Barriers to Force Projection

Climate Change and Aerial Forward Operability

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While US national security and military strategy documents acknowledge climate change will have increasing effects on US military operations alone and with Allies and partners, the specific implications for platforms remain understudied. An analysis of the projected effects of rising temperatures worldwide to 2099 on density altitude and its specific impacts for the C-17 Globemaster, provides insights into developing courses of action to mitigate the certain reduction of logistics capabilities.

In a time plagued by the reemergence of great power competition, the importance of a nation's military cannot be underestimated. The argument for persistent forward stationing of US military forces is based on two key principles of military strategy: assurance and deterrence. As part of its global posture and campaigning effort and in addition to deterring Russia and China in the Indo-Pacific region and Europe, the *2022 National Defense Strategy* states the Department of Defense "will leverage security cooperation and capacity building with partners, backed by a monitor-and-respond approach that takes advantage of the deterrent value of the Department's ability to deploy forces globally at the time and place of [its] choosing."[1]

This research is focused on the impacts that climate warming may have on strategic-level military readiness and decision-making, particularly within the US Air Force. It is known that the aviation industry is a partial contributor to global climate change.[2] What has been somewhat overlooked as a field of study is the reverse dynamic: the impact of climate change on aviation.[3] Considering the forecasted increase in regional mean

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1. Lloyd F. Austin, *2022 National Defense Strategy of the United States of America including the 2022 Nuclear Posture Review and the 2022 Missile Defense Review* (Washington, DC: Office of the Secretary of Defense, 2022), 13, https://media.defense.gov/.

2. Milan Klöwer et al., "Quantifying Aviation's Contribution to Global Warming," *Environmental Research Letters* 16, no. 10 (November 2021), https://doi.org/.

3. Mary McRae et al., "Assessing Aircraft Performance in a Warming Climate," *Weather, Climate, and Society* 13, no. 1 (January 2021), https://doi.org/; and Tianjun Zhou et al., "Impact of 1.5°C and 2.0°C Global Warming on Aircraft Takeoff Performance in China," *Science Bulletin* 63, no. 11 (June 2018), https://doi.org/.

temperatures, what impact will climate warming have on US Air Force strategic airlift capabilities, and how will this affect geostrategic defense priorities? In other words, what theater-level geographic impacts will the Air Force and the Department of Defense experience due to the loss of airlift capacity resulting from extreme climate change?

Strategic- and theater-level implications first emerge at the tactical level of military operations. Accordingly, to reach an understanding of the strategic impacts that climate warming is bound to have on the Air Force's ability to project power globally, the impacts on tactical-level flight operations must be quantified.

As the most flexible transport aircraft in the US Air Force fleet, the Boeing C-17 Globemaster III is an effective case study for such problems likely to be faced across the service. This study converts climate-warming projection data from 2020–2099 to measures of density altitude—"pressure altitude corrected for nonstandard temperature variations"—and assesses the impacts of increasing density altitude based on a set of mathematically approximated thresholds specific to the C-17.[4] The density altitude thresholds provide metrics for quantifying regional performance degradation of the C-17 due to global warming.[5]

Pressure and Density Altitude

Pressure altitude, density altitude, and maximum takeoff weight are common metrics for assessing aircraft performance under limiting circumstances, such as high elevation, high temperature, or low-density air.[6] Both elevation and temperature have a significant impact on the maximum takeoff weight and runway length requirements for all aircraft due to their impacts on lift. Understanding the effects of elevation and temperature on aircraft performance begins with understanding pressure altitude and density altitude, two related aeronautical concepts.

Pressure altitude is defined by the Federal Aviation Administration (FAA) as "the height above a standard datum plane (SDP)," or the theoretical level where the weight of the atmosphere is 14.7 pounds per square inch, or 29.92 inches of mercury (″Hg), measured by a barometer.[7] Restated, pressure altitude refers to the indicated altitude displayed on an altimeter when it is set to standard atmospheric pressure: 29.92 ″Hg.[8]

4. Federal Aviation Administration (FAA), *Density Altitude* (Washington, DC: US Department of Transportation [DoT], 2008), 1, https://www.faasafety.gov/.

5. Mary McRae, "A Risk-Based Approach to Planning Aircraft Acquisitions in a Warming Climate" (PhD dissertation, Villanova University, 2019).

6. Ethan Coffel and Radley Horton, "Climate Change and the Impact of Extreme Temperatures on Aviation," *Weather, Climate, and Society* 7, no. 1 (January 2015), https://doi.org/; and Christopher J. Goodman and Jennifer D. Small Griswold, "Climate Impacts on Density Altitude and Aviation Operations," *Journal of Applied Meteorology and Climatology* 57, no. 3 (March 2018), https://doi.org/.

