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Application of Density Altitude Climatology to General Aviation Impacts

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Abstract

Density altitude (DA) plays a key role in flight safety because it helps pilots anticipate poor aircraft performance when temperatures are warmer than standard. In this study, a 30-year climatology of DA for the conterminous United States was created using the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis of the global climate (ERA5) dataset applied to four separate DA-based, aircraft-performance rules-of-thumb for general aviation (GA) flight. The goal was to demonstrate a technique to create educational visualization tools showing the variation of operational flight impacts with both month and location. Four such parameters were chosen to show the technique's utility: take-off distance, landing distance, climb rate, and engine power, all of which were expressed as multipliers to be applied to the standard altitude values. The study provided results based on the 30-year (1981-2020) July mean DA values as well as those based on the maximum daily values (worst case) at each grid point occurring during the months of June, July, and August during the same period. Results showed performance parameters tended to have the most variation in the east-west direction following terrain rather than the north-south direction following the solar insolation.

Keywords: density altitude, aviation, climatology

Introduction

Density altitude (DA) plays a key role in flight safety because it helps determine an aircraft's performance characteristics under non-standard temperatures. DA physically represents the altitude in the standard atmosphere where the airport's observed air density occurs (Forsythe & Hendrickson, 1946) and can be thought of as the pressure altitude (PA) corrected for non-standard temperature (Federal Aviation Administration [FAA], 2008). Since increases in temperature and humidity result in lower air density, and air density decreases with altitude, warmer temperatures and higher humidities lead to increased DA. Thus, high DA values imply lower density air, which reduces wing lift, decreases engine performance, and decreases propellor thrust. The problem is exacerbated at higher elevations where DA is already naturally high even at standard temperatures. This leads to increased take-off distances, increased landing distances, reduced engine power, and reduced climb-rates (Collins, 2016; Embree, 1984; FAA, 2008).

While the risk posed by high DA conditions affects all sectors of aviation, the risk is especially critical for general aviation (GA) flights where the pilot-in-command is typically solely responsible for calculating the DA and assessing the associated impacts. In contrast, commercial airline pilots have FAA dispatchers to provide DA performance calculations specific to the aircraft. Fultz and Ashley (2016) found that high DA was associated with 1,268 of the 11,354 (~11%) weather-related GA accidents that occurred during 1982-2013. Of these, 297 accidents resulted in fatalities, yielding a lethality rate of 23% (297/1,268). Given these high accident rates, the development of improved educational tools for GA pilots could potentially improve safety of flight.

GA pilots typically determine the DA through an electronic or manual flight calculator or a published FAA DA chart (e.g., FAA, 2016). While this works well for each individual flight, there is currently limited educational information to assist pilots with understanding how the impacts of DA on GA vary with geographic region and season. Such a product, while not appropriate for application to individual flights, could provide private pilots, student pilots, and especially instructor pilots a useful educational tool to promote situational awareness by more clearly communicating the evolution of DA during the year for their areas of interest. More importantly, the tool could highlight the extent of the aviation hazards and potential risks created by increased DA. This paper provides a methodology for creating such visual training tools and provides multiple examples.

Background

Halperin et al. (2022) constructed a 30-year climatology of maximum daily DA over the conterminous United States that adheres to World Meteorological Organization (WMO) guidelines for climate normals (WMO, 2021). They then compared their results to similar calculations using various rules-of-thumb (ROTs). As expected, the greatest DA values occurred at high-elevation locations (i.e., locations with low surface pressure and therefore high surface PA values) during the summer months of June, July, and August (JJA). The climatology was constructed using 30 years of reanalysis data (1991 to 2020) from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5) data set (ECMWF, 2017; Hersbach et al., 2020). Reanalysis data provide a physically consistent grid of past weather variables by blending historic observational data with short-term forecasts from a modern numerical weather prediction model (ECMWF, 2020). To create the reanalysis data, a short-term numerical weather model forecast is nudged using observational data to bring the model data into agreement with the observations. By combining observational data with the forecast model output, the reanalysis process can fill in any observational data voids with model data according to established physical principles. The blended data then serve as the initial conditions for the next short-term forecast, and the process continues. The final product is called a “reanalysis” because the historical observations are reanalyzed using a modern numerical model. The value of reanalysis data is that the output is consistent over the entire historical record because the same numerical model is used for the entire process. This data set can then be used to create climatological products, such as those in Halperin et al. (2022) and the present study. Goodman and Griswold (2018) used a different reanalysis data set to examine climate impacts on DA and aviation operations. However, their focus was specifically on the variation of DA with common seasonal climate teleconnections, namely the El Niño/Southern Oscillation (ENSO) and the Arctic Oscillation (AO).

