

Rising Military Spending Jeopardizes Climate Targets

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I first summarize the argument and then discuss the modeling that underlies it.

Summary of the paper and its results. The aim of the paper is to quantify the impact of global military expenditure as a percentage of GDP (military expenditure ratio) on CO₂ emission intensity. 48-50. The argument is that “Because of the voluntary and inconsistent nature of military fuel use data reporting to the United Nations Framework Convention on Climate Change (UNFCCC), there is significant uncertainty in accurately quantifying global military and conflict emissions. Consequently, most SSP scenarios have not quantitatively integrated the potential impacts of increased global tensions or conflicts on temperature projections.” (31-35). Recent increases in conflict could exacerbate climate change vulnerability, impede climate mitigation efforts, and obstruct multilateral climate action. 40-41.

The method is to “investigate and quantify the relationship between the global military expenditure ratio and CO₂ emission intensity.” 55. And then to “examine the composition of war-related emissions and assess the impact of unaccounted emissions from wars on the anthropogenic CO₂ emission inventory” 59. They “utilize the established relationship between the military expenditure ratio and emission intensity, along with the correlation between annual CO₂ emissions and the annual change in global surface temperature (GST) derived from IPCC AR6 data, to modify the future GST increase projections in the SSP scenarios, considering various levels of global tension.”

The paper’s analysis and conclusions depend on modeling and estimating military emissions as a function of military expenditure ratios and estimating the emissions that result from different scenarios. The author(s) assert that “The global military expenditure ratio serves as a proxy for the level of global tension.”

Their primary finding is that “events such as the 2001–2011 War on Terror and the 2021 prelude to the Russian–Ukrainian war have led to a 0.041% (95% CI: 0.030–0.052) kg/USD increase in CO₂ emission intensity (CO₂ emissions per unit of GDP) for each 1% rise in global tensions.” This increment accounts for 30% of the total change in CO₂ emission intensity from 1995 to 2021.

Military emissions are generally not counted but the global military expenditure ratio significantly influences CO₂ emission intensity, primarily by impacting total CO₂ emissions.

Their argument concludes by saying:

An increase in the global military expenditure ratio prolongs the time required to reduce GST increase below 1.5°C following the initial overshoot. For example, a 5% rise in military expenditure ratio compared with the SSP1-1.9 baseline would delay achieving the 1.5°C 204 climate target by an additional 13 years, resulting in a 0.05°C increase in GST at the end of this century. If the global military expenditure ratio increases beyond 206 11%, it becomes unfeasible to meet the 1.5°C climate target (after the overshoot) by the end of the 207 century, with GST potentially rising by over 0.11°C by 2099. Conversely, in scenarios where 208 global military expenditure decreases by 2% compared to the SSP1-1.9 baseline, humanity could potentially reach the goal of restricting the GST increase below 1.5°C three years ahead of the original schedule.

The present findings suggest that escalating global tensions, leading to a military expenditure ratio exceeding 11% (or 23%), will result in missing the critical opportunity to prevent the climate system from reaching hazardous levels of greenhouse gasses. If emissions from the destruction of carbon reservoirs and post-war reconstruction were comprehensively considered, the threshold for the military expenditure ratio jeopardizing climate targets would likely be lower. Enhancing

transparency and effectiveness in the national reporting of military fuel use within the UNFCCC reporting framework is imperative to foster research on military emissions and their impact on climate change. 247-254.

Discussion of the assumptions, methods and modeling.

The argument is a good, albeit incomplete, summary of some of the previous research and arguments relating military spending, military and conflict emissions, and emissions intensity. It may be significantly underestimating the effects of military spending. They have missed some important literature which would inform their arguments. I make suggestions below.

The heart of the paper is the model, here simplified as a set of propositions.

I. The Global Military Expenditure Ratio (MILEX ratio) defined as Global Military Spending/Global GDP is a function of/proxy for global tension;

II. CO2 emission intensity is a function of MILEX ratio “a significant positive correlation exists between the three-year weighted global military expenditure ratio and the detrended CO2 emission intensity” (114).

They found: An increase (or decrease) of 1% in the global military expenditure ratio leads to an increase (or decrease) of 0.041 (95% CI: 0.030–117 0.052) kg/USD in CO2 emission intensity “The global military expenditure ratio significantly influences CO2 emission intensity, primarily by impacting total CO2 emissions” 125-126. MILEX ratio accounts for 30% of the total change in emission intensity from 2021 to 1995. 118.

III. Overall, emissions intensity change in Global surface temperatures. This will vary according to different levels of MILEX.

While I think their basic conclusions are more right than wrong there is room for improvement in the model. The key element in the model is the assertion in step II: total CO2 emissions are a function of MILEX ratio. The question is whether this is so, and if MILEX ratio is a good indicator. Is there a better way to estimate military and war related emissions? Is everything important included in the model?

The assumption that that total emissions (including military and conflict emissions) are a function of MILEX ratio is correct, but have they quantified the effect appropriately? As the author(s) acknowledge, the military expenditure ratio is a lagging indicator of military emissions (“detrended global CO2 emission intensity demonstrates lagging yet synchronous fluctuations with global military expenditure.” This is why they use a 3 year weighted average of MILEX ratio. That is fine as far as MILEX ratio goes. But there are significant problems with global MILEX ratio as an indicator of military and conflict emissions.

My own calculations suggest that MILEX ratios for the US are strongly correlated with actual military emissions from 1975-2022. However, military spending is not distributed evenly even among the countries with the largest military spending and we can't assume that this correlation is strong for most militaries. The US accounts for the largest share of Global Military Expenditure (c. 38%); China 14% and India 4% in 2022. The states with the largest military spending (the US and China and India) have very large economies relative to their military sectors, which means that their MILEX ratio, for example respectively US 3.45 % and China (1.6%) and India (2.43) in 2022 is relatively low compared to their military spending in absolute terms and as a percent of global military spending. States with smaller economies can have higher MILEX ratios than countries with high absolute levels of MILEX, yet have much smaller militaries and thus contribute less military emissions. — for example, Algeria 4.8% and Israel, 4.5 % in 2022. And there are countries at war with relatively higher MILEX ratios Russia, 4.% Ukraine, 33.5% in 2022 and the US over 4% from 2004-2013.

The quantification of military emissions and conflict emissions is the next important step in the argument. The authors categorize the emissions associated with militaries and war as: “four principal sources of CO2 emissions associated with warfare: i. operational emissions (originating from military bases and operations); ii. military industry (including the production of vehicles, weapons, and equipment); iii. post-conflict reconstruction; and iv. destruction of carbon reservoirs. 126-130.” Further they say, “current accounting for war-related emissions typically includes only sources i and ii, often overlooking the others.” 131 The authors themselves don't take on the destruction of carbon reservoirs in the paper. That could be much better fleshed out, but perhaps not in this paper.