7. FAA, *Pilot's Handbook of Aeronautical Knowledge* (Washington, DC: DoT, 2016), 4-4.

8. FAA, *Density Altitude,* 1.

Standard atmospheric conditions assume a sea-level pressure of 29.92 ″Hg, a temperature of 15 degrees Celsius, and a humidity of zero percent. Nonstandard atmospheric conditions are simply any deviation from any of these conditions. Changes in atmospheric pressure produce nonstandard conditions, necessitating a measure for altitude that takes these factors into account. On a perfectly standard day, pressure altitude is equal to true altitude, the height at which the aircraft is physically flying. Pressure altitude is a function of atmospheric pressure and elevation and is measured independently of temperature.[9]

Density altitude is pressure altitude corrected for temperature.[10] Much like pressure altitude, the density altitude refers hypothetically to the altitude above sea level where one would find the specified atmospheric density in the standard atmosphere: "As temperature and altitude increase, air density decreases. In a sense, it's the altitude at which the airplane 'feels' it's flying."[11] Decreasing near-surface air density is "the single most significant atmospheric parameter" in examining the relationship between climate-warming effects and aircraft performance, specifically maximum takeoff weight.[12]

High-density altitude affects fixed-wing aircraft in the following three critical ways: 1) it causes less lift due to the decreased force exerted on the wings by less dense air, 2) it produces diminished thrust on propeller aircraft from reduced prop efficiency, and 3) it creates reduced power because of the engine taking in less air.[13] These performance limitations produce flight circumstances which do not allow for an aircraft to accelerate as quickly on takeoff, resulting in decreased maximum takeoff weight and increased takeoff distance.[14]

Aircraft Selection

To assess the US Air Force's ability to project power globally, analysis must be done using an effective representative aircraft. The Boeing C-17 Globemaster III is an ideal selection for several reasons. The Air Force refers to the C-17 as its "most flexible cargo aircraft to enter the airlift force."[15] The Globemaster III is lauded for its rapid troop delivery and deployment, versatile mission capabilities, and overall contribution to worldwide airlift demands.[16] The C-17 supports the rapid deployment of logistics supplies, troops, and aircraft/vehicles. The Air Force recognizes the growing requirements for heavy cargo

9. FAA, *Pilot's Handbook*, 4-4.

10. FAA, 4-4.

11. Aircraft Owners and Pilots Association (AOPA), "Density Altitude," AOPA, accessed May 12, 2023, https://www.aopa.org/.

12. Diandong Ren et al., "Impacts of Climate Warming on Maximum Aviation Payloads," *Climate Dynamics* 52 (August 2018), https://doi.org/.

13. McRae et al., "Assessing Aircraft Performance."

14. McRae et al., "Assessing Aircraft Performance"; Coffel and Horton, "Climate Change"; and Zhou et al., "Impact of 1.5°C."

15. US Air Force (USAF), "C-17 Globemaster III," USAF (website), accessed July 21, 2022, https://www.af.mil/.

16. USAF.

aircraft for both wartime and humanitarian missions across the globe. Given its flexibility and wide usage, the C-17 is an appropriate aircraft to use for an assessment of DoD forward projectability.

Further indication of the value and relevance of the C-17 is evidenced by the long list of global users that the aircraft services. According to the manufacturer, while the US Air Force is the C-17's largest customer, seven additional countries and one multinational initiative also own and operate C-17s: Australia, Canada, India, Kuwait, Qatar, the United Arab Emirates, the United Kingdom, and the participating nations of the Strategic Airlift Capability (Hungary, Bulgaria, Estonia, Lithuania, the Netherlands, Norway, Poland, Romania, Slovenia, Finland, Sweden, and the United States).[17] The wide use of the C-17 by the United States and Ally and partner nations suggests results of this research may apply beyond the scope of the US Department of Defense.

Data and Methodology

The key data supporting this research is a set of forecasted temperature and relative humidity values under a "worst-case scenario" global warming model.[18] This data set is called the Coupled Model Intercomparison Project Phase 5 (CMIP5) and is a recurring data source used by other scholars in this field of research.[19] While a more recent release—CMIP6—has a more current baseline period, this newer model has been found to be overly conservative when predicting climate change, and when compared with the earlier released CMIP3 and with CMIP6, CMIP5 shows projections most consistent with climate observations.[20]

The worst-case scenario refers to the projected emissions and human efforts with emissions and associated concentrations increasing considerably. Specifically, the authors used Representative Concentration Pathway 8.5 (RCP 8.5), which models a radiative force of 8.5 watts per square meter by the end of the century. CMIP5 includes model scenarios of varying degrees of severity, but for the sake of this research inquiry, the worst-case global warming outcome is used to demonstrate the importance of mitigation against this potential threat. The forecasted temperature values are relative to CMIP5's historical baseline average temperatures from 1986 to 2005 and are used to estimate

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17. Boeing, "C-17 Globemaster III," Boeing (website), accessed July 21, 2022, https://www.boeing.com/; and Strategic Airlift Capability (SAC), "Member Nations," SAC, accessed July 21, 2022, https://www.sacprogram.org/.

18. Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl, "An Overview of CMIP5 and the Experiment Design," *Bulletin of the American Meteorological Society* 93, no. 4 (April 2012), https://doi.org/; Zhou et al., "Impact of 1.5 °C"; and Wei Yuan et al., "Estimating the Impact of Global Warming on Aircraft Takeoff Performance in China," *Atmosphere* 12, no. 11 (November 2021), https://doi.org/.

19. Coffel, Thompson, and Horton, "Impacts of Rising Temperatures"; McRae et al., "Assessing Aircraft Performance"; and Yuan et al., "Estimating the Impact."

20. D. Carvalho et al., "How Well Have CMIP3, CMIP5 and CMIP6 Future Climate Projections Portrayed the Recently Observed Warming," *Scientific Reports* 12, no. 1 (July 2022), https://doi.org/.

global warming temperatures during two of the four available 20-year prediction periods (2020–2039 and 2080–2099). [21]

The metric used to assess aircraft performance degradation is density altitude. The raw data inputs include forecasted temperature and relative humidity values for each of the 20-year periods from 2020–2099, as well as elevation data across the study area. Global elevation data was compiled from the US Geological Survey Global 30 Arc-Second Elevation (GTOPO30) digital elevation model archive. Forecasted temperature, relative humidity, and elevation can be converted into forecasted density altitude using a series of equations.[22] The formulas used to do this conversion come from the National Oceanic and Atmospheric Administration's (NOAA) online density altitude calculator.[23]

The outcome of this methodology is two separate map visualizations of density altitude values across the geographic combatant commands, representing the forecasted density altitude for each of the prediction periods. These maps are then compared against one another to assess the geographic-based deterioration of flight conditions based on increasing density altitude.

Density Altitude Thresholds and Associated Tactical Impacts

To numerically assess the effects of increasing temperatures on C-17 capabilities, six density altitude thresholds were defined. Increased density altitude results in increased performance degradation, and at each of the six thresholds, a weight restriction is imposed to compensate for that degradation.

Table 1. Density altitude increases and weight reduction compensation for the C-17 Globemaster III

	Density Altitude	Weight Reduction	Cargo Allowance
1	≥ 710 feet	14,500 pounds (8.5 percent payload)	e.g., 1 of 2 UH-60
2	≥ 1,420 feet	29,000 pounds (17.0 percent payload)	e.g., 0 of 2 UH-60
3	≥ 2,440 feet	50,000 pounds (29.3 percent payload)	e.g., 1 of 2 M2A2
4	≥ 4,880 feet	100,000 pounds (58.5 percent payload)	e.g., 0 of 2 M2A2
5	≥ 7,180 feet	147,000 pounds (86.0 percent payload)	e.g., 1 of 2 M1A2
6	≥ 8,350 feet	170,900 pounds (100 percent payload)	No payload

21. Taylor, Stouffer, and Meehl, "Overview."

22. Tim Brice and Todd Hall, "Density Altitude [Calculator]," National Oceanic and Atmospheric Administration (NOAA), 2015, accessed July 21, 2022, https://www.weather.gov/; John M. Wallace and Peter V. Hobbs, *Atmospheric Science: An Introductory Survey* (Amsterdam, NL: Academic Press, 2006); and Mark G. Lawrence, "The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications," *Bulletin of the American Meteorological Society* 86, no. 2 (February 2005), https://doi.org/.

23. Brice and Hall, "Density Altitude [Calculator]."

The C-17 Globemaster III has a maximum takeoff weight of 585,000 pounds, a maximum payload of 170,900 pounds, and cargo configurations which allow for (1) 102 troops/paratroops, (2) 54 ambulatory patients, 36 litter patients, and their medical attendants, or (3) 18-463L cargo pallets.[24] Additionally, a full Globemaster III payload may consist of one M1A2 Abrams tank, two M2A2 Bradley infantry fighting vehicles, up to three Stryker vehicles, or two UH-60 Black Hawk helicopters.[25] For the purpose of this study, the C-17 will be modeled as taking off with the maximum fuel allowance.

Impacts on Aircraft Performance

Density altitude is the metric by which the performance of the C-17 Globemaster III is assessed throughout the warming period from 2020–2099. As temperatures rise, density altitude increases. An aircraft at an elevated density altitude due to either increased field elevation or increased temperatures experiences atmospheric densities that mirror those at a higher altitude, despite the aircraft flying much lower. Flying conditions at higher altitudes are deteriorated compared with lower altitudes, so an aircraft flying at a high-density altitude experiences degraded performance. Therefore, each density altitude threshold defined in the previous section indicates an altitude where the performance of the C-17 is degraded in such a way that a new maximum takeoff weight must be defined.

