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Decreased takeoff performance of aircraft due to climate change

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Abstract

Climate change will likely affect aviation; however, it is not well understood. In particular, the effects of climate change on aircraft's takeoff performance have seldom been studied. Here, we explore the effects of climate change on the takeoff performance of aircraft, including takeoff distance and climb rate. Takeoff performance normally decreases as temperature and pressure altitude increase. Our study confirms an increasing trend of temperature at 30 major international airports. However, the trend of pressure altitude is shown to be either positive or negative at these airports. Such changes of temperature and pressure altitude lead to longer takeoff distance and lower climb rate in the following century. The average takeoff distance in summer will increase by 0.95–6.5% and 1.6–11% from the historical period (1976–2005) to the mid-century (2021–2050) and from the mid- to late-century (2071–2100). The climb rate in summer will decrease by 0.68–3.4% and 1.3–5.2% from the history to the mid-century and from the mid- to late-century, respectively. Taking Boeing 737-800 aircraft as an example, our results show that it will require additional 3.5–168.7 m takeoff distance in future summers, with variations among different airports.

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1 Introduction

Aviation has long been known to be partially responsible for affecting climate, while the relative effects of climate change on aviation is only a new focus recently (Thompson 2016; Moore et al. 2017). Existing studies are primarily confined to turbulence (Williams and Joshi 2013; Williams 2017), travel time (Karnauskas et al. 2015; Williams 2016), and takeoff weight restriction (Coffel and Horton 2015; Coffel et al. 2017; Zhou et al. 2018). The news reports of flights being canceled due to heat waves have begun to draw considerable attention (Graham 2017; Pignataro 2017). There is an urgent need for understanding the effects of increasing temperature on the complex and comprehensive performances of aircraft (Williams and Joshi 2013; Thompson 2016). In particular, heat greatly affects the performance of aircraft, especially during takeoff; however, these effects are not well understood.

High temperature and low air pressure can result in reduced air density. The reductions in air density further lead to reduced lift for aircraft (Coffel and Horton 2015). Low-density air conditions cause aircraft to accelerate more slowly down a runway; under such conditions, aircraft must achieve greater speeds to attain the same lift and climb more slowly (Anderson 2011).

Pressure altitude is an indicator of atmospheric pressure but expressed in terms of altitude that corresponds to the pressure in the Standard Atmosphere (Team 2008). Because air density decreases with altitude, high pressure altitude means that air density is reduced. The air density reduction has an adverse impact on aircraft performance. Therefore, high pressure altitude (i.e., low air pressure) results in decreased aircraft performance.

To perform safe and precise takeoffs, expected takeoff distance and climb rate are determined based on the temperature and pressure altitude that occur during each takeoff (Team 2008). The purpose of this study is to quantify the potential impacts of climate change, particularly the changes in temperature and pressure altitude, on the takeoff performance of aircraft at 30 major international airports. Here, we examine the additional takeoff distance required and the corresponding decrease in climb rate of all aircrafts during summer in response to climate warming. We also take one of the most popular commercial aircraft, Boeing 737-800 (Coffel et al. 2017), as an example and further explore the changes in its takeoff distance.

2 Methodology and data

2.1 Data source

Thirty major international airports around the world are analyzed in this study (Fig. S1, Table S1). Observed climate data at each airport from 1976 to 2005, including daily air temperature and air pressure at sea level, are acquired from the nearest weather station (Table S1). The data of these weather stations are obtained from the Global Surface Summary of Day Data produced by the US National Climatic Data Center (ftp://ftp.ncdc.noaa.gov/pub/data/gsod).

Modeled daily air temperature and air pressure at sea level for the periods of 1976–2005, 2021–2050, and 2071–2100 are from 25 Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Table S2) under the historical and RCP8.5 "business-as-usual" scenarios (Taylor et al. 2012). For these CMIP5 data, we first interpolate values from different models onto a grid with a resolution of $1° \times 1°$. We then calculate target variables from each model and take the multi-model ensemble mean of these variables for each grid cell that includes the airports.

2.2 Methods

We focus on summer including July and August, when air temperatures are highest and heat waves occur most frequently during each year. Our study contains four main steps.