They then take out the post-conflict reconstruction category from their analysis. “most emissions from reconstruction are included in the emission inventory and categorized under the construction sector. Therefore, in quantifying the relationship between the military expenditure ratio and CO2 emission intensity, we do not separately consider emissions from post-conflict reconstruction. However, note that this emission source could significantly affect the CO2 emission accounting in large-scale wars.” 145-148. Eliminating estimates of post-conflict reconstruction is the right move, but they should note as Lennerd DeKlerk does in work on Ukraine that reconstruction can be more or less carbon intensive.

The main point here is that there are gaps in our understanding of the categories, which then makes conclusions about the effect of military spending ratios less robust. Which raises the fundamental question: Have the authors conceptualized military and conflict related emissions appropriately?

I have my concerns. The analysis could be much stronger if the authors separately analyzed the military emissions in category i. Specifically, if they chose to focus on either calculating or estimating direct emissions from bases and operations (including exercises), they could use example cases where we have the military emission numbers and the military spending numbers (both absolute and as a ratio) to estimate the change in emissions with military spending.

The best numbers on total military emissions for a state are Crawford's (2019 and 2022) data on US military emissions from 1975-2020 and Stuart Parkinson's Scientists for Global Responsibility data, for the UK, “the Environmental Impacts of the UK Military Sector,” (<https://www.sgr.org.uk/publications/environmental-impacts-uk-military-sector>) for the UK. (The UK 3% of

the total Milex with a Milex ratio of 2.23%). Keep in mind that both sets of data are conservative.

This data — from Crawford's DOD direct emissions estimates and Parkinson's data on the UK — suggests that military emission intensity is both higher for the US and UK militaries than for the civilian sector and that these ratios may vary significantly among militaries.

The first point is the most important. If emission intensity for military operations and installations is higher than for other sectors, the effect of military spending ratios on overall emissions may be underestimated in the paper. The same goes for military industry.

The second point, that emission intensity varies across militaries, suggests that it may be important to track the emissions of the militaries that are most emission intensive. Specifically, again, the US is the most important case here given that its operations and scale (and MILEX) are so much larger than all other militaries and because the lion's share of its emissions are from aircraft. The German military may be the next most intensive. There is no multiplier in this paper for radiative forcing due to air operations. Further, the military industry of the US is the largest.

So, while I was unable in the time I had to review the paper to do all the necessary calculations, I suggest that the paper suffers from not highlighting the ways military emissions differ across the globe and differ from the civilian sector

Finally, I suggest that the author see several other sources. Axel Michelowa 2001; Neta Crawford 2022; Ho-Chi Lin, et al, 2022. <https://transformdefence.org/publication/climate-crossfire-how-natos-2-military-spending-targets-contribute-to-climate-breakdown/>. The last is quite important. The paper by Lennard de Klerk has an incomplete citation.

Reviewer #2

(Remarks to the Author)

This is an interesting premise, but the article is severely challenged by key assumptions and lack of clarity in how their findings. I would suggest that with very significant revisions this manuscript would be worth reconsideration, but, in its current form, it leaves the reader with too many questions and concerns about the assumptions that they make. I do not think it is a fit for this journal. Despite my recommendation, I commend the authors on finding an interesting topic that could have important implications for climate and defense policy and encourage them to dig into this question further.

Major issues

- There is a lack of clarity in the association between the increase in emissions in the period identified by the authors (1995 – 2021) – see fig 1. Though they do model this out, it is not clear to me (perhaps another reviewer will be able to speak to this) how they controlled for other factors (e.g., the rise in China's wealth and emissions; population growth; general economic growth). This needs to be explained in more detail as it is a central argument. I would note, however, that I am unsure this is the right journal for such analysis as I imagine that has to be a fairly in-depth statistical methods.
- I agree with the authors that there is significant uncertainty in the volume of emissions emanating from global conflict. I encourage them to continue to work through this problem. I do, however, find that their analysis needs to dig deeper. It seems to rely on just a handful of sources and does not examine the issues from other possible angles. For example, do efforts to 'green' militaries potentially lead to major breakthroughs, will global conflict slow global commerce, etc. these questions need to be more clearly examined.
- The writing can at times be hard to follow. For example, I did not understand what the authors meant when they said "The global military expenditure ratio significantly influences CO2 emission intensity, primarily by impacting total CO2 emissions". Perhaps this is just a typo, but the language was unclear throughout the manuscript.
- The authors make some important points that are buried in the manuscript. For example, I would like to see more attention on the 4 types of emissions affected by conflict. 3 and 4 iii. post-conflict reconstruction; and iv. destruction of carbon 129 reservoirs" These are important points but were examined only briefly (again – this might need a longer runway and therefore is better suited for another journal)

Minor issues

- I am unsure how it was determined that global military expenditure was identified as a proxy for global tensions. This needs to be justified more clearly.
- On page 4 line 83, I believe you mean 'enduring freedom' not 'operation ending freedom'
- In lines 203 – 205 the authors point out a 13 year delay in achieving climate targets. They need to make clear why this matters in the context of global emission pathways. This seems fairly minor all things considered

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I think these are acceptable responses to the comments made by both reviewers. They are clarifications and additions which make this a much stronger manuscript.

Reviewer #3

(Remarks to the Author)

The manuscript provides an important contribution to understanding the interplay between global military expenditure and climate change mitigation efforts. By exploring how global tensions, as measured by military expenditure as a percentage of GDP, influence CO2 emissions, the study bridges an important gap in climate policy discussions and military-environmental research. However, while the study is commendable for its elaborate quantitative approach and policy-relevant insights, there are certain areas that I would like to see improved for greater clarity and impact.

Regarding the theoretical expectations, the manuscript discusses the relationship between military activities and CO2 emissions but could elaborate further on the underlying mechanisms. While the focus on operational emissions and supply chains is helpful, the omission of emissions from post-conflict reconstruction and destruction of carbon reservoirs seem to weaken the robustness of the findings.

The study mentions indirect effects, such as resource allocation priorities shifting from climate to military expenditures. However, these implications are not deeply explored or modeled. Is it possible to include qualitative or quantitative evaluations of such shifts to strengthen the analysis?

The relationship between military expenditure and CO2 emissions is also complex and may be influenced by various omitted variables. It was not entirely clear to me if these were included in the analysis, but just to think of a few - some economies rely more on fossil fuels or energy-intensive industries, which could amplify emissions unrelated to military expenditure. The proportion of renewable vs. fossil fuel energy in a country's energy portfolio could also mediate the relationship between military spending and CO2 emissions. In terms of global supply chains, military expenditures often rely on international procurement of equipment and materials, which might result in emissions originating outside the country's borders. Similarly, countries that export large quantities of military equipment may show higher emissions despite local military spending being modest. Finally, countries with opaque reporting practices for military and environmental data may skew results. In any case, I think at least a qualitative discussion of some of these potentially confounding factors will strengthen the arguments and findings of the paper.