In a similar study, McRae et al. (2021) examined climate model forecast data to evaluate potential impacts on aircraft performance resulting from DA increases due to a warming climate. So, whereas Halperin et al. (2022) and Goodman and Griswold (2018) examined the current climate record, McRae et al. (2021) examined potential future climates. In their study, McRae et al. (2021) applied their DA results directly to various GA aircraft performance ROTs (e.g., payload reduction, take-off distance, percent decrease in power) to demonstrate the utility of their method for use with military aircraft that have classified performance limitations. The challenge with the McRae et al. (2021) study was twofold. First, the temperature and pressure data were not physically consistent; that is, maximum daily temperature was provided by the climate model output, but the pressure was not. Instead, DA was calculated using the projected maximum daily temperature values and the current climatology-based monthly mean pressures.

Second, since the climate model provided no moisture information, the humidity had to be inferred from daily minimum temperature. Despite the challenges, their results were meaningful, and their technique served as a motivation for the present study.

Present Study

This study builds upon the efforts of Halperin et al. (2022) and McRae et al. (2021) by creating a physically consistent 30-year climatology of specific, DA-based impacts on GA flight operations for use as an educational tool. The technique demonstrated here can be applied in other aircraft-specific or geographic contexts.

Method

Following Halperin et al. (2022), we used ERA5 data to calculate a 30-year, monthly mean climatology of maximum-daily DA (including the effects of humidity) for the years 1991-2020 over the conterminous U.S., as shown in Figure 1a. In addition, Figure 1b shows the *maximum* daily DA values during any JJA day in the study period at each model grid point to provide a "worst-case" scenario, again following Halperin et al. (2022). The DA values were then used as input to four specific GA ROTs published by Embree (1984) and Collins (2016). These include a landing-distance multiplier (M_{LD}), a take-off distance multiplier (M_{TO}), a climb-rate reduction multiplier (R_{CR}), and an engine-power reduction multiplier (R_{EP}). We chose these four simple ROTs, which are intended for fixed-pitch propellers and normally aspirated aircraft engines, to provide a sample of GA aircraft performance calculations for which this technique may be used. These four ROTs are discussed in detail below.

The first ROT, M_{LD}, provides the multiplier to be applied to the required standard sea-level landing distance. The ROT is derived from Embree's (1984) ROT that states the landing distance should be increased by 4% for every 15°F warmer than standard temperature (for the airport elevation). However, if we combine this ROT with the well-known ROT that DA increases 120 feet for every 1°C warmer than standard (FAA, 2012), then Embree's M_{LD} ROT is identically equivalent to an increase of 4% of landing distance for every 1,000 feet increase in DA. This can be easily shown by noting that a 15°F change in temperature is equivalent to an $8.33\overline{3}$°C change. If we multiply $8.33\overline{3}$°C by 120 feet, we find that a 15°F increase in temperature results in a DA increase of 1,000 feet. Thus, a 4% increase in landing distance for every 15°F increase in temperature converts identically to a 4% increase in landing distance for every 1,000 feet increase in DA, as provided in (1). Here the DA is input in feet, and M_{LD} is unitless. This ROT is consistent with Hurt's (1965) estimate of 3.5% for every 1,000 feet and Hudson's (2013) estimate of 5% for every 1,000 feet. All ROTs presented here are converted from a percentage to a multiplier for ease of application.

$$M_{LD}(DA) = \left\{1 + 0.04\frac{DA}{1000\text{ ft}}\right\} \tag{1}$$

The second ROT, M_{TO}, is the multiplier to be applied to the standard sea-level take-off distance for a fixed-pitch propeller aircraft. The general ROT is to add 15% additional distance for every 1,000 feet increase in DA up to 8,000 feet and add 20% for every 1,000 feet DA above 8,000 feet (Embree, 1984). Mathematically, this relationship is provided in (2), where DA is input in feet, and M_{TO} is unitless.

$$M_{TO}(DA) = \begin{cases} 1 + 0.15\dfrac{DA}{1000\text{ ft}}, & DA \leq 8000\text{ feet} \\ 2.2 + 0.2\left(\dfrac{DA - 8000\text{ ft}}{1000\text{ ft}}\right), & DA > 8000\text{ feet} \end{cases} \tag{2}$$

The third ROT, R_{CR}, provides the multiplier that should be applied to the standard sea-level climb rate for a fixed-pitch propeller aircraft. The ROT states the climb rate should be reduced by 7% for every 1,000 feet increase in DA up to 8,500 feet and reduced by 8% for every

1,000 feet increase in DA thereafter (Embree, 1984). Mathematically, the R_{CR} is provided in (3), where DA is input in feet and R_{CR} is unitless. This ROT is not applicable for DA values greater than approximately 13,562 feet at which point the R_{CR} multiplier is negative.