The study area—including US Northern Command (USNORTHCOM), US Southern Command (USSOUTHCOM), US European Command (USEUCOM), US Central Command (USCENTCOM), US Indo-Pacific Command (USINDOPACOM), and US Africa Command (USAFRICOM)—was classified according to the number of months per year that a particular location within the combatant command would not be subject to the takeoff weight restriction imposed by each of the six density altitude thresholds. The level of performance degradation used in the classification ranges from none to year-round:

- None: 12 months per year that the C-17 is not subject to density altitude threshold limitations
- Minimal: 10–11 months
- Increased: 8–9 months
- Significant: 5–7 months
- Severe: 3–4 months
- Critical: 1–2 months
- Year-round: 0 months

24. SAC, "Boeing Globemaster III C-17," SAC, accessed May 12, 2023, https://www.sacprogram.org/; and USAF, "C-17 Globemaster III."

25. SAC.

The first density altitude threshold is set to 710 feet and signifies the altitude at which the performance degradation of the C-17 necessitates an 8.5 percent decrease in maximum payload. This is equivalent to approximately 14,500 pounds and has a tactical impact of reducing the C-17's cargo allowance by one UH-60 Black Hawk helicopter, despite the C-17 being able to fit two UH-60s in its cargo hold. In just the first segment of the warming period, 2020–2039, USSOUTHCOM, USAFRICOM, USCENTCOM, and USINDOPACOM each experience year-round performance degradation in over 50 percent of their areas. USSOUTHCOM and USAFRICOM are nearly 100 percent geographically degraded year-round at 86.7 percent and 96.6 percent, respectively.

This means that in a majority of locations in four out of the six geographic combatant commands, the C-17 will be under an 8.5 percent payload restriction year-round. All six commands experience some varying degree of increase in the land area that will see year-round weight limitations imposed by the first density altitude threshold, with USCENTCOM and USINDOPACOM showing the largest increase over the warming period. The portion of USCENTCOM that has weight limitations imposed year-round under the first density altitude threshold is expected to increase by 7.6 percent, and USINDOPACOM is expected to see an 8.1 percent increase. USNORTHCOM and USEUCOM also experience an increase in land classified as either critical or severe.

The second and third density altitude thresholds exhibit similar patterns to the first threshold. USSOUTHCOM, USAFRICOM, and USINDOPACOM lead the commands as the regions with the highest percentage of their land area classified as year-round weight restrictions. Again, USCENTCOM trails close behind these three commands. The second density altitude threshold is 1,420 feet, where the maximum allowable payload must be decreased by 17.0 percent (about 29,000 pounds). The tactical impact of such a weight restriction is the complete inability for the C-17 Globemaster III to transport UH-60 Black Hawks.

The third density altitude threshold at 2,440 feet is equivalent to a 50,000-pound decrease in maximum allowable payload at takeoff, which corresponds with a 29.3 percent payload decrease and tactically, the C-17 being limited to transporting only one M2A2 Bradley infantry fighting vehicle. The C-17 is equipped to transport two of these vehicles at full functionality. The third density altitude threshold represents the threshold that is both geographically and mission relevant as compared to the other thresholds. Threshold #3 not only imposes a significant payload reduction at 29.3 percent, but it also has a substantial geographic impact as shown in figure 1.