As for the sensitivity scenarios, in the manuscript they provide valuable insights into how variations in military expenditure impact CO2 emissions and temperature targets. However, I wondered how realistic are the projected increases in military expenditure ratios? Perhaps incorporating expert forecasts or scenario probabilities would increase the credibility to the projections.

On the policy side, while the study identifies global peace as a crucial factor for achieving climate targets, its recommendations could be a bit more specific. Suggestions for practical mechanisms to integrate military emissions into global climate agreements, such as the UNFCCC framework, could increase the paper's impact.

Finally a few minor comments:

The figures and graphs are well-designed but could benefit from additional explanatory notes for clarity, particularly for non-specialist readers.

A brief discussion on the limitations of the data sources, especially regarding inconsistencies in military emissions reporting, would help the manuscript's credibility.

While the study focuses on the global context, mentioning specific case studies (e.g., Russia-Ukraine conflict) in greater detail could illustrate the mechanisms more clearly.

Version 2:

Reviewer comments:

Reviewer #3

(Remarks to the Author)

I have now reviewed the revised manuscript and find that the authors have addressed my comments and suggestions satisfactorily. I have no further suggestions and recommend the manuscript for publication.

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Response to Reviewer #1

The term “revised manuscript” in this context denotes the PDF file we have submitted, which clearly highlights the modifications made from the previous version. We have addressed each comment made by Reviewer #1 and Reviewer #2. For clarity, we have presented [the reviewers’ comments in blue](#) and our responses in black.

General Comments:

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III. Overall, emissions intensity change in Global surface temperatures. This will vary

according to different levels of MILEX.

Response: Thank you for your comprehensive and accurate summary of our work and for your constructive comments. We have improved the manuscript based on your helpful suggestions. Below, we divide your comment into 7 parts and insert our replies below each part of the comment.

Specific Comments:

Comment 1. While I think their basic conclusions are more right than wrong there is room for improvement in the model. The key element in the model is the assertion in step II: total CO₂ emissions are a function of MILEX ratio. The question is whether this is so, and if MILEX ratio is a good indicator. Is there a better way to estimate military and war related emissions? Is everything important included in the model?

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Response: The total CO₂ emissions are a function of global MILEX ratio is proved in the revised manuscript (L137-140). The Stockholm International Peace Research Institute (SIPRI) statistics for military expenditures used in this study include inputs to military operations, military industry, and partially post-conflict reconstruction (Supplementary Table 2), indicating that the statistical relationship between the global MILEX ratio and CO₂ emission intensity accounts for the effects of these emission sources. However, as post-conflict reconstruction and carbon reservoir destruction are directly linked to actual warfare, our approach may underestimate the impact of global

MILEX ratio on total emissions (**L157-163** in the revised manuscript).

Based on the military related emission data (Crawford, 2022; Lin et al., 2023) you suggested, we find that military expenditures, expressed as a percentage of GDP, can serve as an effective indicator of military related emissions for most North Atlantic Treaty Organization (NATO) members, particularly the United States (Supplementary Fig. 7). This relationship is evidenced by a strong correlation between U.S. MILEX ratios and emissions from the U.S. Department of Defense (DOD; Crawford, 2022) from 1975 to 2020 (dark blue dots in Supplementary Fig. 7; Supplementary Fig. 8), with a Pearson correlation coefficient of 0.89 that passes the 95% confidence level. Similarly, other European NATO members, notably Germany, France, and Spain, exhibit a clear positive correlation between their military-related emissions (including sources i and ii) and MILEX ratios from 2021 to 2023 (Supplementary Fig. 7). In fact, we do not need to assume the correlation between MILEX ratios and total emission intensities is strong for every country. Due to global trade and supply chains, the impact of regional conflicts on carbon emissions (particularly from the military industry) tends to be global. Analyzing a country in isolation may overlook important information. The above discussion has been added in the section “Mechanism behind the relationship between global MILEX ratio and CO₂ emission intensity” in the revised paper (**L208-228**).

Comment 2. The quantification of military emissions and conflict emissions is the next important step in the argument. The authors categorize the emissions associated with militaries and war as: “four principal sources of CO₂ emissions associated with warfare: i. operational emissions (originating from military bases and operations); ii. military industry (including the production of vehicles, weapons, and equipment); iii. post-conflict reconstruction; and iv. destruction of carbon reservoirs. 126-130.” Further they say, “current accounting for war-related emissions typically includes only sources i and ii, often overlooking the others.” 131 The authors themselves don’t take on the destruction of carbon reservoirs in the paper. That could be much better fleshed out, but perhaps not in this paper.

Response: We agree that carbon emissions from destroyed reservoirs (source iv) need more accurate estimation in future studies. Current estimates of these emissions are limited and highly uncertain, yet they potentially have a significant impact on climate change during large-scale conflicts. In this study, we briefly examine their implications for modeling the relationship between global MILEX ratio and CO₂ emission intensity. The global CO₂ emission intensity will increase by 0.042 kg/USD (95% CI: 0.030–0.054) for each 1% increase in global MILEX ratio if emissions from the destruction of carbon reservoirs are considered (assuming an additional emission of 320 million tons of CO₂ annually during Phase II, and 32 million tons of CO₂ from 2022 to 2023 owing to reservoir destruction). This rise to 0.042 kg/USD marks a 5% increase from the initial 0.04 kg/USD. Notably, 20th-century conflicts produced higher carbon emissions from destroyed carbon reservoirs than recent wars. For instance, the Gulf War resulted in approximately 300 million tons of CO₂ emissions, whereas the 2022 Russia-Ukraine

war has led to an estimated 17.7 million tons of CO₂ equivalent. The above analysis has been added in **L179-191** of the revised manuscript.

Comment 3. They then take out the post-conflict reconstruction category from their analysis. “most emissions from reconstruction are included in the emission inventory and categorized under the construction sector. Therefore, in quantifying the relationship between the military expenditure ratio and CO₂ emission intensity, we do not separately consider emissions from post-conflict reconstruction. However, note that this emission source could significantly affect the CO₂ emission accounting in large-scale wars.” 145-148. Eliminating estimates of post-conflict reconstruction is the right move, but they should note as Lennerd DeKlerk does in work on Ukraine that reconstruction can be more or less carbon intensive.

