could yield nothing. Another potential hazard of this approach is that it could lure China into a position where successive Chinese leadership would move to exert control of internal governance in Taiwan, when otherwise that leadership might have been willing to continue the "one country, two systems," approach.

If the United States eventually decides in any case not to commit to maintaining Taiwan's autonomy in perpetuity, there are still options for supporting broader U.S. humanitarian and/or political goals. Immigration to the United States could be offered to Taiwanese, either those who would be expected to otherwise satisfy political asylum criteria after a takeover of Taiwanese governance by the mainland, or potentially much more broadly over a suitably extended preparatory time. The United States could also strengthen its commitments to other countries in the region in order to make it clear that Taiwan is considered to be within China's sphere of influence but the land occupied by other peoples is not. One consideration is that, by the time China's economic strength grows to the point where it becomes clearer that it is not in the U.S. interest to maintain Taiwan's internal autonomy, then the Taiwanese may not be materially disadvantaged by mainland interference in the governance of Taiwan. That interference may in any case be primarily at the national level in order to avoid disruption of governance at a more local level. The main effect would then be that Taiwanese would be to some or great extent politically disenfranchised. There were, however, as of 2015, over fourteen million international refugees in the world who are both severely materially

disadvantaged and politically disenfranchised, not including about five million Palestinians under the mandate of the UN High Commission on Refugees (Amnesty International 2015). By redirecting resources towards addressing the international refugee problem, the United States might be more efficacious in pursuing its humanitarian ends and bolstering its own credibility. There may even be opportunities for the United States and China to cooperate on helping refugees; China already has a People's Liberation Army battalion protecting a refugee camp in Africa (DoD 2016).

Policy Options

Having outlined the challenges facing the relationship between China and the United States concerning naval nuclear weapons, it remains here to examine some possibilities for meeting those challenges more creatively. The first two of four such possibilities have already been mentioned here, and will not be discussed further.

1. Decide not to configure naval forces and deployments to try to influence China's use of South China Sea oil, gas, and fisheries

2. Decide not to use conventional naval forces to try to influence Chinese policy on Taiwan

3. Seek an agreement with China to limit patrol zones of nuclear-armed submarines

4. Seek an agreement with China to mutually limit total numbers of assembled nuclear explosives

Stand-off Zones

Scott Sagan (1989) discussed nuclear submarine standoff zones in a bipolar nuclear-armed-navy context. Sagan described reasons why the U.S. government "never seriously pursued SSBN standoff zones in arms control negotiations." These include inference with other naval operations, crisis stability, and difficulties with verification and compliance.

The context discussed here differs in several respects from the bipolar nuclear-armed-navy context analyzed by Sagan. The main advantage of a standoff zone discussed by Sagan was a modest increase in the response time available after an SLBM launch. Given the limited amount information collection and decision-making time available between launch and impact of any type of nuclear-armed ballistic missile, a few minutes increase in that time was deemed insufficient to compensate for perceived disadvantages of trying to implement standoff zones. However, in the context described above of multiple nuclear-armed navies roaming at will for much or all of this century, the potential advantages of countries knowing that their SLBM launches can reasonably likely be correctly attributed are very much larger than just adding a few minutes to warning times.

An agreement with China on SLBM patrol areas is more likely to be achievable in the context of an understanding that the U.S. submarines will also not have missions of a non-nuclear weapons nature near China unless as part of jointly agreed upon operations. In that context, standoff zones could be configured so as to make the objection of interference with other submarine operations mute. Concerning crisis stability, a concern noted by Sagan is that correct or incorrect indications of the presence of a submarine not supposed to be in a standoff zone could either trigger a crisis or aggravate an ongoing one. Should there be multiple indications of such submarines, this could indeed be a problem. However, that inadvertent straying would occur with modern navigation aids would be remarkable even for a single submarine. Multiple contemporaneous detections either indicating inadvertent straying or being incorrect seems even more unlikely. Hostile action based perception of single straying submarine could be restricted to cases where independent evidence was determined at a higher command level to justify such action. The extent to which straying might be considered a problem depends on the level of confidence that verification measures would provide that a standoff restriction was being observed, which appears to really be the crux of the problem.

