

# BRIEFER

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## Climate Change Implications for U.S. Military Aircraft

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### Abstract

Climate change is radically altering the physical environment in the theater of conflict, making future military successes dependent on adaptation today. New research shows that climate change is reducing performance of military aircraft. As the environment grows hotter and more humid, military aircraft will not be able to carry as much payload or travel long distances without refueling. More missions will be cancelled or modified due to decreased aircraft performance on hot and humid days, which diminishes the U.S. military's ability to project power and respond effectively to conflicts.

Changes in the operational environment require corresponding changes in infrastructure, logistics, and acquisitions. To be effective long-term, these modifications must be informed by data-driven analysis of climate projections.

The adverse impacts of climate change on military-readiness are especially evident in aircraft and airbases. As heat and humidity rise, aircraft struggle to perform: meaning today's inventory might not be fit to operate in tomorrow's conflict. Anticipating the strain that climate change places on current inventory will help make current operations and infrastructure more resilient to climate threats. To this end, U.S. military and

military stakeholders would benefit from a vulnerability assessment model that predicts the frequency and severity of climate-related performance impacts for both airbases and aircraft.

This brief explores one such model developed by [Air Force Colonel Mary McRae](#) (ret.). McRae's model translates future climate projections from Global Climate Models into Density Altitude (DA) measurements that communicate specific changes in aircraft performance influenced by heat and humidity. Using this DA approach, McRae maps the vulnerability of various airbases and aircraft to DA conditions that limit the viability of future operations.<sup>1</sup> This vulnerability assessment tool will help military, policy and industry constituents determine the most critical threats to aircraft and airbase operations; effectively mitigate climate threats through more informed military acquisitions, infrastructure and mission planning.

More accurate and detailed climate threat assessments like McRae's make critical threats to military-readiness more visible. In doing so, updated vulnerability assessments enable current

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<sup>1</sup> "PhD Candidate Develops Novel Method for Assessing Impact of Climate Change on Aircraft Performance." Villanova University.

acquisitions processes to take climate change into account. These assessments also help the acquisitions community inform industry stakeholders about climate threats and ensure that infrastructure in development today is being designed in a climate-conscious manner. The information these assessments provide also encourages research into innovative design solutions that can adapt existing infrastructure to fit more challenging environments.

### **The mechanics explaining why lower air density decreases aircraft performance**

High, hot and humid are the three worst words a pilot can hear.

This flight-school phrase refers to the way air density and aircraft performance decrease with higher altitude, air temperature, and humidity.

Hotter air is less dense because the increased energy of warmer air molecules causes them to collide with greater frequency and intensity, ricocheting away from the collisions and dispersing across space.

Though humid air feels heavier, it is actually less dense than dry air. In humid conditions, water molecules displace nitrogen and oxygen molecules. This changes the air's composition, making it lighter and less dense because water molecules weigh less than nitrogen and oxygen molecules.

Aircraft rely on air to generate lift and thrust, so less dense air means less available power for fixed and rotary wing aircraft. In the same way that it grows harder to hike in higher elevations, it becomes more difficult for planes to operate in less dense air.

To predict how an aircraft will perform on a given flight, then, it is critical to know the air density where the plane is operating. Density Altitude, a measurement that translates air density into a relative altitude, helps pilots understand the altitude that the aircraft is experiencing. This relative altitude is often higher or lower than the real altitude, capturing the impact that temperature, atmospheric pressure and humidity have on air density.

The higher the DA, the less dense the air and the less well the aircraft will perform.

To understand why increased DA results in decreased aircraft performance, one should think about aircraft dynamics in simple terms: aircraft push against air molecules to generate lift in the same way a person pushes themselves up from a couch. Higher DA means less dense air, which means less air molecules to push on and less resistance against the airfoils. This lack of resistance makes it more difficult for aircraft to lift off the ground.

As aircraft push against air molecules to generate lift, their engines and propellers simultaneously bite into the air to produce power. As air gets thinner, less air molecules flow into the engine and propellers, making it harder for them to produce power.

So, high DA results in less power because there's less air available for engines to take in; less thrust because propellers are less effective in thin air; and less lift because thin air provides less resistance against airfoils.