Response: Thank you for acknowledging the step of “eliminating estimates of post-conflict reconstruction.” The relevant rationale is further refined in **L164-169** in the revised paper. However, this source could significantly affect the CO₂ emission accounting in large-scale wars, as the construction sector is more carbon-intensive than other civilian sectors (de Klerk et al. 2023). For instance, the expected emissions from rebuilding civil infrastructure due to the Russia-Ukraine war in 2022 are approximately 50 million tons, accounting for 50% of all war-related emissions for that conflict (de Klerk et al. 2023). We have added this discussion to the revised manuscript (**L169-173**).

Comment 4. The main point here is that there are gaps in our understanding of the categories, which then makes conclusions about the effect of military spending ratios less robust. Which raises the fundamental question: Have the authors conceptualized military and conflict related emissions appropriately?

I have my concerns. The analysis could be much stronger if the authors separately analyzed the military emissions in category i. Specifically, if they chose to focus on either calculating or estimating direct emissions from bases and operations (including exercises), they could use example cases where we have the military emission numbers and the military spending numbers (both absolute and as a ratio) to estimate the change in emissions with military spending.

The best numbers on total military emissions for a state are Crawford’s (2019 and 2022) data on US military emissions from 1975-2020 and Stuart Parkinson’s Scientists for Global Responsibility data, for the UK, “the Environmental Impacts of the UK Military Sector,” (<https://www.sgr.org.uk/publications/environmental-impacts-uk-military-sector>) for the UK. (The UK 3% of the total Miledex with a Miledex ratio of 2.23%). Keep in mind that both sets of data are conservative.

This data — from Crawford’s DOD direct emissions estimates and Parkinson’s data on the UK — suggests that military emission intensity is both higher for the US and UK militaries than for the civilian sector and that these ratios may vary significantly among militaries.

Response: We found a significant positive correlation between the global MILEX ratio and the detrended global CO₂ emission intensity after the end of the Cold War. However, this manuscript does not provide a sufficient explanation for this statistical relationship. To more convincingly analyze whether and how the MILEX ratio affects the detrended CO₂ emission intensity, we have conducted an in-depth analysis by country and military sector based on the method and military emission data you suggested (L193-228 in the revised manuscript).

Regarding whether military and conflict-related emissions were conceptualized appropriately in our modeling, please see the response to **Comment 1** (also shown in L157-163 of the revised manuscript). Based on your suggested methodology and data, we have taken North Atlantic Treaty Organization (NATO) members as examples to analyze the relationship between military emissions (source i or ii) and the MILEX numbers (both absolute and as a ratio; Supplementary Figs 7 and 8). Please see the response to **Comment 1** (also L208-216 of the revised manuscript). Besides, we have compared emission intensities across various military categories with the national total emission intensity, using the United States as an example. Please see the response to **Comment 5** for more details.

Comment 5. The first point is the most important. If emission intensity for military operations and installations is higher than for other sectors, the effect of military spending ratios on overall emissions may be underestimated in the paper. The same goes for military industry.

Response: We have incorporated a comparison of emission intensities across various military categories with the national total emission intensity, using the United States as an example (Supplementary Fig. 6; L195-206 of the revised manuscript). The military industry (source ii) shows significantly higher emission intensity than the U.S. total (red vs. orange markers), while military bases and operations (source i; blue markers) are less emission-intensive. The combined military emission intensity (sources i and ii) exceeds the national total emission intensity (green markers vs. orange markers), indicating that military activities are generally more emission-intensive than civilian sectors. The emission intensity for the U.S. military industry is estimated based on two alternative methods described by Crawford (2022), both showing nearly double the U.S. total emission intensity during 2018-2019. Notably, European arms companies typically demonstrate lower emission intensities than their U.S. counterparts (evident in the different shapes of pink markers), as also discussed by Lin et al. (2023).

We believe that historical carbon emission data already incorporates the impact of differences in carbon emission intensity between various military sectors and other civilian sectors. However, in future emission projections, using only the global MILEX ratio without including information on expenditures in different military sectors (military bases, operations or military industry) may underestimate or overestimate the impact of the MILEX ratio on overall emissions.

Comment 6. The second point, that emission intensity varies across militaries, suggests that it may be important to track the emissions of the militaries that are most emission intensive. Specifically, again, the US is the most important case here given that its operations and scale (and MILEX) are so much larger than all other militaries and because the lion's share of its emissions are from aircraft. The German military may be the next most intensive. There is no multiplier in this paper for radiative forcing due to air operations. Further, the military industry of the US is the largest.

Response: We calculate military emission intensities for different militaries (Table R1) based on the estimated military carbon footprint (including sources i and ii) of NATO members during 2021-2023 (Lin et al., 2023) and the SIPRI military expenditure data. The 2021-2023 average carbon emission intensity of the U.S. military of 0.37 kg CO₂e/USD is significantly higher than other European NATO members. Regarding the military industry, European manufacturers are generally considered to be more energy-efficient than their North American counterparts (discussed in **L204-206** of the revised manuscript).

Nevertheless, we should emphasize the importance of analyzing the impact of military activities on carbon emissions from a global perspective, given the interconnected nature of global supply chains. The influence of MILEX ratios on CO₂ emissions extends beyond the countries directly involved in conflicts. Between 1995 and 2019, North America (particularly the U.S.) was the primary driver of changes in the global MILEX ratio (Supplementary Fig. 2), while East Asia (especially China) contributed the most to global CO₂ emission changes during this period (Supplementary Fig. 9). This pattern is linked to a significant increase in military-related imports from China to the U.S. during the War on Terror (Supplementary Fig. 10). More recently, Eastern Europe has become the main contributor to the rise in global MILEX ratio from 2021 to 2023, largely due to the Russo-Ukrainian war. However, global emission intensity has remained relatively stable since 2020, with detrended carbon emissions increasing in Western, North, and Central Europe while decreasing sharply in East Asia. These observations highlight the necessity of adopting a global perspective when evaluating the environmental impact of military activities. The above discussion has been added in **L218-228** of the revised manuscript.

Table R1. The average military emission intensity (including sources i and ii; kgCO₂e/USD) for the 2021–2023 period for some NATO members.

Country	The US	Canada	Poland	France	Germany	Greece
Military emission intensity	0.37	0.10	0.25	0.17	0.13	0.28
Country	Italy	Netherlands	Spain	United Kingdom	Turkey	/
Military emission intensity	0.15	0.15	0.17	0.16	0.32	/

Currently, approximately 5% (90% confidence interval: 2–14%) of climate change can be attributed to global civil aviation emissions (Lee et al., 2009). The emissions from aircrafts mainly include CO₂, NO_x, aerosols and their precursors, and water vapor (H₂O), which exert either positive or negative forcing on the Earth's radiation balance. Additionally, water vapor emissions from aircraft form contrails and contrail cirrus, affecting the solar radiation entering the atmosphere and the infrared radiation emitted by the Earth's surface and atmosphere. In summary, the impact of aircraft emissions on the climate is highly complex and is not the primary focus of this work.