2.2.1 Step 1: Pressure altitude calculation

As mentioned previously, pressure altitude is an important factor of evaluating takeoff performance. We calculate the pressure altitude (HP, m) at each airport during the historical period (1976–2005), during the middle of the century (2021–2050), and during the end of the century (2071–2100) as follows (Brice and Hall n.d.):

$$HP = \left(1 - \left(\frac{P}{101325}\right)^{0.1903}\right) \times 44308 \tag{1}$$

where p (Pa) represents the actual air pressure or the station pressure (also known as the absolute pressure) and is obtained using the barometric formula,

$$p = p_0 \left(\frac{T}{T + 0.0065h}\right)^{5.257} \tag{2}$$

where p_0 (Pa) represents the air pressure at sea level, T (K) denotes the air temperature, and h (m) represents the height above sea level. The equations suggest that as air pressure decreases, pressure altitude increases.

2.2.2 Step 2: Bias-correction and the Koch chart

We apply a bias-correction method (Piani et al. 2010) to correct the modeled temperature and pressure altitude. Then, we approximate their impact on takeoff according to a Koch chart. The advantage of using the Koch chart is that it is not limited to a particular type of aircraft, and it is simple and quick to check takeoff parameters (Team 2008). Given certain temperature and pressure altitude, there are a corresponding takeoff distance factor and a climb rate factor in the Koch chart (Fig. S2).

2.2.3 Step 3: Takeoff distance determination

The takeoff distance (TD) of an aircraft can be estimated from the product of the takeoff distance at sea level (TD_{sl}) under standard atmospheric conditions and the takeoff distance factor (f_t) from sea level obtained from the Koch chart:

$$TD = TD_{sl} \times f_t \tag{3}$$

As the takeoff distance at sea level under standard atmospheric conditions for each airport is fixed, the change of takeoff distance factor can reflect the change of takeoff distance.

Each type of aircraft has its own specifications, such as weight and engine performance; therefore, the takeoff-related factors differ among aircrafts. Given the pressure altitude and temperature, we can also determine the takeoff distance for Boeing 737-800 at the international airports, according to the 737 Aircraft Characteristics for Airport Planning (Boeing 2013).

2.2.4 Step 4: Climb rate calculation

In addition to the general increase in the takeoff distance, climate change may also result in reduced climb rate. Climb rate determines how fast an aircraft can climb and how long it takes to reach a certain altitude (Anderson 2011). The climb rate (CR) can be estimated from the climb rate at sea level (CR_{sl}) multiplied by the climb rate factor (f_c) from sea level according to the Koch chart:

$$CR = CR_{sl} \times f_c \tag{4}$$

As the climb rate at sea level under standard atmospheric conditions for each airport is fixed, the change of climb rate factor can reflect the change of climb rate.

3 Results and discussions

3.1 Temperature and pressure altitude

During summer (July and August), daily air temperatures robustly increase at all studied airports (Figs. 1 and S3). The probability distributions of daily air temperatures show increasing temporal trend across all airports. From the historical period (1976–2005) to the mid-century (2021–2050), the increase in mean temperature ranges from 0.7 °C (Bangkok,
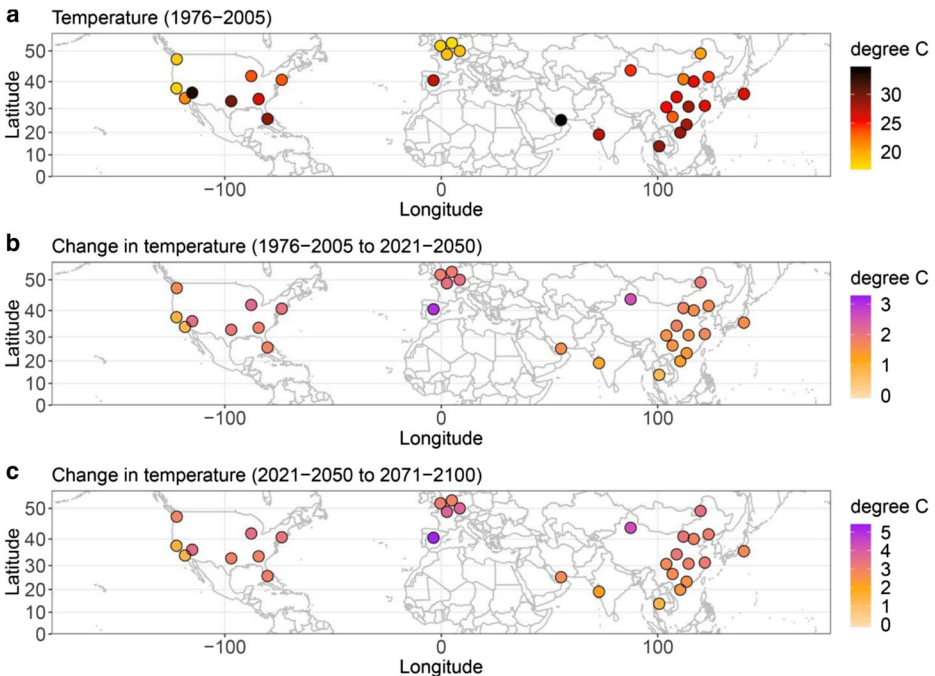

