Climate Change and the Impact of Extreme Temperatures on Aviation

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ABSTRACT

Temperature and airport elevation significantly influence the maximum allowable takeoff weight of an aircraft by changing the surface air density and thus the lift produced at a given speed. For a given runway length, airport elevation, and aircraft type, there is a temperature threshold above which the airplane cannot take off at its maximum weight and thus must be weight restricted. The number of summer days necessitating weight restriction has increased since 1980 along with the observed increase in surface temperature. Climate change is projected to increase mean temperatures at all airports and to significantly increase the frequency and severity of extreme heat events at some. These changes will negatively affect aircraft performance, leading to increased weight restrictions, especially at airports with short runways and little room to expand. For a Boeing 737-800 aircraft, it was found that the number of weight-restriction days between May and September will increase by 50%–200% at four major airports in the United States by 2050–70 under the RCP8.5 emissions scenario. These performance reductions may have a negative economic effect on the airline industry. Increased weight restrictions have previously been identified as potential impacts of climate change, but this study is the first to quantify the effect of higher temperatures on commercial aviation. Planning for changes in extreme heat events will help the aviation industry to reduce its vulnerability to this aspect of climate change.

1. Introduction

Surface temperatures over the United States have increased by approximately 0.8°C since the start of the twentieth century, with most of that change occurring after 1980 (Walsh et al. 2014; Karl et al. 2009). Temperature increases exhibit spatial variation (Portmann et al. 2009), with the most significant changes occurring in the central and eastern United States (Walsh et al. 2014). Extreme temperature events have been observed to increase more rapidly than the mean, with changes of 1°–1.5°C over much of the continental United States (Brown et al. 2008; Frich et al. 2002). As climate change progresses, temperatures are projected to increase, with approximately 4°–5°C of mean warming expected by 2100 under the RCP8.5 emissions scenario (Hartmann et al. 2014; Moss et al. 2010), with potentially larger changes in the magnitude of extreme events (Fischer et al. 2013; Donat et al. 2013; Easterling et al. 2000).

Weather is the most significant factor affecting aircraft operations, accounting for 70%–80% of passenger delays (Rosenberger et al. 2002) and costing airlines hundreds of millions of dollars per year in lost revenue (Lan et al. 2006). Thus far, few studies have investigated the effects of climate change on aviation-relevant weather parameters (Williams and Joshi 2013). Here we quantify the expected impact of increasing mean and extreme temperatures on aircraft performance. As air warms at constant pressure it becomes less dense, and an airplane wing traveling through this thinner air will produce less lift at a given speed than in cooler, thicker air. As a result, on warm summer days, commercial airplanes have higher takeoff speeds (Anderson 1999). Barometric pressure variations are used in day-to-day flight planning, but since weather-related pressure changes are usually less than

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TABLE 1. Airport characteristics. Runway lengths are for the longest runway at the airport; weather or other operating conditions may require a different and potentially shorter runway to be used for departures. Data obtained from FAA airport charts.

Airport	Maximum runway length (ft)	Elevation (ft)
PHX	11 500	1135
DEN	16 000	5433
LGA	7003	21
DCA	7169	15

30 hPa at all airports worldwide, this is a much smaller factor than temperature and is not considered here; all performance data assume a standard pressure of 1013 hPa. For each airport and aircraft type, there is a temperature threshold above which the airplane's minimum flying speed at its maximum takeoff weight is too high to reach on the available runway, and the airplane must be weight restricted. Airlines respond by removing either passengers or cargo to decrease the aircraft's weight and thus lower its takeoff speed. Here we investigate how the number of days per summer (May–September) on which a Boeing 737-800 must be weight restricted may change during the twenty-first century as a result of climate change. We use the period May–September rather than the standard June–August in order to capture the vast majority of weight-restriction events in the future. The 737-800 is one of the most common short-to-medium-range aircraft, operating 426 789 flights in 2013 (www.transtats.bts.gov). The trends we find here hold with some variation for other commercial aircraft types.

2. Methods

We conduct a detailed analysis of four airports in the United States that may be particularly susceptible to increasing temperatures: Phoenix Sky Harbor International Airport (PHX), Denver International Airport (DEN), New York's LaGuardia Airport (LGA), and Washington, D.C.'s Reagan National Airport (DCA). PHX was chosen because of its frequent extremely high summer temperatures; DEN because of its relatively high elevation; and LGA and DCA because of their short runways, limited space for expansion, and high traffic loads. The maximum runway lengths and elevations for these four airports are shown in Table 1.