Comment 7. So, while I was unable in the time I had to review the paper to do all the necessary calculations, I suggest that the paper suffers from not highlighting the ways military emissions differ across the globe and differ from the civilian sector

Finally, I suggest that the author see several other sources. Axel Michelowa 2001; Neta Crawford 2022; Ho-Chi Lin, et al, 2022. <https://transformdefence.org/publication/climate-crossfire-how-natos-2-military-spending-targets-contribute-to-climate-breakdown/>. The last is quite important. The paper by Lennard de Klerk has an incomplete citation.

Responses: We appreciate your helpful suggestions. Based on the useful and reliable data and references you suggested, we have added a section analyzing how military-related emissions differ globally and from the civilian sector, exploring the mechanism behind the relationship between global MILEX ratio and CO₂ emission intensity (L193-228 of the revised paper). Our analysis shows that military activities, especially within the military industries, are typically more carbon-intensive than civilian sectors. An increase in a country's MILEX ratio typically results in expanded military-related activities, leading to elevated carbon emissions. This relationship extends beyond national borders through international trade and global supply chains in the military industry, necessitating a worldwide perspective when evaluating the environmental impact of military activities. Moreover, increased global tensions may hinder global efforts to combat climate change by altering resource allocation priorities. Governments may prioritize security concerns over environmental issues, potentially diverting funds that could otherwise support climate finance initiatives in vulnerable nations towards military preparations and operations (Lin et al., 2023). The above results have been added to the Discussion section of the revised manuscript (L310-319).

In the future, we can estimate the military-related emissions of more developing countries and emerging economies (e.g., China, India, etc.) when more transparent data are available. This will help explore micro-level phenomena and impact mechanisms in the context of global relations. Additionally, we would like to conduct further studies on the emissions and emission intensities of the different military services (the Army Navy, Air Force, etc.) and the impact of these emissions on radiative forcing and climate. These insights are crucial for providing recommendations for green military development in the future.

Response to Reviewer #2

General Comments:

This is an interesting premise, but the article is severely challenged by key assumptions and lack of clarity in how their findings. I would suggest that with very significant revisions this manuscript would be worth reconsideration, but, in its current form, it leaves the reader with too many questions and concerns about the assumptions that they make. I do not think it is a fit for this journal. Despite my recommendation, I commend the authors on finding an interesting topic that could have important implications for climate and defense policy and encourage them to dig into this question further.

Responses: Thank you for your positive comments, specific suggestions, and encouragement. We have tried to revise the manuscript by addressing the issues and questions you raised.

Major issues:

Comment 1. There is a lack of clarity in the association between the increase in emissions in the period identified by the authors (1995 – 2021) – see fig 1. Though they do model this out, it is not clear to me (perhaps another reviewer will be able to speak to this) how they controlled for other factors (e.g., the rise in China's wealth and emissions; population growth; general economic growth). This needs to be explained in more detail as it is a central argument. I would note, however, that I am unsure this is the right journal for such analysis as I imagine that has to be a fairly in-depth statistical methods.

Response: The statistical modelling in this manuscript has eliminated the impact of global economic growth and corresponding increase in carbon emissions. We choose to use global military expenditure as a percentage of GDP (MILEX ratio) rather than the absolute value of MILEX to reduce the impact of general economic growth (including the rapid rise in China's wealth). The use of CO₂ intensity (CO₂ emissions per unit of GDP) removes to some extent the impact of the increase in global total emissions associated with general economic growth. Besides, we detrend the linear downward trend (the grey line in Fig. R1) of global total emission intensity to eliminate the impact of technological progress on the analysis. We then find that the fluctuations of global emission intensity during 1995 and 2023 are related to the changes in the global MILEX ratio. The above explanation has been added to the Method Section of the revised manuscript (L364-367).

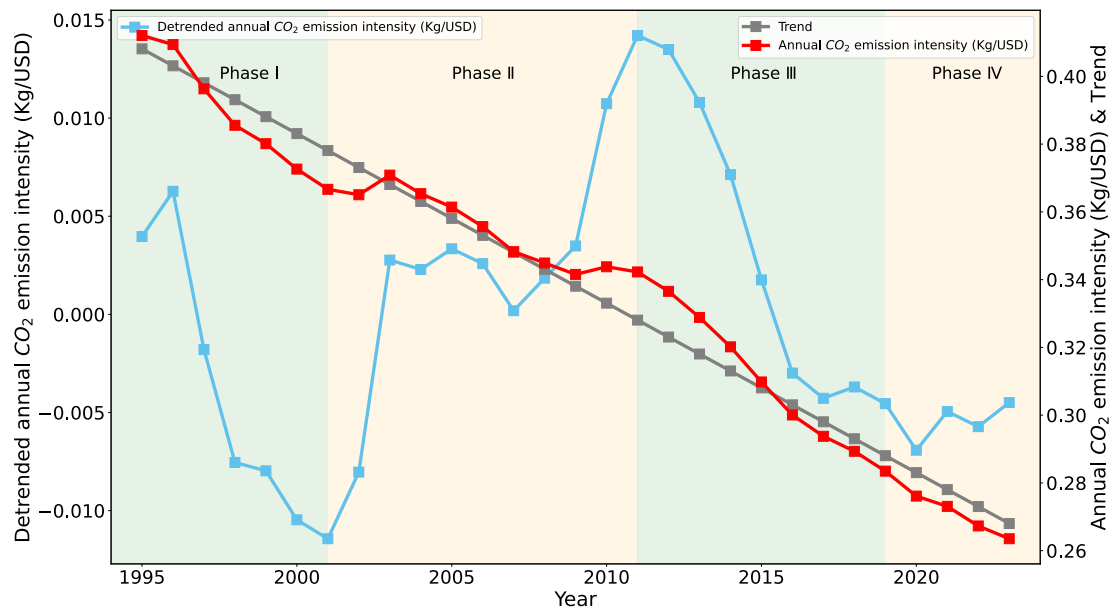


Figure R1. CO₂ emission intensity from 1995 to 2023. Global annual CO₂ emission intensity (kg/USD) (red line), the downward trend of global annual CO₂ emission intensity (grey line), and the detrended global annual CO₂ emission intensity (blue line).

Comment 2. I agree with the authors that there is significant uncertainty in the volume of emissions emanating from global conflict. I encourage them to continue to work through this problem. I do, however, find that their analysis needs to dig deeper. It seems to rely on just a handful of sources and does not examine the issues from other possible angles. For example, do efforts to ‘green’ militaries potentially lead to major breakthroughs, will global conflict **slow** global commerce, etc. these questions need to be more clearly examined.