Fig. 1 **a** Historical (1976–2005) daily mean temperature (°C). **b** Change in the daily mean temperature (°C) in the mid-century (2021–2050), relative to the historical period. **c** Change in the daily mean temperature (°C) in the late-century (2071–2100), relative to the mid-century (2021–2050). The changing magnitude from the middle to the end of the century is larger than that from the history to the mid-century

Thailand, BKK) to 3.0 °C (Madrid, Spain, MAD). While from the mid- to late-century (2071–2100), the increase in mean temperature ranges from 1.3 °C (Los Angeles, USA, LAX) to 5.2 °C (Madrid, Spain, MAD). Historical temperatures at these airports generally decrease as latitude increases (Fig. 1a). Such spatial pattern is less obvious in the change of temperature (Fig. 1b-c). Although the spatial pattern of increase in temperature from the history to the mid-century is similar with that from the mid- to late-century, the magnitude of the temperature increase at each airport from the mid- to late-century is larger than that from the history to the mid-century. That means the increase in temperature is more and more intense in the future. The elevated temperatures indicate that aircraft may need to travel over longer takeoff distance in the future than during the historical period in order to reach certain pressure and take off safely.

Daily pressure altitudes at 30 international airports do not change as consistently as temperature (Figs. S4 and S5). Pressure altitude decreases in 14 airports from the history to the mid-century, while increases slightly in the other 16 airports. While from the mid- to late-century, pressure altitude decreases and increases in 18 and 12 airports, respectively. As shown in Eqs. 1 and 2, pressure altitude is determined by the temperature and the air pressure at sea level. The temporal trend of temperature is significantly positive. However, the temporal trend of air pressure at sea level is either positive or negative in different regions due to complicated changes of precipitation, solar radiation, and winds (Haarsma et al. 2015). Therefore, the pressure altitude trend is also shown to be either positive or negative at different international airports. In addition, the change of pressure altitude is negatively correlated ($r = -0.68$ for the history to the mid-century, $r = -0.66$ for the mid- to late-century) with the airport altitude. That is, the pressure altitude decreases more at the higher-altitude airports.

3.2 Takeoff distance and climb rate

The takeoff distance factor shows a consistent increase across the examined airports (Figs. 2 and S6) from the historical period (1976–2005) to the middle of the century (2021–2050) and its end (2071–2100). The increasing level of the takeoff distance factor increases over time. Since 1976–2005, about 7% summer time have takeoff distance factor exceeding 1.2 at Beijing, while more than 50% and 90% summer time will have takeoff distance factor exceeding this value by the mid- and late-century, respectively. Such rapid increases are clearly seen in other airports as well (Fig. S6). The change in takeoff factor shows similar spatial pattern as temperature change (Figs. 1 and 2). Overall, the increase at each airport from the mid- to late-century is larger than that from the history to mid-century. From the historical period to the mid-century, the increase in the takeoff distance factor ranges from 0.95% (Amsterdam, Netherland, AMS) to 6.5% (Madrid, Spain, MAD), while from the middle of the century to its end, the increase in the takeoff distance factor ranges from 1.6% (Los Angeles, USA, LAX) to 11% (Madrid, Spain, MAD). As informed by Eq. 3, increases in takeoff distance factor will cause corresponding increases in takeoff distance.