We define three levels of weight restriction: 1000 lb (454 kg), 10 000 lb (4536 kg), and 15 000 lb (6804 kg). Each level indicates how much the aircraft's maximum takeoff weight must be reduced as compared to a day with no restriction. At each airport, 737-800 performance charts from Boeing (Boeing 2013) are used to calculate the

TABLE 2. Boeing 737-800 temperature thresholds for three chosen levels of weight restriction. "N/A" indicates a restriction that is always in effect because of airport characteristics, regardless of temperature. Data obtained from Boeing (2013).

Airport	1000-lb (454 kg) reduction (°C)	10 000-lb (4536 kg) reduction (°C)	15 000-lb (6804 kg) reduction (°C)
PHX	38	47	53
DEN	N/A	30	37
LGA	N/A	31	33
DCA	N/A	31	33

temperature that will result in each level of weight restriction. These temperature thresholds are shown in Table 2. The required temperatures vary significantly because of runway length and airport elevation, and at DEN, LGA, and DCA, "N/A" indicates that a 1000-lb weight restriction is always in effect. At LGA and DCA, a 737-800 cannot take off at its maximum weight at any temperature because of the relatively short runways, and at DEN the runways are sufficiently long, but the required takeoff speed would exceed the maximum tire speed of 225 mph (Boeing 2013).

We use 17 general circulation models from the CMIP5 multimodel ensemble (Taylor et al. 2012; see Table 3) to project future temperatures under the RCP8.5 high emissions scenario (Moss et al. 2010). We use daily maximum temperature observations from the National Climatic Data Center (NCDC), recorded on the airport grounds, for historical verification. Historical weight-restriction trends are examined during the period 1981–2005. However, the Denver International Airport opened in 1995, and thus, only 10 years of observational data are available at that site. The other three airports—PHX, LGA, and DCA—have observational data for the entire historical period. It should be noted that while the particular variant of 737 analyzed here was not in operation in 1981, aircraft with similar weights and flight characteristics were.

The CMIP5 ensemble has been shown to represent extreme temperature events relatively well (Sillmann et al. 2013a; Field et al. 2012), but significant biases are still present in CMIP5 daily maximum temperature. We use a bias-correction procedure to reduce the spread between the CMIP5 daily maximum temperature distributions and the observed distributions. We separate the observed and modeled temperature distributions at each airport into 20 five-percentile bins, and the mean bias between the modeled and observed temperatures in each bin is subtracted from the model data. This correction is performed for each of the 17 CMIP5 models, and the corrected model data are then averaged to form a multimodel mean. The bias-correction and averaging procedure is seen to significantly improve both the shape

TABLE 3. CMIP5 models used.

Modeling center	Institute ID	Model name
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM
Canadian Centre for Climate Modeling and Analysis	CCCma	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	National Science Foundation (NSF), DOE, NCAR	CESM1 (BGC)
Community Earth System Model Contributors	NSF, DOE, NCAR	CESM1 (CAM5)
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CM
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CMS
Centre National de Recherches Meteorologiques–Centre Europeen de Recherche et Formation Avancee en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL CM3
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2M
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadGEM2-ES
L'Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-MR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-MR
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NorESM1-M

and range of the distributions at all airport sites (see Fig. A1).

Each bias-corrected CMIP5 model is used to project future temperatures at the airport sites during the period 2021–69 under the RCP8.5 scenario, and a multimodel mean is calculated by averaging the mean and extreme daily maximum temperatures across the models. During this period, significant mean temperature increases of 2.5°–3.5°C are projected across the United States as shown in Fig. 1a. However, as found by other studies (Diffenbaugh and Ashfaq 2010; Meehl and Tebaldi 2004; Sillmann et al. 2013b), the projected change in temperature extremes is larger, with average increases of 3°–5°C in the annual maximum temperature as shown in Fig. 1b. All four airports are projected to see significant increases in temperature by midcentury. Figure 2