$$R_{CR}(DA) = \begin{cases} 1 - 0.07\dfrac{DA}{1000\text{ ft}}, & DA \leq 8500 \text{ feet} \\ 0.405 - 0.08\left(\dfrac{DA - 8500}{1000\text{ ft}}\right), & 8500 > DA < 13562 \text{ feet} \end{cases} \tag{3}$$

The fourth ROT, R_{EP}, represents the multiplier applied to the standard sea-level engine power for a normally aspirated aircraft engine. The engine power should be reduced 3.5% for every 1,000 feet increase in DA (Collins, 2016). Mathematically, this is provided in (4), where DA is in feet and R_{EP} is unitless. This equation is not valid for DA values greater than approximately 28,500 feet, at which point the R_{EP} yields negative values.

$$R_{EP}(DA) = \left\{1 - 0.035\frac{DA}{1000\text{ ft}}, \quad DA < 28500 \text{ feet}\right\} \tag{4}$$

We also note that negative DA values are possible in winter months at lower elevations. In these instances, all ROTs result in increased aircraft performance rather than decreased performance. This information is not shown since the focus of the present study is on DA impacts associated with warmer than standard temperatures and degraded aircraft performance.

The methodology described above is not limited to these four ROTs. Once the DA climatology is created, the same technique can easily be applied to a variety of general DA-based ROTs as well as aircraft-specific DA-based operational impacts. These four ROTs were chosen for their broad applicability to GA operations to demonstrate the utility of the technique.

Results and Discussion

To create the basis for all ROTs, we first developed a 30-year climatology of DA over the conterminous U.S. as discussed in the “Methods” section. Figure 1a shows the 30-year mean daily-maximum July DA for the U.S., and Figure 1b shows the 30-year maximum DA value at each grid point during any JJA day in the study period. While twelve months of data are available for the region, we chose July as a representative warm month to demonstrate DA-related GA impacts.

In examining the data, we observe several features worth noting. First, we note that DA tends to vary primarily in the longitudinal direction associated with terrain rather than in the latitudinal direction associated with solar insolation. This demonstrates the key role elevation plays in DA due to lower station pressures (higher surface PA). Second, the maximum (worst case) DA values tend to be roughly 1,000 feet higher than the 30-year *mean* daily-maximum July values. Likewise, the maximum (worst-case) DA values can be 3-4 times higher than the elevation of the region. This is especially noticeable in the U.S. central plains where the maximum DA values are 4,000-5,000 feet while the terrain height is typically 1,000 feet or less. Finally, there are noticeable swaths of higher DA values on the 30-year maximum DA plots over the Gulf of Mexico and Atlantic Ocean. As pointed out in Halperin et al. (2022), these are related to hurricane tracks where the resulting surface pressure was abnormally low. While DA is most frequently considered to be associated with warm temperatures, these swaths remind us that low pressure (i.e., high PA) also plays an important role in increasing the DA. While interesting, the swaths pose little threat to GA because the winds associated with hurricanes make most GA flights (i.e., those associated with small, single-engine aircraft) impractical.