For fixed wing pilots, higher DA means increased true air speed, decreased maximum takeoff weight, as well as increased takeoff and landing distances.

Similarly, higher DA means rotary wing pilots must deal with decreased maximum takeoff weight, decreased hover ceiling and rate of climb, as well as decreased power margins while the power required increases and the power available decreases.

Without physical changes in aircraft and airbase infrastructure, pilots operating in high DA environments must carry less payload to achieve mission objectives with diminished aircraft power, lift and thrust. The strain on existing military logistics and infrastructure will intensify as pilots spend more time operating in higher DA environments due to climate change.

### **Impacts of high DA on military operations**

Higher DA drastically diminishes aircraft performance and decreases the viability of current military operations.

“If we don’t change the aircraft performance by putting in better engines or redesigning for more aerodynamic performance, the current inventory of aircraft will require longer runways and be able to carry less payload because we will be operating in a hotter, more humid climate,” said [Rear Admiral David Titley](#), US Navy (Ret.). Titley served as Oceanographer and Navigator of the Navy and led the US Navy’s Task Force on Climate Change. Titley is a member of the Center for Climate and Security Advisory Board.

In higher DA conditions, pilots of both fixed and rotary-wing aircraft are not able to carry as much weight at takeoff. Reducing payload means carrying less weapons, less fuel, or less supplies — all of which are critical to mission success and safety.

Pilots often choose to carry less fuel because they can refuel en route. This means current missions must be adapted to accommodate a greater number of refuelings. More refuelings mean more airmen and aircraft must be deployed to sustain the same mission, which increases both the cost and risk of airborne operations.

Dr. Philip Brown flew reconnaissance two-seater aircraft and A-10 single seaters before serving as Deputy Chief of the Joint Resources and Readiness Division for NORAD & US-NORTHCOM J74.

Brown said that during Operation Desert Storm, hot weather made it very difficult for aircraft to support full payloads especially when pilots were carrying heavy combat equipment.

“Our choice was to take fewer weapons or less gasoline and hit an airborne tanker. This happened quite frequently in Desert Storm because so much of the combat took place in hot weather at high altitudes,” Brown said.

At the same time as pilots are forced to carry less fuel to reduce payload, fuel consumption rises due to the decreased aircraft power and efficiency brought on by higher heat and humidity. This means that aircraft must be refueled more frequently, which increases overall greenhouse gas production per ton mile.

This all changes how effectively the US is able to project power over space. Increased demand for in-flight refueling due to diminished payload capacity and fuel efficiency makes it more difficult for pilots to get from their base to the theater of operation. This limits the military’s ability to project power from its bases to zones of conflict.

This becomes especially problematic in regions like the Pacific, where pilots must travel incredible distances between bases with refueling mid-air their only option for resupply.

In addition to decreasing payload, pilots of fixed-wing aircraft must increase their takeoff and landing distances to compensate for lost power and lift by giving the aircraft more time to get up to speed and slow down. This modification is not possible in combat situations with limited runways, though, nor is it feasible on airbases where airstrips are boxed-in by residential or commercial development.

To artificially generate more lift, pilots must also increase their true air speed in order to send more air molecules over and under the aircraft’s wings.

These aircraft performance impacts can be mitigated by expanding aircraft power and efficiency through wing modification, more aerodynamic design, and more powerful engines. Other mitigation strategies involve lengthening runways and decreasing payloads.

### **Real-world examples**

To better visualize how military operations are being impacted by increasing heat and humidity, one can look at the impacts that changing climate conditions have had on commercial airlines. Commercial airlines are fighting a losing battle with climate change. Increasing heat and humidity is driving flight cancellations and threatening the viability of various airports and flight routes.

In June 2017, American Airlines [cancelled over 40 flights in Phoenix](#), Arizona and limited service during peak daytime heat window from 3pm to 6pm. Smaller, regional jets were unable

to take off due to extremely hot weather and daytime temperatures of 120 degrees.<sup>2</sup>

“We are not used to having commercial airlines disrupted because of hot weather,” Titley said. “This is a harbinger of things to come.”

Rising temperatures become especially problematic for airports at higher altitudes, like Denver, that already operate in thinner air.

While some airports can solve this lack of lift by extending their runways and providing aircraft more time to get enough speed to takeoff, not all airports have this luxury. La Guardia Airport in New York, for example, has a short airstrip that cannot be extended without running into the neighboring East River.