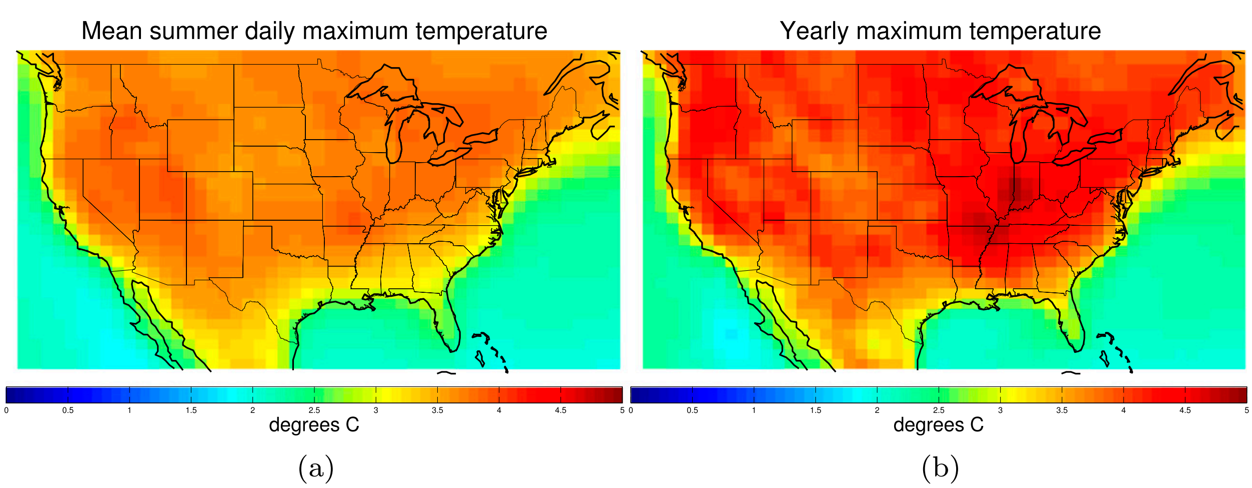

FIG. 1. Change in summer temperatures in the CMIP5 multimodel mean in 2050–69 relative to 1981–2005. (a) Mean summer daily maximum temperature and (b) annual summer maximum temperature.