Given the importance of knowing that there are areas where multiple-fleet SSBNs are *not* patrolling*,* it could be worthwhile to reexamine modern technological verification options, some of

which might reduce or eliminate the need for on-board human monitoring. Since 1989, marine inertial navigations systems have had over a quarter century to take advantage of technological improvements. There is considerable experience with tamper proof seals and encryption that might allow design of sealed units that could verify patrol locations only adequate enough to verify avoidance of standoff zones. Miniaturization might allow occasional release of transmitters that move in unpredictable patterns and provide confirmation of verification information with a substantial but not excessive delay after release. Combined with port monitoring of nuclear missiles on ships, standoff zones may well turn out to be technologically verifiable.

Ideally, there would be sufficient cooperation from all countries with deployed SSBNs to build a useful degree of confidence that the source of an SLBM launch would be known. If not all countries with SSBN fleets cooperated on deployments and verification, then a launch from a zone verified not to contain a cooperating country's SSBN would cast additional suspicion on one or more non-cooperating countries. For example, if China, NATO, and India were observing such a cooperation agreement and had sufficient confidence in it, then a ballistic missile launch from one of their standoff zones from which their SSBNs were excluded would put any non-cooperating country with an SSBN fleet at risk of being considered by the target country to be the source of the launch. The existence of verification procedures pursuant to such an agreement could then provide an incentive for one or more additional countries to cooperate in order to avoid potentially being targeted because of ambiguity about the zones in which their SSBNs patrol.

There could be an advantage to a three rather than one or two patrol zone types. In special oceanographic zones such as seas defined by island chains and near countries with SSBNs, naval military activities by other cooperating SSBN states would be avoided. Oceanographic research that could compromise SSBN locations could be limited to the neighboring SSBN country, which would compensate non-SSBN states neighboring such seas by funding oceanographic research and sharing oceanographic research for mutual environmental and economic benefit. Beyond the special oceanographic zone would be an exclusive patrol zone for the country's SSBN fleet. Between these patrol zones would be nuclear weapons free ocean zones.

This discussion has so far concentrated on SSBNs, so there remains a need to consider submarines with nuclear-armed cruise missiles and other nuclear munitions. With adequate and more readily verifiable controls on the numbers of such deployed nuclear weapons, non-ballistic missiles need not necessarily constitute the kind of existential threat that SSBNs armed with about a hundred or more nuclear weapons on MIRVed SLBMs do. However, cooperating countries with nuclear weapons would need to limit all naval nuclear weapons to their own patrol zones, and non-cooperating countries would remain potential targets for retaliation in case of a nuclear attack that could be traced to them, e.g. by virtue of other possibilities having been eliminated.

Nothing here is meant to suggest that it is known that limits on nuclear-armed submarines are technologically, much less politically, feasible to implement. The point is that potential political feasibility over the long run cannot be usefully explored until technical feasibility with current and reasonably likely developable technology is more broadly understood.

Nuclear Explosives Build Down

It has become commonplace to observe that the damage from even a single thermonuclear explosion could outweigh the economic benefits that a country could normally hope to achieve through use of conventional forces (e.g. by considering the above-mentioned value of the fossil fuels and fishery yields from contested areas of the South China Sea). A challenge is for leaderships to keep non-economic considerations from overshadowing their countries' economic interests. To the extent that this can be done without increasing the probability of nuclear war, nuclear arsenals could be then held at much lower levels than, for example, the current U.S. and Russian holdings.

Since about 1985, the maximum number of assembled nuclear explosives has been decaying at about the radioactive decay rate of tritium, an isotope that is essential in high-yield to weight ratio nuclear weapons and has a half-life of 12.3 years. Barring an unexpected breakthrough in U.S.-Russian negotiations, it appears that the decline of this maximum number of Russia's assembled nuclear explosives will halt somewhere above about 4,500. It is interesting to ask what might occur if the United States were to continue reducing its stock of assembled nuclear weapons, e.g. at about the rate of tritium decay, provided that China agreed to limit its total amount to a number substantially lower that 4,500. Such an approach would leave Russia as the global outlier on Title VI of the Nuclear Nonproliferation Treaty, which requires the nuclear weapons states parties to the treaty to work in good faith in the direction of nuclear disarmament. How coordinated an effective international effort on enlisting Russia's cooperation in such circumstances would be could depend on domestic political developments in Russia over the coming decades. The United States and China could reassess their understanding on this about once a decade, with the United States retaining a formidable nuclear arsenal for two decades if starting from a total stockpile of assembled nuclear weapons of about 7,000.