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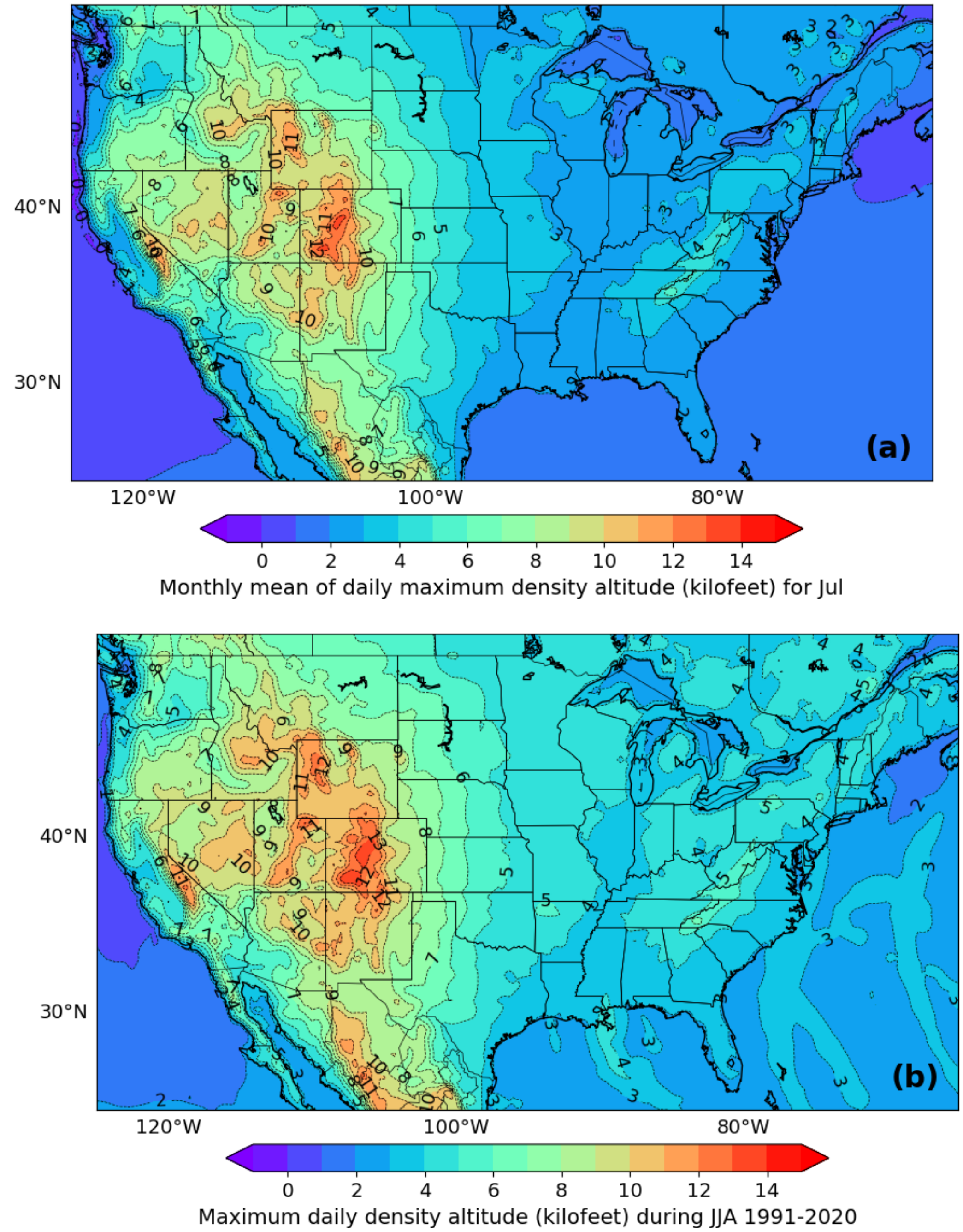
Figure 1

Maximum Density Altitude



Note. (a) Thirty-year July mean maximum-daily density altitude (*DA*) calculated with humidity for 1991-2020, and (b) the maximum daily *DA* during June, July, and August for the same period. Adapted from Halperin et al. (2022). Copyright 2022 by the American Meteorological Society. Used with permission.

Using the DA data as input, we next applied the above ROTs to graphically depict GA impacts. First, we examined the landing and take-off distance multipliers, M_{LD} and M_{TO}, respectively by creating maps using the formulas in (1) and (2). The impact of DA on M_{LD} is minimal (see Figure 2). In most cases, the increase in required landing distance is less than 20% of the standard mean sea-level value except in regions of high elevation. In contrast, Figure 3 shows M_{TO} is much more greatly impacted by high DA values. For example, in the central U.S. the M_{TO} is 40-60% higher than the standard mean sea-level value. Higher elevation areas are significantly impacted as well; however, the maximum values are found at elevations which are prohibitive to most GA aircraft. In contrast, coastal regions are less impacted because of their proximity to the oceans, which tend to moderate summer temperature maximums. For both M_{LD} and M_{TO}, the worst-case values show similar patterns but with slightly higher values, especially for M_{TO}, which increases by approximately 20% over most of the region of interest.

Finally, we apply the ROTs for two flight performance parameters, the climb rate multiplier (R_{CR}) and engine power multiplier (R_{EP}) as shown in Figures 4 and 5, respectively, by creating maps using the formulas in (3) and (4). As with the previous ROTs, the greatest variation appears in the longitudinal direction associated with changes in terrain. Also, as expected based on the ROTs, the impact on climb rate is roughly double the impact on engine power owing to the 7% reduction per 1,000 feet for R_{CR} compared to the 3.5% reduction per 1,000 feet for R_{EP}. The worst-case climb rate (Figure 4b) shows a variation across the eastern U.S., ranging from 50-60% of the standard sea level value over the high plains and increasing to 70-80% over the eastern seaboard states. In contrast, the worst-case engine power (Figure 5b) is relatively uniform for the entire eastern half of the U.S. at approximately 80-90% of the standard sea-level values. As with the previous ROTs, both the climb rate and engine power