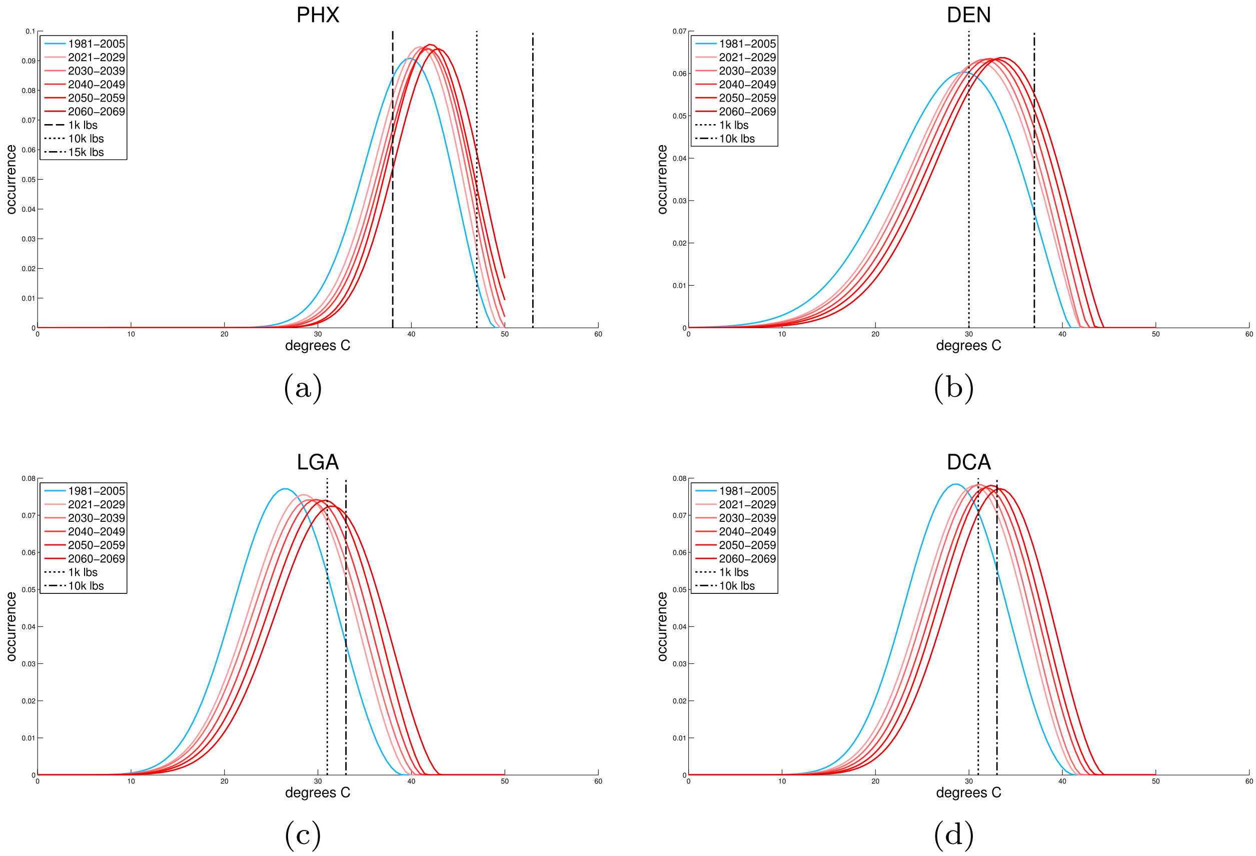

FIG. 2. Generalized extreme value distributions at selected airports: (a) PHX, (b) DEN, (c) LGA, and (d) DCA. Distributions shown for the base period (1981–2005) and each decade between 2021 and 2069. Dashed and dotted black lines indicate the temperature thresholds for the three weight-restriction levels: 1000 lb, 10 000 lb, and 15 000 lb.

shows generalized extreme value distributions for the historical period (1981–2005) and each decade between 2021 and 2069. The weight-restriction temperature thresholds at each airport are shown by vertical dashed and dotted lines. Changes in yearly maximum temperatures of 3°–4°C are seen at all four airports with smaller changes of 3°–3.5°C in the summertime mean daily maximum.

3. Results

We define a weight-restriction day as any day when the daily maximum temperature matches or exceeds the weight-restriction temperature threshold. Determining the amount of time that the threshold is exceeded is not possible with the CMIP5 model data. The number of weight-restriction days per year is calculated using the observed temperatures, bias-corrected historical CMIP5 data, and bias-corrected future CMIP5 data. Our results are shown in Fig. 3. We find that the number of weight-restriction days increases significantly at each airport, with the number of 10 000-lb restriction days going from near zero to approximately 20 at PHX and doubling at LGA. Large increases in the number of 15 000-lb restriction days are seen at DEN, LGA, and DCA, although they remain a rare event at PHX. Because of the short runway lengths at LGA and DCA and the high elevation at DEN, the 1000-lb weight-restriction level is met every day in the current climate (and is therefore not shown).

The maximum takeoff weight of a 737-800 is 174 200 lb. However, the empty weight (no payload or fuel) is 91 300 lb, leaving 82 900 lb available for both fuel and payload of passengers and cargo (Boeing 2013). On a cross-country route, the aircraft will need nearly 100% of its 46 000 lb fuel capacity (Boeing 2013). In this situation, a 15 000 lb weight restriction represents approximately 30% of the payload capacity of the aircraft. Thus, the weight restriction directly translates into less cargo or fewer passengers that can be carried. A 737-800 in a typical two-class configuration seats 177 passengers, and in a high-density, one-class configuration, it seats 189 passengers (Boeing 2013). Using the current Federal Aviation Administration (FAA) average summertime passenger weight of 190 lb (including carry-on baggage;