The approach just described would be facilitated if NATO could come to a realization that Russia having a larger total stock of assembled nuclear weapons was essentially irrelevant from a military perspective, and thus also from a political perspective. Even if not, any perceived disadvantage of such a numerical disparity could be balanced by advantages to United States and China of pursuing their common interests even as the United States is in the process of building down its number of assembled nuclear explosives closer to that of China.

There are both technical and international political problems with implementing any or all of the four policy options listed above. These likely pale in the face of the political challenge of getting acceptance of any of them, starting from the current U.S. domestic political environment. Achieving such acceptance within the U.S. political system will require both patience and perseverance; but the challenge will likely be there as long as the Cold War was, so patience and perseverance are indeed what are called for.

Appendix: GDP Extrapolation

At the time of this writing, China and the United States were planning substantial expenditures on weapons systems relevant to submarine fleets. Some of these weapons systems, including ballistic missile submarines, are expected to have operational lifetimes of several decades. It was thus thought prudent here to consider extrapolation for several decades of economic production capabilities pertinent to fielding such systems. Such extrapolations can give very different answers, depending on the care taken with the underlying empirical or theoretical framework and the data sources and data calibration methods used. To provide insight into why the methods used here may or may not correspond to readers' expectations, this appendix describes those methods and some of the implications of the approximations used. Only a brief and minimally mathematical description of the methodology is given here, since more detail can be found in Appendix B of Singer, Milligan, and Rethinaraj (2014), which is in an open source publication.

The data set used has annual estimates of population and PPP GDP from 1820–2021, mapped onto the current geographical boundaries of all countries and other entities that provide reports to the United Nations. Estimates through 2008 are from Maddison-Project (2014). Estimates and extrapolations after 2008 are from the International Monetary Fund (2016) for GDP and from the United Nations (2015) for population, with those numbers multiplied by the ratio of the Maddison data to their data for 2008. The population for 1820 was subtracted from population data from 1950–2021, and the result was least squares fit with logistic functions of the form $a/(1+\text{Exp}[-b(t-c)])$, where t is time and a, b, and c are constants. The 1820 GDP values were subtracted from GDP, and the results used with the population data to calculate annual the annual growth rates for per capital GDP are shown in figure 3. There were large GDP perturbations during World War II for the

United States. At the beginning of the present century, there was pronounced change in the slope of a graph of per capita GDP versus time for China, as the effects of earlier economic reform there became evident. Thus, only the values shown by the closed and open circles in figure 3 for the United States and China were used to calibrate the GDP extrapolation.

We are interested here in that part of GDP that requires some minimum amount of commercial energy use per unit of GDP, since nuclear weapons systems fall in that category. The future of that portion of GDP is necessarily limited, since annual commercial energy use is physically limited. We thus divide GDP into three parts, pre-industrial, industrial, and post-industrial. The pre-industrial part is operationally defined as the GDP in the year 1820, which approximately marks the start of the part of the industrial revolution when commercial energy use started to play a major role. (The post-industrial part can include intellectual property and other components of GDP that can in principle grow without bound, but it is assumed that that part of GDP is small enough in the data stream used as to not appreciably affect the results.) For the industrial part of GDP, it is assumed that the division between consumption and investment at each time is allocated in order to maximize the utility of per capita consumption, multiplied by the population, discounted over time at a 2.3 percent annual social discount rate and integrated over all future time. GDP for a given capital stock and labor supply is assumed to grow as another logistic function proportional to a productivity factor of the form $1/(1+\text{Exp}[-r(t-t_{1/2})])$, where r is the initial growth rate of the productivity factor and $t_{1/2}$ is the time at which it reaches half of its maximum value.