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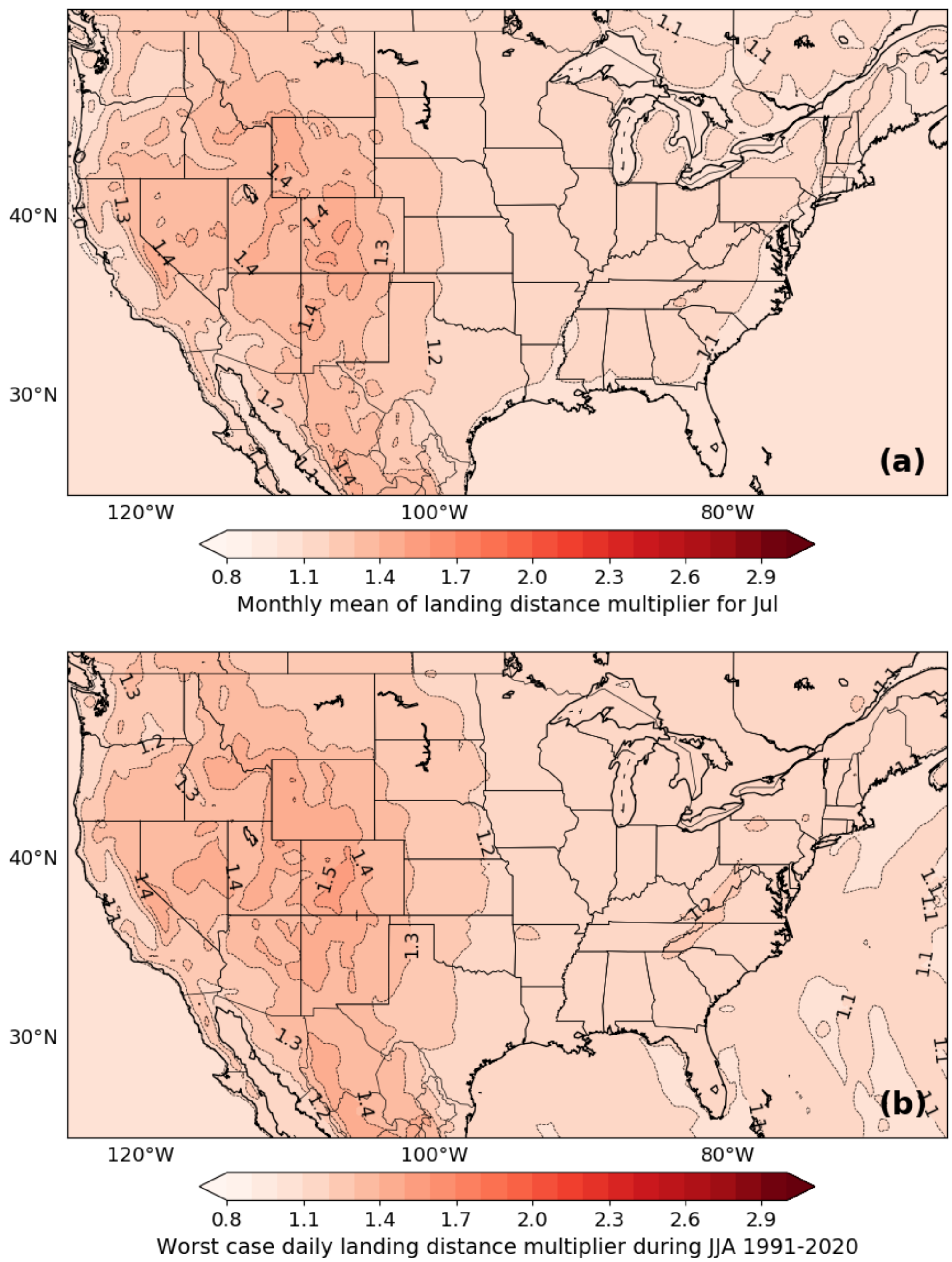
Figure 2