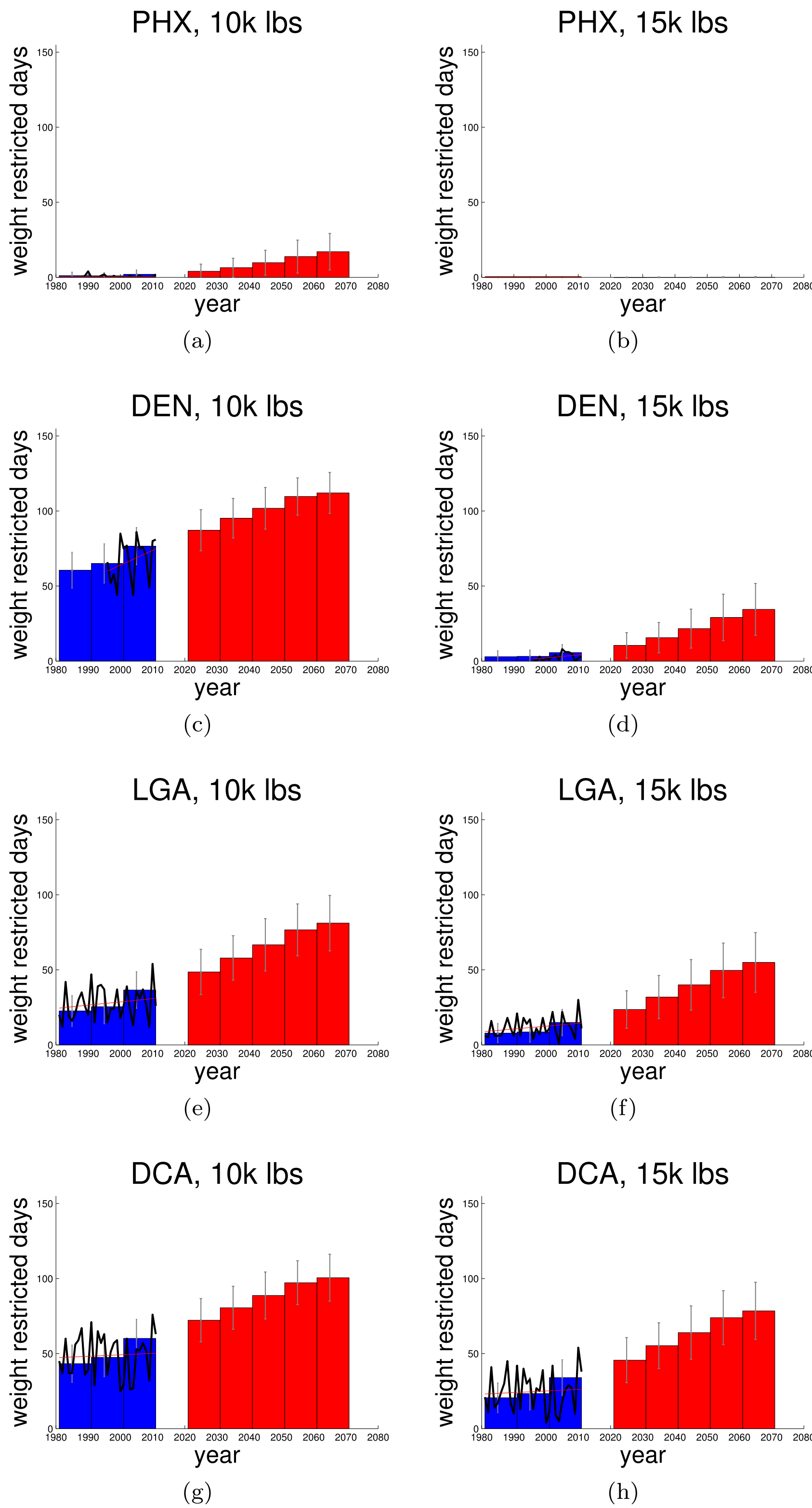

FIG. 3. Number of weight-restriction days per year in the past and future. (a),(b) PHX; (c),(d) DEN; (e),(f) LGA; and (g),(h) DCA for (left) 10 000-lb restriction and (right) 15 000-lb restriction. The black line is calculated from observations and the red line is the observed trend. The gray error bars represent the standard deviation of the number of weight-restriction days per year between the 17 CMIP5 models. Note that the historical CMIP5 data end in 2005.

Federal Aviation Administration 2005), the 1000-, 10 000-, and 15 000-lb restrictions translate into 5, 52, and 79 passengers, respectively, that cannot be carried. In 2013, 163 883 flights departed from LGA, 137 262 from DCA, 180 044 from PHX, and 267 649 from DEN (www.transtats.bts.gov). Thus, the projected increase in weight restrictions presented here will affect a significant number of flights. In real-world operations, cargo will likely be displaced before passengers, but a loss of cargo capacity will also reduce per-flight revenue and may be economically significant given the low profit margins on some routes (Leon et al. 2013).