The only option left, then, is to reduce payload. At La Guardia, Boeing 737s reduce their payloads by at least a thousand pounds to compensate for the shorter airstrip. They must decrease payload even more dramatically on hotter days: cutting as much as 15,000 pounds on days that exceed temperatures of 90 degrees.

For commercial airlines, this simply means reducing the number of passengers on flights and sacrificing summertime profit margins. For the military, however, reducing payload poses an existential threat to military options.

And the temperatures we are witnessing at domestic airports pale in comparison to the temperatures in territories where the US operates abroad. While Phoenix might see temperatures of 120 degrees, pilots in regions like Africa and the Middle East can find themselves flying in temperatures above 130 degrees.

“If this is happening to American Airlines in Phoenix on one side of the runway, it is also happening to the Air Force on the other side of the runway,” Brown said.

The impacts that high temperatures have on aircraft performance are compounded by high alti-

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<sup>2</sup> Wichter, Zach. “Too Hot to Fly? Climate Change May Take a Toll on Air Travel.” *The New York Times*. June 21, 2017.

tude. This becomes especially problematic for the US military, which operates in some of the more mountainous regions of the world.

Increasing air temperatures are dramatically changing the nature of battlefields around the world. During the Osama bin Laden raid in 2016, for example, one of the Black Hawk helicopters was [critically damaged during a hard landing](#). In a statement about the crash, President Barack Obama highlighted the role that temperature played in the accident.<sup>3</sup>

“Despite the fact that they had practiced these landings repeatedly in a mock-up, we couldn’t account for temperature and the fact that helicopters start reacting differently in an enclosed compound where heat may be rising,” Obama said.

The walls of the compound trapped heat, making it significantly warmer inside the compound than outside, which the pilots were not adequately prepared for.

This example demonstrates that preparing for higher temperatures and higher humidity is necessary for military success. Accounting for climate change-related impacts on aircraft performance falls under the purview of the [US Department of Defense directive](#) issued in 2016 that requires all US military branches assess and mitigate the risks associated with climate change.<sup>4</sup>

This risk assessment and management involves detailed data analysis that translates projected climate change into real-world impacts on military-readiness. These models currently exist, but

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<sup>3</sup> Gaouette, Nicole. “Obama: Bin Laden Raid Didn’t Have Ideal Start.” *CNN*. May 03, 2016.

<sup>4</sup> USA. Department of Defense. Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. *Climate Change Adaptation and Resilience*. DOD DIRECTIVE 4715.21. January 14, 2016.

must be automated in order to be incorporated effectively into military decision-making processes. One of these models was developed by Air Force Colonel Mary McRae. During her time in the Sustainable Engineering PhD program at Villanova University, McRae used her military experience to approach this directive through the lens of military acquisitions. Her research generated a vulnerability assessment model designed to inform future military aircraft acquisitions that draws on Global Climate Models, identifying specific heat and humidity-related impacts on aircraft and airbase performance.

### Vulnerability assessment model

McRae’s vulnerability assessment model isolates projections of environmental conditions that decrease aircraft performance, namely high heat and humidity, and translates these conditions into direct impacts on aircraft and airbase operations.

By translating climate projections into impacts on aircraft and airbase operations, McRae’s model helps inform mission planning and aircraft acquisitions processes that are more resilient to climate change.



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<sup>5</sup> Research approach (McRae, 2017)

“We are making aircraft decisions now for planes that will be flying in thirty, fifty years,” McRae said. “We need to understand future climate and how that will impact aircraft performance.”

To assess the impacts of climate change on aircraft performance, McRae first collected temperature and humidity projections from Global Climate Models for Little Rock Air Force Base in Arkansas. Scientists create these Global Climate Models by extrapolating from climate data to predict future climate conditions given different warming scenarios ranging from moderate to severe.

McRae translated these climate projections into DA to communicate increases in temperature and humidity in terms of specific impacts on aircraft performance. McRae then tested the frequency that different aircraft will surpass the DA threshold at which they experience performance deterioration in these hotter, more humid operating conditions.

McRae found that the frequency of occurrence of high DA increases with climate change, meaning the incidence of temperature and humidity-related aircraft performance issues will continue rising.