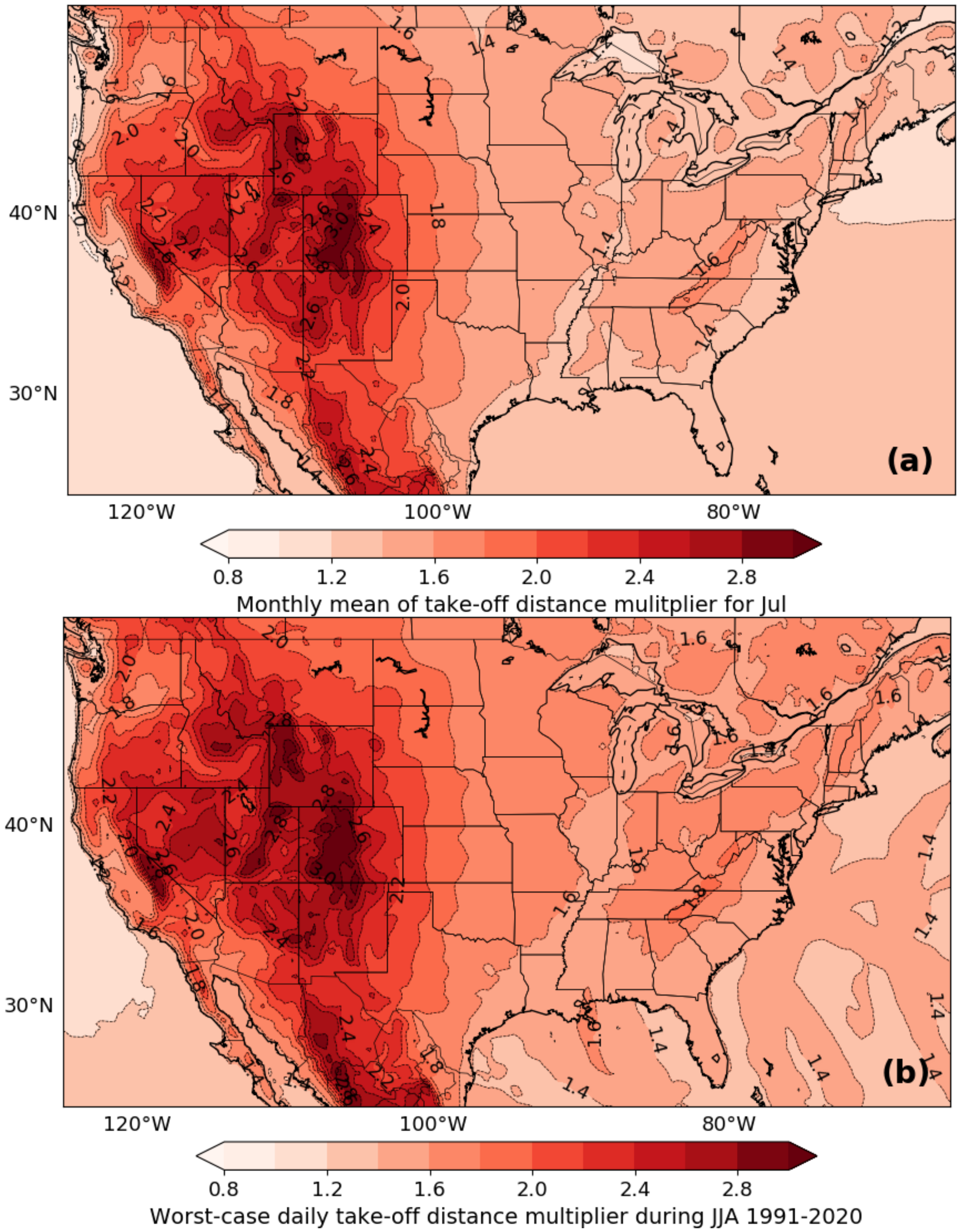
Landing Distance Multiplier



Note. Landing distance multiplier (unitless) calculated using (a) the 1991-2020 July mean daily-maximum *DA*, and (b) the worst-case (maximum) *DA* during JJA for the same period.

Figure 3

Take-off Distance Multiplier



Note. As in Figure 2, except for the take-off distance multiplier.

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ROTs also show the greatest impacts over the high elevations in mountainous regions due to their high surface-PA values.