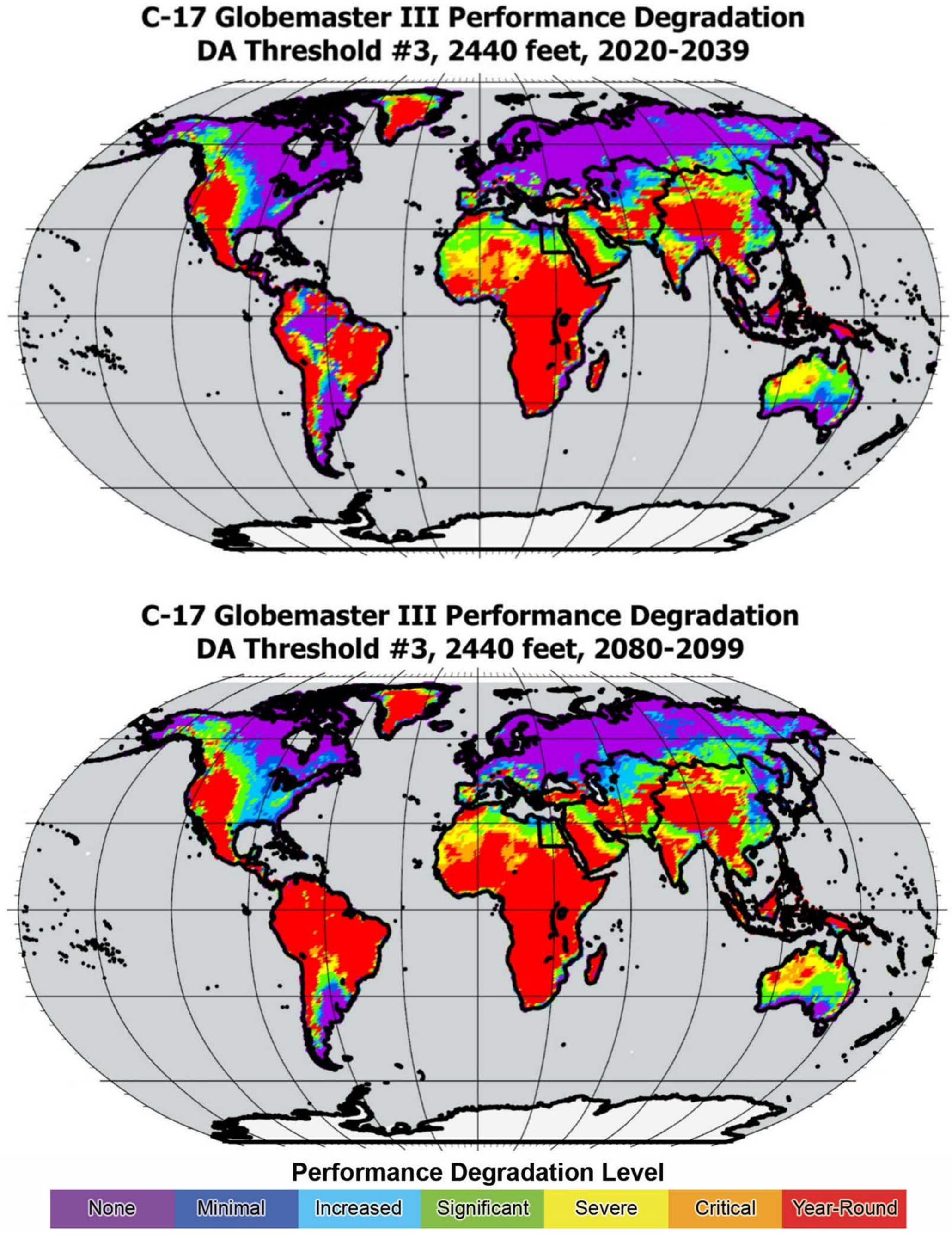

Figure 1. Performance degradation experienced by the C-17 imposed by the third density altitude threshold

Approximately 68.9 percent of USSOUTHCOM, 72.6 percent of USAFRICOM, and roughly 36 percent of both USCENTCOM and USINDOPACOM are expected to experience a year-round 29.3 percent payload reduction by the year 2099. An additional 9.4 percent of USAFRICOM, 4.5 percent of USCENTCOM, and 7.7 percent of USINDOPACOM are predicted to be classified as critical performance degradation by 2099, indicating only one to two months per year that the C-17 is not subject to the 29.3 percent payload reduction.

Between the third and fourth density altitude thresholds, the percentage of each combatant command that will experience year-round weight restrictions decreases substantially more than what is observed between the first and second thresholds, and again between the second and third thresholds. Under threshold #3, 25 percent of the land area in four out of the six combatant commands is classified as requiring year-round weight restrictions. For threshold #4, however, the maximum land-area percentage needing year-round limitations by 2099 is 17.1 percent in USAFRICOM.

All six commands will experience increases in land area classified at these extreme degradation levels. But given that the land area no longer exceeds 25 percent of the geographic region, it is much more realistic that loss of functionality at this threshold could be more easily managed and adapted to. For reference, density altitude threshold #4 corresponds with a 58.5 percent payload reduction, which has a tactical impact of the C-17 no longer being able to carry any M2A2 Bradley vehicles, despite being outfitted to carry two. This is the equivalent of a 100,000-pound decrease in takeoff weight.

As a consideration of which commands might experience the most noticeable changes through the model process, this article computes the percentage of land area for each combatant command that exceeded various thresholds. Figure 2 shows these regions where the density altitude increases by 100 percent or more between 2020 and 2099. In particular, this graphic offers interesting perspectives on USNORTHCOM and USEUCOM. The top 25 percent of the study area that experiences the most rapidly increasing density altitude corresponds with the regions that at the very least double in their value. These regions are experiencing increasing density altitude at a rate that is greater than the remaining 75 percent of the study area and should be considered a unique threat to the Department of Defense.

Even at the lowest density altitude threshold of 710 feet, USNORTHCOM only sees density altitude conditions mandating a year-round weight restriction across approximately 25 percent of its area, with a portion of that area belonging to the higher elevation Rocky Mountains. Despite USNORTHCOM not showing substantial evidence of strategic-level threat from climate warming, figure 2 highlights how USNORTHCOM is increasing in threat more rapidly than surrounding regions. The threat to C-17 performance may not exist substantially during the warming period in this study, but combatant commanders and other senior leaders should pay close attention to which portions of the map are expected to deteriorate more rapidly than others.