4. Conclusions

Our results highlight weight restriction as an important factor in planning future flight operations. Airlines may need to allocate summertime cross-country flights to aircraft with better takeoff performance, such as the 757 today or perhaps a new aircraft in the future, and heavily loaded flights may need to be rescheduled out of the hottest parts of the day. Airports may need to extend existing runways or build new, longer runways. At urban airports like LGA and DCA, runway extension is likely to be difficult, leading to more constrained summertime operations and potentially the loss of longer flights to nearby airports with longer runways, such as the John F. Kennedy International Airport in New York, Newark Liberty International Airport in New Jersey, and Washington Dulles International Airport in Virginia. However, such decisions would require advanced planning, especially since these airports operate at near 100% capacity today.

The temperature thresholds used in this study assume that maximum takeoff power is used (as opposed to a 10%–20% derated thrust level, which is often used when possible to reduce fuel burn and engine wear). Thus, for the 737-800, increasing takeoff thrust is not feasible with the current generation of engines, and since aircraft and engines must be designed together, a new generation of engines cannot be installed on existing aircraft without significant effort. Aircraft design changes are unlikely to significantly mitigate the weight-restriction problem. The wings of commercial aircraft are designed to be most efficient at high speeds, since the vast majority of flight time is spent in cruise. There is a trade-off between high speed efficiency and low speed lift generation, and both cannot generally be increased together (Anderson 1999).

The aircraft analyzed here, the 737-800, is still in production, and individual airframes will likely be in operation for several decades. The effects of climate change on weight restriction are already detectable and are projected to become increasingly significant within the lifetime of these aircraft. All other commercial aircraft will also experience the effect of increasing temperatures to varying degrees, making the results presented here highly relevant for current and future airline operations. Changes in technology will no doubt revolutionize the aviation industry in the next 50 years. Carbon fiber structures will make aircraft lighter and new engines will produce more thrust with less fuel. However, these changes do not inherently result in better takeoff performance—aircraft manufacturers may need to prioritize this in the future.

Internal variability in the climate system (Deser et al. 2012) as well as human decisions concerning greenhouse gas emissions (Moss et al. 2010) may alter the time frame on which temperature changes occur. However, even under lower emissions scenarios, significant changes in temperature—and thus weight-restriction days—are projected (Hartmann et al. 2014). It is also possible that changes in extreme heat events will be different than currently projected by climate models because of potential changes in the general atmospheric circulation, urban heat island effects, and soil moisture feedbacks, among other mechanisms. This study demonstrates one potential effect of climate change on aircraft operations. However, more work is needed to analyze the effect of heat on ground personnel safety and performance, airport infrastructure, and airline on-time performance. In addition, other potential climate impacts could affect aviation: sea level rise could threaten some airports (LGA is especially vulnerable), and changes in the frequency and magnitude of summer, winter, and tropical storms could have a major impact on airline activity. Of course, climate is only one factor influencing the industry; changes in passenger behavior and weight, general economic conditions, and technology will have large and unknown effects. However, the aviation industry should begin to consider the effects of climate change on aircraft operations sooner rather than later in order to construct loss-reducing adaptation plans.