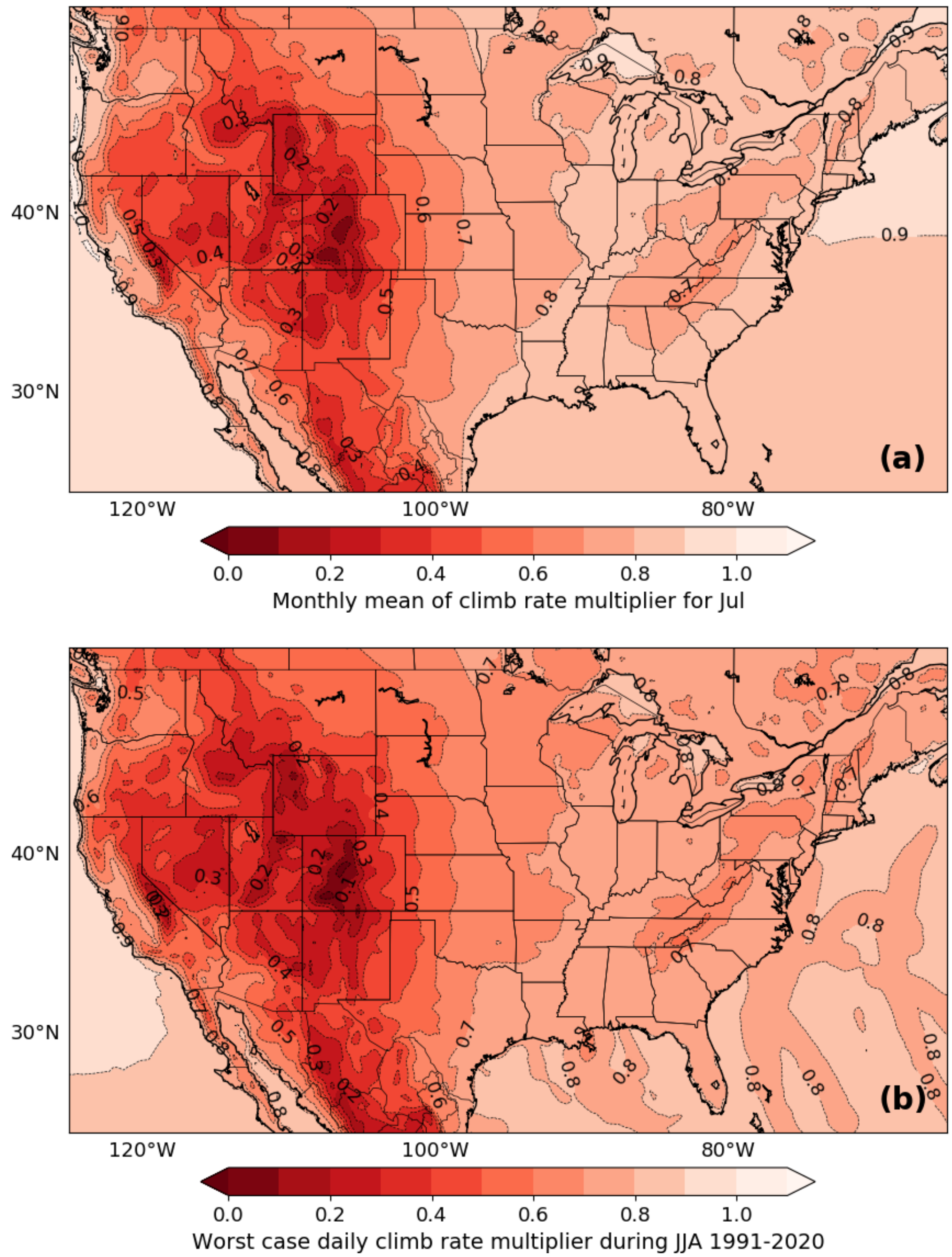
The results demonstrate how DA-based, aircraft-performance ROTs can be applied to a DA climatology to visualize impacts to all types of aviation, not just GA. Although not shown, the same techniques can be applied to visualize the evolution of the impacts on a month-by-month basis. As stated previously, while this may not be useful for individual flight planning, flight instructors could use visual aids to increase student awareness of the seasonal changes in DA-based impacts for their geographic regions. Importantly, this tool explicitly quantifies the typical and worst-case DA impacts on specific flight performance metrics to highlight, especially for student pilots, the sometimes-substantial reduction in performance associated with high DA. If needed, the visualizations could also be produced for smaller geographic regions with higher fidelity contours to produce more refined results.

Limitations

The technique is not without limitations. The horizontal grid resolution is approximately 31 km, so terrain elevations are somewhat smoothed (ECMWF, 2017; Hersbach et al., 2020). In addition, the temperature, pressure, and humidity data used for the calculation of DA are only available on the hour (ECMWF, 2020), so the true daily maximum could have occurred outside of the hourly report. Finally, the aviation ROTs used in this study are relatively broad and not specific to any aircraft. The results therefore only provide general impacts to a relatively broad range of aircraft.

Figure 4

Climb-Rate Multiplier



Note. As in Figure 2, except for the climb-rate multiplier.