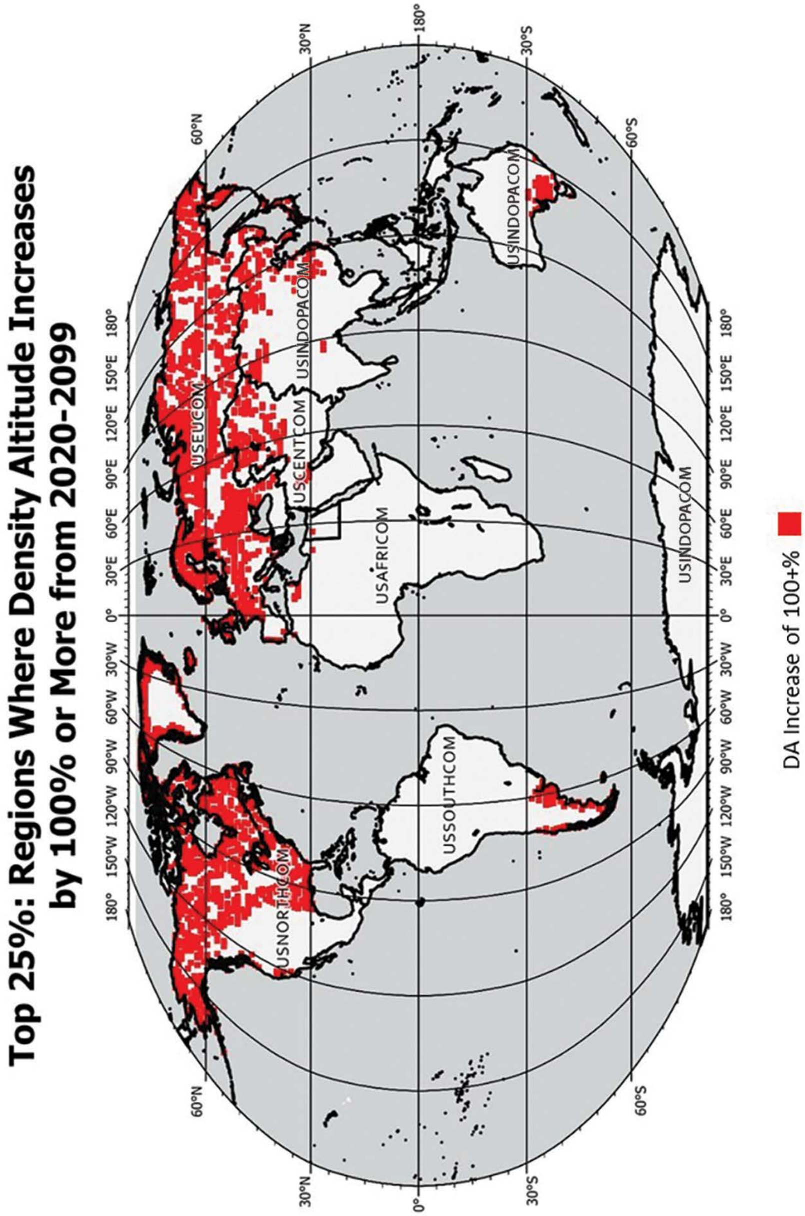

Figure 2. Top quartile of rates of density altitude increases between 2020 and 2099

Reassurance and Deterrence

Forward stationing and deployment of US military forces, whether for offensive military campaigns or peacekeeping and humanitarian purposes, is based on the principles of reassurance and deterrence. The *2022 National Defense Strategy* declares the US military responsible for assuring US Allies and partners through its commitment to nuclear nonproliferation and arms control by means of forward deployment of strategic bombers and fighter aircraft and the ability to posture nuclear weapons globally.[26] Forward deployment and force projection are strategic shows of force; the United States "will work with Allies and partners to identify opportunities to increase the visibility of US strategic assets to the region as a demonstration of US resolve and commitment."[27]

The *Strategy* calls for a force that is agile and responsive, meaning the Department of Defense "rapidly mobilizes forces, generates combat power, and provides logistics and sustainment, even given adversary regional advantages and climate change impacts."[28] Rapid mobilization of force enables contingency responsiveness and allows the United States to deter threats and assure Allies and partners.

Regarding contingency responsiveness, the position of the US government since the end of World War II is that preventing larger-scale attacks against Allies and partners requires forward presence—a ground force already in place to take immediate action.[29] This presence, enabled by strategic lift capabilities, promotes rapid response to conflict and crisis. Yet, climate change will impact in-theater resourcing. As one study states,

> if, instead, ground forces have to deploy from elsewhere by sea or air, even for relatively short distances, the advantage of forward presence will often be limited. . . . Beyond giving attention to specific major threats, the US defense strategy calls for a global response capability, so posture decisions should maintain an effective global en route infrastructure. The United States can maintain relatively rapid global response capabilities as long as this infrastructure and strategic lift assets are maintained.[30]

This is precisely the point of weakness identified by this study: by the year 2099, strategic lift assets will likely be substantially degraded, particularly those located in USAFRICOM and USSOUTHCOM. USNORTHCOM and USEUCOM show evidence of rapidly deteriorating conditions that while underwhelming by 2099, promise more substantial threat levels in years to follow. Although these commands may not be exceeding the