Response: Based on existing reliable military-related emission data from various sources, we have added a section analyzing how military-related emissions differ globally and from the civilian sector, exploring the mechanism behind the relationship between global MILEX ratio and total CO₂ emission intensity. Please see **L193-228** of the revised manuscript. Besides, we have added more discussion on the carbon emissions resulting from post-war reconstruction (**L157-173**) and the destruction of carbon reservoirs (**L175-191**).

Regarding the “green transition” in the military, despite efforts by some military entities and defense contractors to reduce carbon emissions, it remains challenging because the lack of viable alternative fuels for military transportation and equipment (Lin et al., 2023; Crawford, 2022). We have added this point in the revised paper (**L150-153**).

We believe that global conflicts will not significantly slow down the global economy between 1995 and 2023. Supplementary Fig. 5 in the revised manuscript shows that the slowdown in the annual global GDP growth rate is mainly influenced by the financial crisis rather than wars or conflicts during this period. Except for the sharp global economic downturn caused by the 2008 financial crisis and the COVID-19 lockdown

in 2020, the global GDP growth rate remained between 2% and 4%. We emphasized this point in **L137-140** of the revised paper. The 2022 Russia-Ukraine war demonstrates how regional conflicts can redistribute rather than reduce global emissions. While Ukraine's economy contracted by nearly 30% in 2022, lowering its emissions, production shifted to other European regions due to disruptions in Ukraine. This is particularly evident in the global steel market, where competitors increased output to fill the gap left by Ukraine. As a result, Ukraine's decreased emissions were largely offset by increases elsewhere, leading to minimal overall climate impact reduction (de Klerk et al., 2023).

Comment 3. The writing can at times be hard to follow. For example, I did not understand what the authors meant when they said "The global military expenditure ratio significantly influences CO₂ emission intensity, primarily by impacting total CO₂ emissions". Perhaps this is just a typo, but the language was unclear throughout the manuscript.

Response: We acknowledge the need to improve our writing and have made extra efforts to ensure clarity of the revised texts. To answer your specific question, we would like to clarify that we meant to explain how the global MILEX ratio affects the total carbon intensity. We have revised this sentence as follows: "The global CO₂ emission intensity is significantly influenced by the global MILEX ratio, primarily due to its effect on total CO₂ emissions (Supplementary Figs 4.1 vs. 4.2)." Please see **L137-138** of the revised manuscript.

Comment 4. The authors make some important points that are buried in the manuscript. For example, I would like to see more attention on the 4 types of emissions affected by conflict. 3 and 4 iii. post-conflict reconstruction; and iv. destruction of carbon 129 reservoirs" These are important points but were examined only briefly (again – this might need a longer runway and therefore is better suited for another journal)

Responses: Thank you for your suggestions to improve the readability. We have added more discussion on the carbon emissions from source iii (**L157-173**) and source iv manuscript (**L175-191**) in the revised manuscript.

Minor issues:

Comment 5. I am unsure how it was determined that global military expenditure was identified as a proxy for global tensions. This needs to be justified more clearly.

Responses: The trends in the global MILEX ratio from 1995 to 2023 are linked with regional conflicts and wars, effectively reflecting the degree of global tension during different periods (Fig. 1a). Please see **L82-100** of the revised paper for more details.

Comment 6. On page 4 line 83, I believe you mean 'enduring freedom' not 'operation ending freedom'

Responses: Thank you for pointing this out. We have modified the expression to "Operation Enduring Freedom".

Comment 7. In lines 203 – 205 the authors point out a 13 year delay in achieving climate targets. They need to make clear why this matters in the context of global emission pathways. This seems fairly minor all things considered.

Responses: Well, this matters as climate change has already caused widespread negative impacts and related losses and disasters to human society and ecological systems. More than 3 billion people globally live in environments that are highly vulnerable to climate change, facing severe challenges such as water scarcity, food insecurity, health issues, and damage to urban infrastructure (IPCC, 2023). In the SSP1-1.9 scenario, a 5% rise in the global MILEX ratio would extend the period of global surface temperature exceeding 1.5°C after the initial overshoot by 13 years, significantly increasing the risk of the above climate change-related disasters.

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<https://doi.org/10.1016/j.atmosenv.2009.04.024>

Lin, H.C., Buxton, N., Akkerman, M., Burton, D., de Vries, W. (October 2023), Climate crossfire: how NATO's 2% military spending targets contribute to climate breakdown, Transnational Institute <http://www.tni.org/climatecrossfire>

Response to Reviewers

The term “revised manuscript” in this context denotes the PDF file we have submitted, which clearly highlights the modifications made from the previous version. We have addressed each comment made by Reviewer #3. For clarity, we have presented the reviewers’ comments in blue and our responses in black.

Response to Reviewer #1

General Comments:

I think these are acceptable responses to the comments made by both reviewers. They are clarifications and additions which make this a much stronger manuscript.

Response: Thank you for your constructive suggestions to make our manuscript better.

Response to Reviewer #3

General Comments:

The manuscript provides an important contribution to understanding the interplay between global military expenditure and climate change mitigation efforts. By exploring how global tensions, as measured by military expenditure as a percentage of GDP, influence CO₂ emissions, the study bridges an important gap in climate policy discussions and military-environmental research. However, while the study is commendable for its elaborate quantitative approach and policy-relevant insights, there are certain areas that I would like to see improved for greater clarity and impact.

Response: Thank you for recognizing the contribution of our work. We have improved the manuscript based on your helpful suggestions. Below, we provide our replies under each part of the comment.

Comment 1. Regarding the theoretical expectations, the manuscript discusses the relationship between military activities and CO₂ emissions but could elaborate further on the underlying mechanisms. While the focus on operational emissions and supply chains is helpful, the omission of emissions from post-conflict reconstruction and destruction of carbon reservoirs seem to weaken the robustness of the findings.

Response:

We appreciate the reviewer’s suggestion to consider emissions from post-war reconstruction and the destruction of carbon reservoirs. To address this, we have evaluated their potential impact on our analysis of the relationship between the global MILEX ratio and CO₂ emission intensity in the Results section.

Previous research suggests that emissions from post-war reconstruction are relatively small compared to those from military bases, operations, and industry (Lin & Burton, 2020; Parkinson & Cottrell, 2022; Michaelowa et al., 2022; Matsunaga, 2019). This is primarily due to the limited number of large-scale regional wars over the past 30 years. Additionally, most reconstruction-related emissions are already accounted for in national emission inventories under broader

categories such as construction and industry (L155-160 in the revised manuscript). Therefore, explicitly attributing these emissions to military activities would introduce potential double counting.

To assess the possible effect of emissions from the destruction of carbon reservoirs, we incorporated estimates from Supplementary Table 3 into our analysis. Assuming additional emissions of 320 million tons of CO₂ annually from 2001 to 2011 and 32 million tons from 2022 to 2023, the CO₂ emission intensity increases by 0.042 kg/USD (95% CI: 0.030–0.054) for each 1% rise in the MILEX ratio—representing a 5% increase from our original estimate of 0.04 kg/USD (L172-180).