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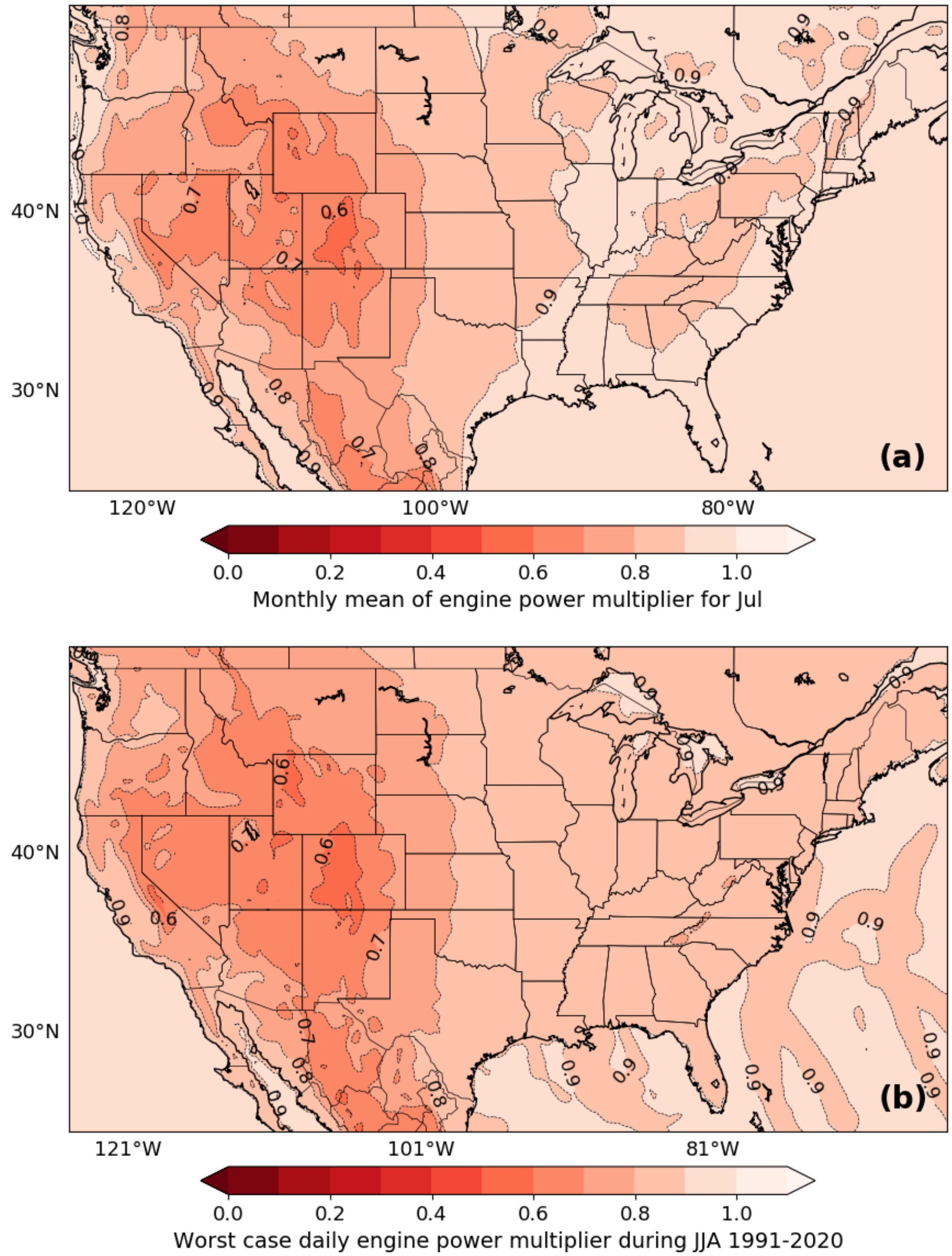
Figure 5

Engine-Power Multiplier



Note. As in Figure 2, except for the engine-power multiplier.

Summary and Conclusions

Halperin et al. (2022) demonstrated the effectiveness of using ERA5 reanalysis data to create climatological visualizations of DA values over the conterminous U.S. for use in aviation education. In this study, we expanded that work by applying the same DA climatology data directly to four GA aircraft-performance ROTs for minimum landing distance, minimum take-off distance, climb rate, and engine power. In addition to the monthly means of the daily-maximum DA, the maximum DA values at each grid point occurring during any day in June, July, and August were also created to demonstrate the “worst-case” scenarios of performance calculations. This technique led to the development of the first visualizations of the variation of DA-based aviation performance characteristics over the U.S. In addition to Halperin et al. (2022), this study was also inspired by McRae et al. (2021) who used a similar technique but with forecasted climate information.

The results indicate the greatest variation in impacts occurs in the longitudinal direction following the terrain, with the worst-case impacts occurring near higher terrain associated with the Rocky and Appalachian Mountain ranges. Most importantly, the results demonstrate the technique’s utility for creating training visualizations directly relating DA to aircraft performance. While the focus of this study was on the month of July, the technique can also show the seasonal variation by creating plots of each month. These were created, but not included in this study. In addition, the technique could easily be applied to any DA-based performance calculation, no matter how complicated, if the supporting equation is a single-variable function of DA. The equation need not be a simplified ROT as used in this study and could therefore be applied to the performance characteristics of any aircraft.

Since the reanalysis data used as the basis for the DA climatology in this study is global, future work could focus on using this same technique to create similar visualizations for any part of the world. In addition, as the reanalysis data set expands to include longer historical records, the data could also be used to examine impacts resulting from a changing climate by, for example, statistically comparing the 1961-1990 climatology of aviation impacts with the 1991-2020 impacts.

Another area of study could be to combine the climate data with Geographic Information Systems (GIS) visualization platforms to allow the user to overlay multiple impacts as well as to use adaptive grids for zooming in on smaller geographical regions for greater fidelity. Furthermore, web-based applications could be developed to allow the user to input DA-based ROT criteria for any aircraft via a graphical user interface and immediately display the results.

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