26. Austin, *National Defense Strategy*.
27. Austin, 15.
28. Austin, 18.
29. Dave Shunk, Charles Hornick, and Dan Burkhart, "The Role of Forward Presence in U.S. Military Strategy," *Military Review* (July-August 2017), https://www.armyupress.army.mil/.
30. Michael Lostumbo et al., *U.S. Overseas Military Posture: Relative Costs and Strategic Benefits* (Santa Monica, CA: RAND Corporation, 2013), 1, https://www.rand.org/.

density altitude thresholds during the study period, they are approaching them at a more rapid pace when compared to the other four commands.

Deterrence and assurance are based on the United States demonstrating to a host region it is committed to the region's security and preservation. Forward presence of US forces and the capability to transport troops and equipment within a theater "show that the United States is willing to involve itself in conflicts to stabilize situations, secure US interests, and protect the global commons."[31] Global stationing of US troops is the physical demonstration and symbol of commitment to defend its Allies and partners, but also its ability to act against any nation or group that challenges that commitment. The US military cannot guarantee responsiveness if strategic lift assets are severely degraded throughout much, if not all, of the calendar year. The ability to respond to global demands quickly becomes contingent on the timing of those demands and the level of performance degradation associated with that timing.

National Defense Priorities and Regions of Interest

The 2022 *National Security Strategy* discusses the priorities for national security, including fostering a competitive edge over China and Russia and collaboration to address global food insecurity in places like sub-Saharan Africa.[32] The Indo-Pacific and European regions are additional likely locations for future US conflicts.[33] China, North Korea, Iran, and Russia each pose varying degrees of risk and threat to US security interests.[34]

Regarding the Middle East, this *Strategy* describes the need for the United States to continue its commitment to de-escalation of conflict in the region. The United States will "combine diplomacy, economic aid, and security assistance to local partners to alleviate suffering, reduce instability, and prevent the export of terrorism . . . while working with regional governments to manage the broader impacts of these challenges."[35]

The document reinforces that US involvement in the region no longer requires blanket use of offensive US military force, but rather support and backing for stability and prosperity built by regional partners:

> [US forces] have too often defaulted to military-centric policies underpinned by an unrealistic faith in force and regime change to deliver sustainable outcomes. . . . It is time to eschew grand designs in favor of more practical steps that can advance US interests and help regional partners lay the foundation for greater

31. Lostumbo et al., 2.
32. Joseph R. Biden Jr., *National Security Strategy* (Washington, DC: The White House, October 2022), https://www.whitehouse.gov/.
33. Raphael S. Cohen et al., *The Future of Warfare in 2030: Project Overview and Conclusions* (Santa Monica, CA: RAND Corporation, 2020), https://www.rand.org/.
34. Cohen et al.
35. Biden, *National Security Strategy,* 42.

> stability, prosperity, and opportunity for the people of the Middle East and for the American people.[36]

Regardless of whether US presence in the Middle East is offensive, defensive, or support-based, the need to maintain a military footprint in the region continues.

The national security priorities surrounding Africa include facilitating partnerships and providing aid to relieve food insecurity, health crises, and economic burdens.[37] Based on its longstanding role as a global leader, there is substantial pressure for the United States to intervene in instances of mass suffering and humanitarian crises.[38] Unfortunately, global climate warming will likely affect America's ability to carry out those missions.

The *Strategy* declares climate change to be "the greatest and potentially existential" shared challenge across all nations.[39] The document emphasizes that existing conflict and tensions will only worsen as they are compounded by the threats of climate change, including increased competition for resources, food insecurity, regional instability, and more frequent natural disasters.[40]

Combatant Command-Level Implications

While all six geographic combatant commands share the same strategic-level concern regarding increasing density altitude over the next century, the tactical impacts vary depending on the severity of each region during the warming period noted in this study. Combatant commands can expect to experience either mission-inhibiting levels of degradation during the warming period or a trajectory of rapidly deteriorating conditions that may manifest following the warming period included in this research.

USAFRICOM, USCENTCOM, USINDOPACOM, and USSOUTHCOM face serious degradation to airlift assets departing from within their geographic boundaries. The assessment presented in the results section was completed using C-17 specifications concerning takeoff weight reduction, but the principles learned from the study can and should be extended to what is to be expected with implications for landing weight, despite the specifications varying slightly due to required air speed. While tactical-level impacts are provided only for USAFRICOM, these four combatant commands face the most substantial year-round reduction in payload over the largest percentage of their land area.

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36. Biden.
37. Biden, 43–44.
38. Grant T. Harris, "Why Africa Matters to US National Security," Atlantic Council, May 25, 2017, https://www.atlanticcouncil.org/.
39. Biden, *National Security Strategy*, 9.
40. Biden.