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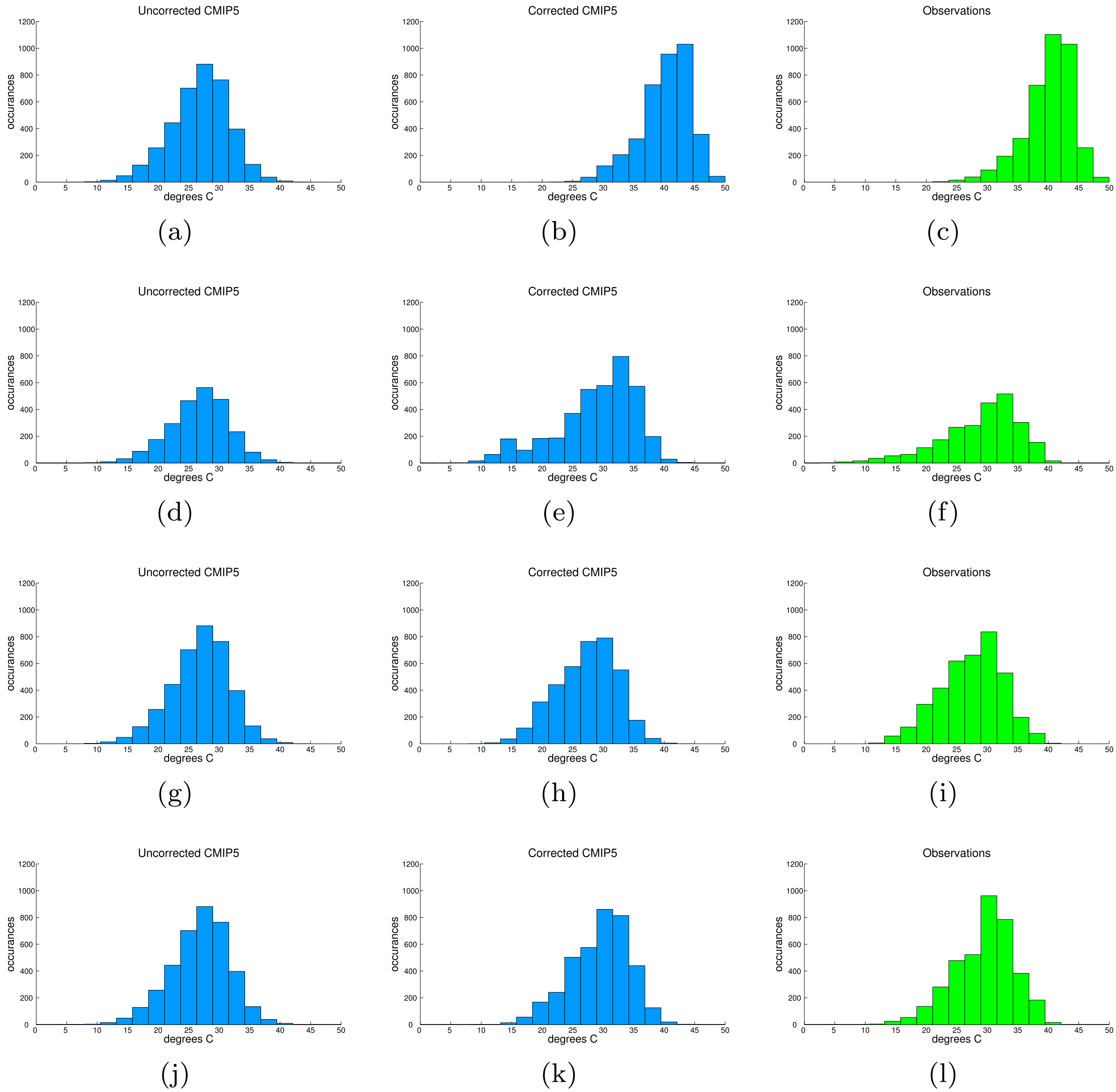

FIG. A1. Temperature distributions at (a)–(c) PHX, (d)–(f) DEN, (g)–(i) LGA, and (j)–(l) DCA from (left) uncorrected CMIP5 multimodel mean, (middle) bias-corrected CMIP5, and (right) ground observations.

APPENDIX

Methods

a. Data sources

Daily maximum temperature (tasmax) data are obtained from one ensemble member taken from each of the 17 chosen CMIP5 (Taylor et al. 2012) models (see Table 3). Each model is regridded to a resolution of 0.94° in latitude and 1.25° in longitude. The regridded model data are bias corrected by calculating the mean bias in each of 20 five-percentile bins. This mean bias is then subtracted from each bin in the historical and future model data. The number of weight-restriction days is calculated for each model and then averaged to form a multimodel mean. The changes in mean daily maximum and yearly maximum temperature are computed for each model and then averaged in Fig. 1. The generalized extreme value distribution parameters are calculated for each model individually and then averaged in Fig. 2. Observational temperature data from each airport site is obtained from the NCDC. Weight-restriction temperatures