It is critical that military decision-makers and acquisitions personnel understand this trend in order to ensure future infrastructure and invento-

ry is designed to withstand future climate challenges.

“The future will no longer resemble the past,” Titley said. “For decades, we would look back 50 to 100 years and build for the historic averages. We can’t do this any longer: the only pragmatic way forward is to account for these changes in climate.”

McRae found that these changes in climate will have tremendous impacts on aircraft and airbase operations. To understand the magnitude of this impact, take the month of July, for example. Using a 30-year sample, Little Rock Air Force Base has historically experienced DA of 3,000ft or higher during 20% of July. At this DA, aircraft experience diminished performance and power. Fifty years from now, under the worst emissions scenario, Little Rock AFB is projected to experience a DA of 3,000ft or higher approximately 80% during that same time period. This means that aircraft are likely to run into performance issues during most of July, which severely limits military readiness.

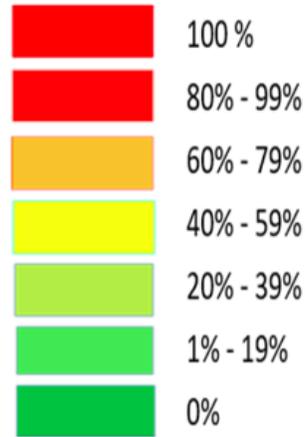
“You’re going to have to modify the missions or modify the aircraft,” McRae said.

McRae demonstrates how often current aircraft and airbases are going to struggle to perform in hotter and more humid climates by mapping the frequency that airbases and aircraft will be faced with DA operating conditions that exceed their operating capacity.

# Risk Probability Matrix Chart

Percent of Global Climate Model agreement:

- Horizontal (x) axis = Threshold
- Vertical (y) axis = % of time period threshold is surpassed
- Cell Color = % of GCM agreement



## Density Altitude $\geq$ 3000 ft., Little Rock Air Force Base, JULY

% of Time Period > Threshold JULY	Observed (1970-1999): DA $\geq$ 3000 ft.	2020-2049: DA $\geq$ 3000 ft.	2040-2069: DA $\geq$ 3000 ft.	2060-2089: DA $\geq$ 3000 ft.
1 day	100%	100%	100%	100%
10% (93 days)	100%	100%	100%	100%
20% (186 days)	100%	100%	100%	100%
30% (279 days)	0%	100%	100%	100%
40% (372 days)	0%	100%	100%	100%
50% (465 days)	0%	70%	100%	100%
60% (558 days)	0%	40%	100%	100%
70% (651 days)	0%	15%	85%	100%
80% (744 days)	0%	0%	45%	95%
90% (837 days)	0%	0%	15%	60%
100% (930 days)	0%	0%	0%	0%

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<sup>6</sup> These figures based on RCP 8.5 projections from 20 Global Climate Models. (McRae, 2017).

This risk assessment informs a vulnerability map helps the military predict when they will encounter significant aircraft performance impacts at a given airbase under a certain warming scenario.

By mapping the agreement of different climate models, McRae captures the uncertainty inherent in climate modeling and allows program managers and acquisitions personnel to calibrate their desired level of risk by choosing a specific confluence of certainty of the GCMs.

This model has already caught the military's attention: McRae was asked to present her research findings to the Air Force.

“Our work in the Villanova Sustainable Engineering program is validated by implementation, not just publication,” Professor Ross Lee said. Lee served as McRae's advisor and is a Professor of Practice in the Villanova Sustainable Engineering department.

Lee said Villanova is committed to supporting McRae and her research by continuing their work with NASA and the Department of De-

fense to convert this vulnerability assessment model into an automated tool to be implemented in military decision-making.

This tool would be incredibly useful for military decision-makers because, unlike McRae's vulnerability assessment model, most aircraft performance calculations do not currently include dew point and humidity. This can be problematic because temperature interacts with humidity to change the operating conditions and influence DA.

Ignoring humidity is increasingly worrisome as humidity is rising and becoming a more significant factor in decreasing air density and aircraft performance.

Now that climate change is increasing the number and intensity of hot and humid days, it is critical that military acquisitions and logistics personnel address climate-related impacts on aircraft performance in their plans.

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