USAFRICOM

The ability to efficiently provide future humanitarian support and aid to the African continent decreases substantially as 2099 approaches. Specifically, the USAFRICOM area of operations presents challenges to C-17 operations—a critical airpower element in humanitarian aid—due to particularly high density altitude conditions.[41] This threatens the US national security priority of providing humanitarian relief and support within the African continent. Operations will be significantly reduced in efficiency, and the time and resource expenditure required for these relief operations will increase substantially, both in terms of manpower and supplies.

Furthermore, even within the first portion of the warming period, 2020–2039, 94.4 percent of USAFRICOM is under a year-round 17.0 percent takeoff weight reduction, and 72.6 percent of the command is under a year-round 29.3 percent reduction. Tactically, this means that in nearly the entire combatant command, what previously would have required only five C-17 flights at maximum allowable payload would require an additional sixth flight to airlift the same total payload. And in approximately three-quarters of the command, every maximum payload for the C-17 would require about two flights. Although the ability to use the C-17 in a place such as USAFRICOM will not be lost entirely by 2099, it will be severely reduced in efficiency.

USCENTCOM

Iran, Iraq, and other countries within the boundaries of USCENTCOM are immediate regions of concern to US national security and will likely continue to be so through the end of the century.[42] Moreover, inherent strategic risk related to decreased lift capabilities will likely increase based on the large regions within the command that are subject to year-round weight limitations.

USINDOPACOM

USINDOPACOM has the potential to become an increased destination for US military forces, as the need to deter China continues to grow.[43] The very first defense priority listed in the *2022 National Defense Strategy* is to "[defend] the homeland, paced to the growing multi-domain threat posed by the PRC [People's Republic of China]."[44] China is cited as the "most consequential strategic competitor" that the United States is currently facing.[45] Therefore, any degradation experienced throughout the USINDOPACOM boundaries should be considered a critical-level threat to the national defense and se-

41. "C-17 Globemaster III: An Aircraft as Versatile as AE Crews," USAF Medical Service (website), accessed July 21, 2022, https://www.airforcemedicine.af.mil/.
42. Austin, *National Defense Strategy*.
43. Austin.
44. Austin, 7.
45. Austin, III.

curity of the United States, given the level of priority associated with combatting the threat from China.

USSOUTHCOM

Although there are only two ongoing conflicts in USSOUTHCOM of current concern to the United States, the command should remain on alert for any emerging conflicts in the region due to the severe degradation expected within the area of operations.

Conclusion

The Department of Defense must view climate change and global warming as tactical and strategic variables that threaten the military's ability to execute operations across the geographic combatant commands with the level of efficiency promised by its current aircraft and assured to its Allies and partners. USAFRICOM and USSOUTHCOM face climate change projections in a worst-case scenario (RCP 8.5) that render a significant majority of those commands in a critical degradation status by the year 2099. Such a scenario would place the C-17 Globemaster III under a 17.0 to 29.3 percent payload reduction year-round across nearly the entire land areas of USAFRICOM and USSOUTHCOM. USCENTCOM and USINDOPACOM trail closely behind.

USNORTHCOM and USEUCOM show evidence of substantially higher rates of density altitude increase relative to the other commands. By the year 2099, these two commands would make up a substantial majority of the top quartile for the distribution of values representing the percent increase in density altitude. While USNORTHCOM and USEUCOM might not be facing mission-inhibiting levels of degradation during the warming period included in this study, it is expected their degradation levels will continue to rise to the same level of severity seen in USAFRICOM and USSOUTHCOM as global warming continues to alter the operational environment.

Tactically, the Department should expect to sustain dramatic performance degradation to all aviation assets, most clearly evidenced by the decreasing thrust production that mandates reduced takeoff weight in strategic airlift platforms. While this study assumes the C-17 to be taking off with maximum allowable fuel, regional commanders will have the option to reduce takeoff weight by other means, such as less fuel on takeoff and increased utilization of aerial refueling assets. Commanders may also choose to sacrifice distance for payload. Reducing payload, then, is just one solution available to current and future commanders with regard to decreased aircraft performance in terms of total payload capacity.

Coping with this performance degradation will additionally fall on aircraft maintainers, aircrew mandated to fly extra missions, and taxpayers expected to help cover the added maintenance and operating costs.[46] The values of the density altitude thresholds are the

46. Ren et al., "Climate Warming."

only component of the data processing and analysis that is aircraft specific; different airframes within the Department of Defense or civilian aviation industry could be assessed in this same manner using new thresholds based on aircraft specifications.

The performance degradation of the C-17 Globemaster III, illustrated in this study, is only a small portion of the larger field of impact. Performance and capabilities of fighter, bomber, tanker, and rotary assets will also be diminished as the Earth continues to heat. Additional climate change scenarios may provide further opportunities for research and strategic planning. China and Russia may be the United States' regional and global competitors, but the universal adversary that is climate change knows no geopolitical boundaries.