The assumptions used lead to a pair of ordinary differential equations. The industrial portion of GDP, defined operationally as described above, is assumed to remain non-negative and also not grow without bound in the long-time limit. This assumption leaves one free boundary condition for the differential equations and the parameters r and $t_{1/2}$ to be adjusted to minimize the sum of the squares between the data and the model fit. The dotted line in figure 3 shows the result of that calculation. The nearly identical solid line in figure 3 shows the result with an analytic formula (Singer, Milligan, and Rethinaraj 2014). Only the analytic formula was used for the United States, since previous work had shown that to also be an adequate approximation.

To obtain the results shown in figure 4, the population and GDP growth rates were added and integrated over time and used to obtain formulas to be multiplied by a different constant for each case, with the value of that constant chosen to provide a least squares fit to the GDP data for each case. The 1820 values of the GDP for each case were added and the ratio taken to give the result shown in figure 4.

There is an assumption used in the calibration model that may lead to a modest underestimate of the future ratio of China's to United States' GDP. That is that the 1820 level population of each produces no more contribution to GDP than in 1820. For the United States, that population was only 11 million, but for China it was 388 million. Thus, the assumption that China has such a large permanent non-industrial peasant population is more significant than the implicit assumption that a small fraction of the United States is economically unproductive during their working age years. If one accounted for China managing to move a substantial fraction of the assumed 388 million portion of its population productively into its industrial sector, then the extrapolated ratio of GDP for China and the United States could be higher.

It is also interesting to note that the ratio of Chinese to U.S. GDP shown in figure 3 starts to decline slightly after 2034, even though at that point China still has a high growth rate for per capita GDP. The reason for this behavior is that increment of China's population over its 1820 value reached half of its maximum in 1976, while that of the United States reached its half maximum only in 2008 and continues to have a larger rate annual percentage growth rate than China's. For the logistic fits to population used here to apply, China might have to switch to more pronatalist policies, while the United States would need to continue to allow for substantial levels of in-migration for several decades. United Nations extrapolations show a slight decline in China's population by the

mid twenty-first century. Also, the U.S. administration may try to restrict immigration starting in 2017. Qualitatively, assuming that the United Nations' extrapolation of China's population holds up, and that more effective restrictions on immigration into the United States are persistently maintained, would tend to have opposite effects on the long-term evolution of the China/U.S. GDP ratio shown in figure 4. However, in practice neither of these two possibilities seems likely to alter the basic result shown in figure 4, which is that China appears headed towards a substantially larger purchasing power GDP than the United States during much of the remainder of the first half of the twenty-first century.

Acknowledgment

References

Amnesty International. 2015. Global refugee crisis—by the numbers, https://www.amnesty.org/en/latest/news/2015/10/global-refugee-crisis-by-the-numbers/, accessed 22 September 2016.

Blair, Bruce. 1993. *The Logic of Accidental Nuclear War*, Washington: The Brookings Institution.

Bloembergen, N., C. K. N. Patel, P. Avizonis, R. G. Clem, A. Hertzberg, T. H. Johnson, T. Marshall, R. B. Miller, W. E. Morrow, E. E. Salpeter, A. M. Sessler, J. D. Sullivan, J. C. Wyant, A. Yariv, R. N. Zare, A. J. Glass, L. C. Hebel, G. E. Pake, M. M. May, W. K. Panofsky, A. L. Schawlow, C. H. Townes, and H. York, Report to The American Physical Society of the study group on science and technology of directed energy weapons, *Reviews of Modern Physics* **59**, S1.

Churchill, Winston. 1941. Broadcast on the Soviet-German War, http://www.jewishvirtuallibrary.org/jsource/ww2/churchill062241.html, accessed 23 September 2016.

Clark, Bryan. 2015. The emerging era in undersea warfare, https://issuu.com/csbaonline/docs/csba_new_era_undersea_warfare_repor?e=15123547/10966511, accessed 21 September 2016.

Cunningham, Fiona, and M. Taylor Fravel. 2015. Assuring assured retaliation: China's nuclear posture and U.S.-China strategic stability, *International Security* **40**, No. 2, 7–50.

Davenport, Kelsey. 2016. Nuclear weapons: Who has what at a glance, https://www.armscontrol.org/factsheets/Nuclearweaponswhohaswhat, accessed 21 September 2016.