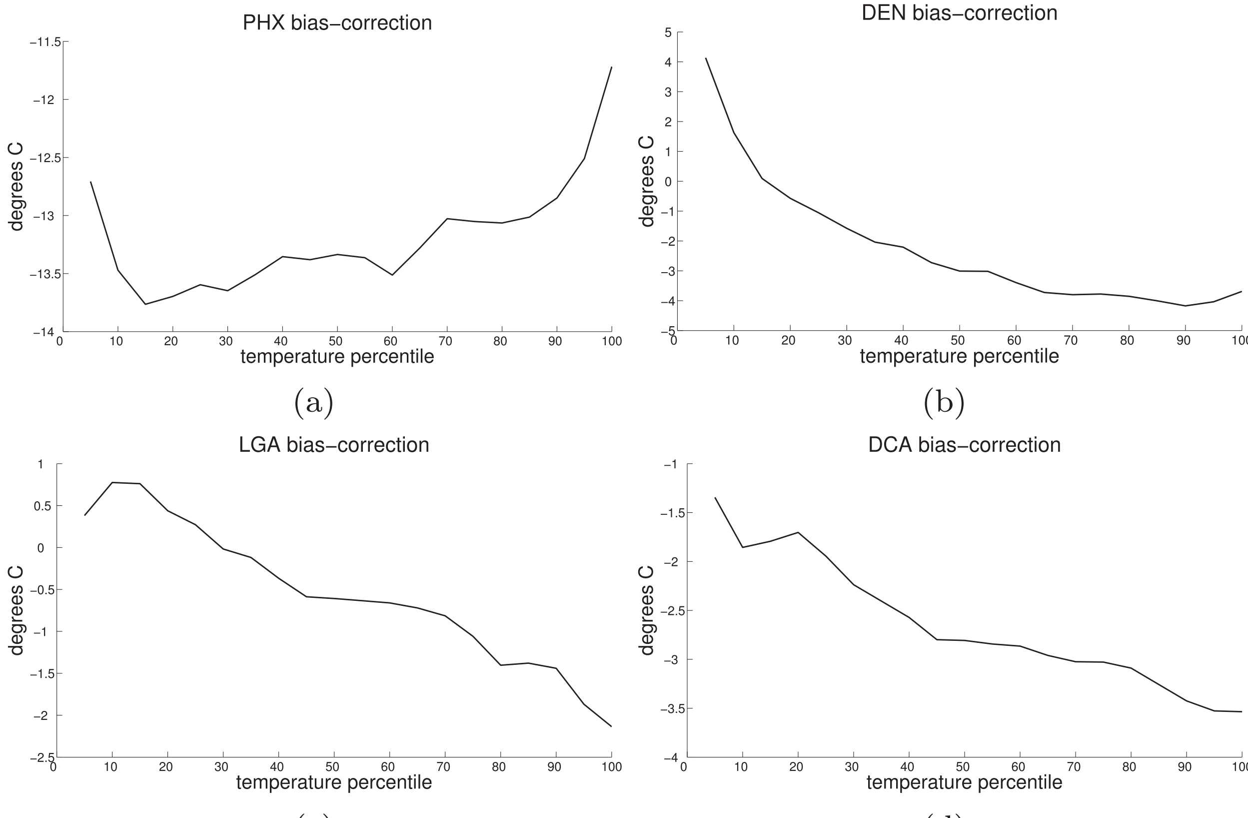

FIG. A2. Bias correction applied to each 5% temperature percentile bin at (a) PHX, (b) DEN, (c) LGA, and (d) DCA. Results are shown for the CMIP5 multimodel mean. Significantly different biases are seen in different parts of the temperature distributions. A horizontal line would indicate that the model bias is equal in all parts of the distribution. The deviation from horizontal indicates the degree to which bias changes at the upper and lower extremes. At all four airports, the bias correction acts to increase the range of the distribution, especially at the upper end. The correction at PHX indicates a large cool bias of 10°–15°C across the distribution, likely due to the effect of terrain and the relatively large model grid-box size.

are obtained from the 737-800 performance charts (Boeing 2013) for sea level temperatures of 30°, 40°, and 50°C. These charts take airport elevation into account and assume a standard pressure of 1013 hPa. Linear interpolation was used to find exact temperature thresholds as is allowed by the document guidelines. Runway lengths and airport elevations are obtained from official FAA airport maps. Weight-restriction days are calculated as the number of days between May and September, with a daily high temperature above the temperature threshold for each restriction category.

b. *Bias correction*

The bias-correction procedure used on the CMIP5 model data is seen to improve the model temperature distributions in the historical period. Figure A1 shows the temperature distributions for the uncorrected CMIP5 (left), corrected CMIP5 (middle), and observations (right) at each airport (rows). The corrected distributions are seen to match the observed distributions well, especially at the high end, which is what this study is concerned with.

Figure A2 shows the correction applied to each temperature percentile, averaged across the 17 models. The bias correction is performed by dividing the temperature distribution of each model at each site into 20 five-percentile bins and calculating the mean bias for each bin using observed temperatures from the airport sites. These mean biases are then subtracted from the percentile bins from which they were calculated. This method allows for a correction of the mean bias as well as some correction of the distribution variance and range.

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