While our study focuses on emissions directly linked to military bases, operations, and supply chains, we acknowledge that emissions from post-conflict reconstruction and carbon reservoir destruction could be more significant in the event of a large-scale war. However, during our study period (1995–2023), their impact remains relatively minor compared to operational emissions and supply chains. This discussion has been added to the Discussion section (L346-349).

Comment 2. The study mentions indirect effects, such as resource allocation priorities shifting from climate to military expenditures. However, these implications are not deeply explored or modeled. Is it possible to include qualitative or quantitative evaluations of such shifts to strengthen the analysis?

Response: Thank you for this insightful suggestion. The potential indirect effects of increased global tensions—such as shifting resource allocation away from climate action—are indeed an important consideration. While these effects may further strengthen the link between global tensions and CO₂ emission intensity, a thorough evaluation would require a different methodological approach, potentially involving economic modeling or policy analysis. As this indirect effect is beyond the primary scope of our study, we have acknowledged its relevance and the need for further investigation in the revised manuscript (L349-353).

Comment 3. The relationship between military expenditure and CO₂ emissions is also complex and maybe influenced by various omitted variables. It was not entirely clear to me if these were included in the analysis, but just to think of a few - some economies rely more on fossil fuels or energy-intensive industries, which could amplify emissions unrelated to military expenditure. The proportion of renewable vs. fossil fuel energy in a country's energy portfolio could also mediate the relationship between military spending and CO₂ emissions. In terms of global supply chains, military expenditures often rely on international procurement of equipment and materials, which might result in emissions originating outside the country's borders. Similarly, countries that export large quantities of military equipment may show higher emissions despite local military spending being modest. Finally, countries with opaque reporting practices for military and environmental data may skew results. In any case, I think at least a qualitative discussion of some of these potentially confounding factors will strengthen the arguments and findings of the paper.

Response: Thank you for raising these important considerations. We acknowledge that the relationship between military expenditures and CO₂ emissions is complex and can be influenced by various omitted variables.

Regarding the role of national energy structures, we appreciate the reviewer's insightful point. We have added a discussion on this aspect and recognize that future research will require extensive data collection and analysis to explore whether the widespread adoption of renewable energy, green military technologies, and shifting global trade patterns could weaken the link between military expenditures and carbon emissions—or whether heightened global tensions could indirectly hinder climate action and reinforce this relationship (L349-353). However, we believe that over the past few decades, this influence has been relatively limited, as the military sector's green transition remains highly challenging (L143-146), and we have already accounted for the impact of technological progress on total CO₂ emission intensity (L112-115).

With respect to the global supply chain, we have explicitly analyzed its role in the Results section (L210-221). Our findings indicate that the influence of military expenditures on CO₂ emissions extends beyond the countries directly involved in conflicts. Between 1995 and 2019, North America—particularly the United States—was the dominant driver of changes in the global MILEX ratio (Supplementary Fig. 2), while East Asia, especially China, contributed the most to global CO₂ emission changes (Supplementary Fig. 9). This pattern is linked to the substantial increase in U.S. military-related imports from China during the War on Terror (Supplementary Fig. 10). More recently, from 2021 to 2023, Eastern Europe has been the primary contributor to the rise in global MILEX ratios due to the Russo-Ukrainian war. However, despite these shifts, global CO₂ emission intensity has remained relatively stable since 2020. During this period, detrended carbon emissions have increased in Western, Eastern, and Central Europe while declining sharply in East Asia. These findings highlight the necessity of adopting a global perspective when assessing the environmental impact of military activities.

Finally, regarding opaque reporting practices for military and environmental data, our methodological approach—modeling the relationship between the global MILEX ratio and global CO₂ emission intensity—helps mitigate challenges posed by potential data gaps. Since our analysis does not rely on isolating military-related emissions from total CO₂ emissions at the national level, it remains robust despite variations in military and environmental data transparency.

Comment 4. As for the sensitivity scenarios, in the manuscript they provide valuable insights into how variations in military expenditure impact CO₂ emissions and temperature targets. However, I wondered how realistic are the projected increases in military expenditure ratios? Perhaps incorporating expert forecasts or scenario probabilities would increase the credibility to the projections.

Response: Thank you for this suggestion. To assess the potential impact of varying levels of global military expenditures on CO₂ emissions, we developed a series of sensitivity scenarios based on historical shifts in military expenditure ratios, particularly those observed during World War II and the Cold War (L233-235).

During the Cold War, the global MILEX ratio was approximately 6% (World Bank, 2023). In contrast, military expenditures during World War II were significantly higher, with Japan, Germany, and the United States reaching 80%, 67%, and 33%, respectively (Barnum et al., 2024). If a future arms race or large-scale global conflict were to occur, the global MILEX ratio could rise substantially—potentially increasing by 10% or even exceeding 30%.

In recent years, military expenditures have already been on an upward trajectory. In 2023, global military spending reached a record 2.443 trillion USD, representing a 6.8% increase from the previous year. If this annual growth rate continues, the global MILEX ratio is projected to surpass 3.5% by 2030.

Given these historical and projected trends, we believe it is reasonable to define a sensitivity range of -2% to 30% (in 1% increments) in our experiments. This range effectively captures potential future scenarios, from reduced global tensions to intensified military build-ups similar to those observed in past conflicts.

Comment 5. On the policy side, while the study identifies global peace as a crucial factor for achieving climate targets, its recommendations could be a bit more specific. Suggestions for practical mechanisms to integrate military emissions into global climate agreements, such as the UNFCCC framework, could increase the paper's impact.

Response: Thank you for this valuable suggestion. We have expanded the Discussion section (L359-366) to include specific policy recommendations. Achieving the 1.5°C or 2°C climate targets and mitigating the risks of extreme temperatures require a stable international environment and strong global cooperation. To integrate military emissions into international climate frameworks, we suggest mandatory military emissions reporting under the UNFCCC framework and advancing the green transition of the military sector through targeted policies. These measures could include incorporating military emissions in Nationally Determined Contributions (NDCs), establishing independent verification mechanisms, and promoting multilateral agreements to reduce the military sector's carbon footprint.

Finally a few minor comments:

The figures and graphs are well-designed but could benefit from additional explanatory notes for clarity, particularly for non-specialist readers.

Response: Thank you for your valuable suggestions. To enhance clarity, we have revised the figure captions, including replacing 'global MILEX ratio' with 'global military expenditure as a percentage of GDP' for better readability. Additionally, we have improved explanations of the Shared Socioeconomic Pathways (SSPs) in the revised manuscript (L224-227). Specifically, we now provide context on the five SSP scenarios assessed in the IPCC Sixth Assessment Report, which integrate different socioeconomic development pathways (SSP1-SSP5) with projected radiative forcing levels (1.9 to 8.5 W/m²) by 2100. To further aid interpretation, we have also added a legend to Figure 2 that clearly explains the SSP scenarios used in this study.