DoD 2016. Military and security developments involving the People's Republic of China 2016, Washington DC: Office of the Secretary of Defense.

EIA (U.S. Energy Information Agency). 2013. South China Sea, https://www.eia.gov/beta/international/regions-topics.cfm?RegionTopicID=SCS, accessed 23 September 2013.

Forsberg, Tuomas, and Hiski Haukkala. 2016. *The European Union and Russia*, London: Palgrave.

Glaser, Charles. 2015. A U.S.-China Grand Bargain? The hard choice between military competition and accommodation, *International Security* **39**, No. 4, 49–90.

Glaser, Charles, and Steve Fetter. 2016. Should the United States reject MAD? Damage limitation and U.S. nuclear strategy toward China, *International Security* **41**, No. 1, 49–98.

Greer, Adam. 2016. The South China Sea is really a fishery dispute, http://thediplomat.com/2016/07/the-south-china-sea-is-really-a-fishery-dispute/, accessed 22 September 2016.

International Monetary Fund. 2016. World economic outlook database, https://www.imf.org/external/pubs/ft/weo/2016/01/weodata/index.aspx, accessed 12 June 2016.

International Student and Scholar Services. 2015. Fall 2015 international statistics, http://isss.illinois.edu/download_forms/stats/fa15_stats.pdf, accessed 21 September 2016.

Kimball, Daryl. 2016a. The nuclear testing tally, https://www.armscontrol.org/factsheets/INFtreaty, accessed 20 November 2016.

Kimball, Daryl. 2016b. The Intermediate Range Nuclear Forces (INF) Treaty at a glance, https://www.armscontrol.org/factsheets/nucleartesttally, accessed 23 September 2016.

Kristensen, Hans. 2007. Russian submarine patrols, http://www.nukestrat.com/russia/subpatrols.htm, accessed 23 September 2016.

Maddison-Project. 2014. http://www.ggdc.net/maddison/maddison-project/data.htm, accessed 18 November 2014.

Open Doors. 2015. International Students in the U.S., http://www.iie.org/Research-and-Publications/Open-Doors#.V-LOOYXsdOe, accessed 21 September 2016.

Phillips, Tom, Oliver Holmes, and Owen Bowcott. 2016. Beijing rejects tribunal's ruling in South China Sea case, *The Guardian*, July 12.

Ploughshares 2016. World nuclear weapon stockpile, http://www.ploughshares.org/world-nuclear-stockpile-report#, accessed 23 September 2016.

Sagan, Scott. 1989. *Moving Targets: Nuclear Strategy and National Security,* Princeton, NJ: Princeton University Press.

Singer, Clifford. 2008. *Energy and International War: From Babylon to Baghdad and Beyond*, Singapore: World Scientific.

Skypec, Thomas. 2010. China's sea-based nuclear deterrent in 2020: For alternative force structures for China's SSBN fleet, in *A Collection of Papers from the 2010 Nuclear Scholars Initiative,* Washington DC: Center for Strategic and International Studies.

Singer, Clifford, Timothy Milligan, and T. S. Gopi Rethinaraj, 2014. How China's options will determine global warming, *Challenges* **5**, 1–25.

Swain, Sanjaya, K. Trinath, and Tatvarti. 2012. Non-acoustic detection of moving submerged bodies in ocean, *International Journal of Innovative Research and Development* **10**, 361–372.

United Nations. 2015. Revision of world population prospects, https://esa.un.org/unpd/wpp/, accessed 28 May 2016.

U.S. State Department. 2010. New Start Treaty text, http://www.state.gov/t/avc/newstart/c44126.htm, accessed 23 September 2016.

U.S. State Department. 2015 Report on Adherence to and Compliance With Arms Control, Nonproliferation, and Disarmament Agreements and Commitments, http://www.state.gov/t/avc/rls/rpt/2015/243224.htm, accessed 21 September 2016.

Xiang, Biao. 2016. Emigration trends and policies in China: Movement of the wealthy and highly skilled, Transatlantic Council on Migration, http://www.migrationpolicy.org/sites/default/files/publications/TCM_Emigration-China-FINAL.pdf, accessed 1 February 2017.