Furthermore, to streamline the manuscript and improve readability, we have revised the final paragraph of the Introduction section, moving some methodological descriptions to the Methods section, making the introduction more concise and focused.

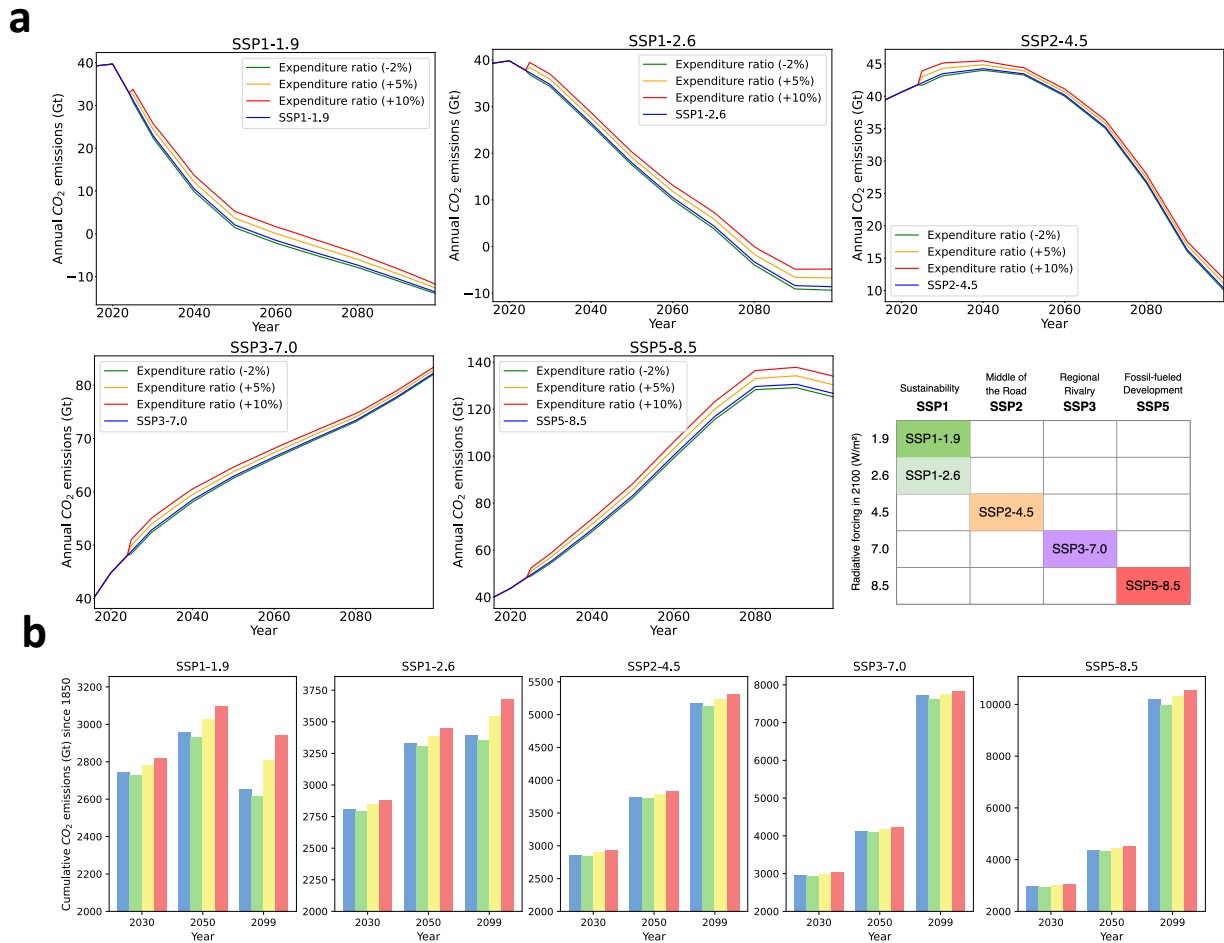


Figure 2. Global CO₂ emissions in the five baseline shared socioeconomic pathways (SSPs) and the sensitivity scenarios with various global tensions. a, Annual CO₂ emissions from 2015 to 2099 under baseline SSP scenarios (blue lines) and sensitivity scenarios when global military expenditure as a percentage of GDP (MILEX ratio) decreases by 2% (green lines) or increases by 5% (orange lines) or 10% (red lines) compared with the baseline. We assume equal variations in the global MILEX ratio of each year in the sensitivity experiment relative to the baseline. b, Cumulative CO₂ emissions since 1850 in 2030, 2050, and 2099, under the baseline SSP scenarios (blue bars) and sensitivity scenarios, when the global MILEX ratio decreases by 2% (green bars) or increases by 5% (yellow bars) or 10% (red lines) compared with the baseline. The five baseline scenarios integrate the SSP (SSP1–SSP5) and the projected radiative forcing levels by 2100 (1.9–8.5 W/m²), representing possible future socioeconomic and climate pathways.

A brief discussion on the limitations of the data sources, especially regarding inconsistencies in military emissions reporting, would help the manuscript's credibility.

Response: We have added an explanation for the data limitations in the revised manuscript (L383-385): Due to inconsistencies and incompleteness in the reporting of military fuel use data, the national military emissions data used in this study are limited to specific countries and years.

While the study focuses on the global context, mentioning specific case studies (e.g., Russia-Ukraine conflict) in greater detail could illustrate the mechanisms more clearly.

Response: Thank you for this valuable suggestion. Our manuscript already includes detailed discussions of specific case studies in both the Results section and the Abstract to illustrate our findings. To ensure clarity, we highlight below where these cases are explicitly addressed:

- **Linking Conflicts to Global MILEX Trends:** We explicitly connect major conflicts and wars to trends in the global MILEX ratio from 1995 to 2023 (**L81-97, Figure 1a**), demonstrating how military expenditure patterns have evolved in response to geopolitical tensions.
- **Assessing Post-Conflict Emissions:** We examine the Russo-Ukrainian war and the Gulf War to evaluate whether emissions from post-conflict reconstruction and carbon reservoir destruction significantly impact our model's robustness (**L164-167, L170-174, L180-183**).
- **Illustrating Mechanisms with Case Studies:** To elucidate the mechanisms driving the relationship between global MILEX ratio and CO₂ emission intensity, we analyze the War on Terror and the Russo-Ukrainian war as examples, showing how military expenditures influence global emissions beyond the directly involved countries (**L217-226**).

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