From the historical period to the middle of the century and its end, there is also a consistent decrease in climb rate factor across the examined airports (Figs. S7 and S8). The decreasing level of the climb rate factor increases over time. From the historical period to the mid-century, the decrease in the climb rate factor ranges from 0.68% (Bangkok, Thailand, BKK) to 3.4% (Madrid, Spain, MAD). On the other hand, from the middle of the century to its end, the climb rate factor decreases by amounts that range from 1.3% (Bangkok, Thailand, BKK) to 5.2% (Paris, France, CDG). From 1976 to 2005, less than 2% summer time of climb rate factor in summer is below
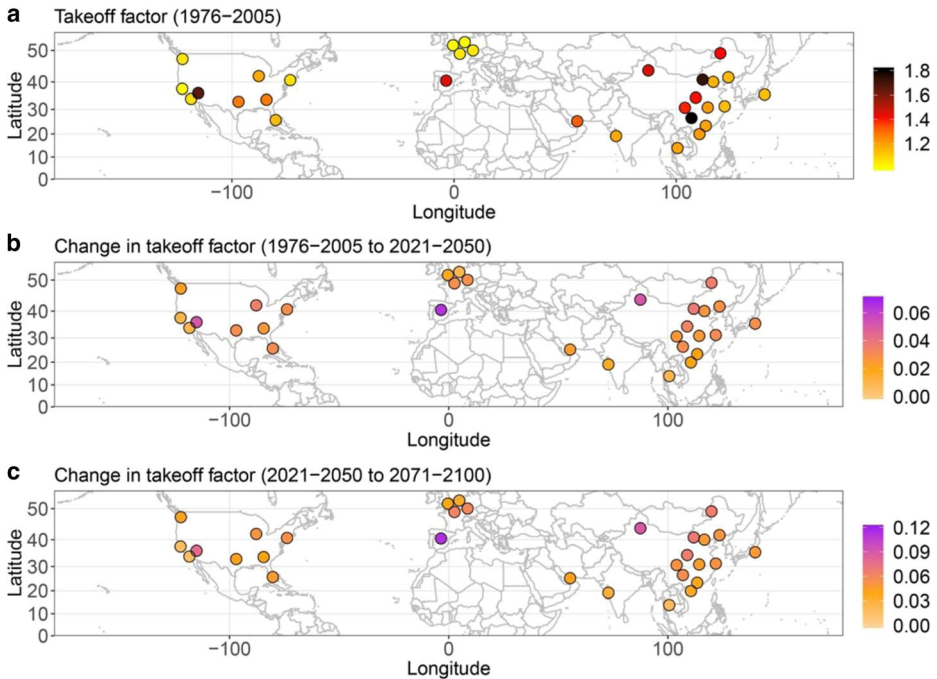
Fig. 2 **a** Historical (1976–2005) daily mean takeoff factor. **b** Change in the daily mean takeoff factor in mid-century (2021–2050), relative to the historical period. **c** Change in the daily mean takeoff factor in late-century (2071–2100), relative to the mid-century. Similar to temperature change, the changing magnitude of takeoff factor from the middle to the end of the century is larger than that from the history to the mid-century

0.83 at Beijing. This number dramatically increases to 40% and 90% by the mid- and the late-century, respectively. Again, this observation applies in general to other airports as well.

3.3 Effect of temperature and pressure altitude on takeoff performance

Theoretically, the increasing temperature and decreasing pressure altitude can decrease takeoff performance, and the decreasing temperature and increasing pressure altitude can improve the performance. Our results show that takeoff performance decreases at the 30 airports due to temperature increase, regardless of the change of pressure altitude. Although the decreasing pressure altitude at some airports could slightly improve the takeoff performance, the increasing temperature at these airports decreases the performance more. Among all the 30 international airports, the maximum decrease in pressure altitude is around 10 m, such as Las Vegas (LAS, USA) and Hohhot (HET, China). The impact of a 10-m decrease in pressure altitude on the takeoff performance is equivalent to that of 0.3–0.4 °C decrease in temperature (Fig. S2). However, the minimum temperature increase at all airports is 0.7 °C, which is high enough to counter the impact of pressure altitude. Such results indicate that the takeoff distance and climb rate are projected to increase and decrease following from the increased temperature. The temperature increase from the history to the mid-century explained 69% of the takeoff distance factor increase and 74% of the climb rate factor decrease, while the temperature increase from the mid- to late-century explained 84% of the takeoff distance factor increase and 73% of the climb rate factor decrease (Fig. 3).
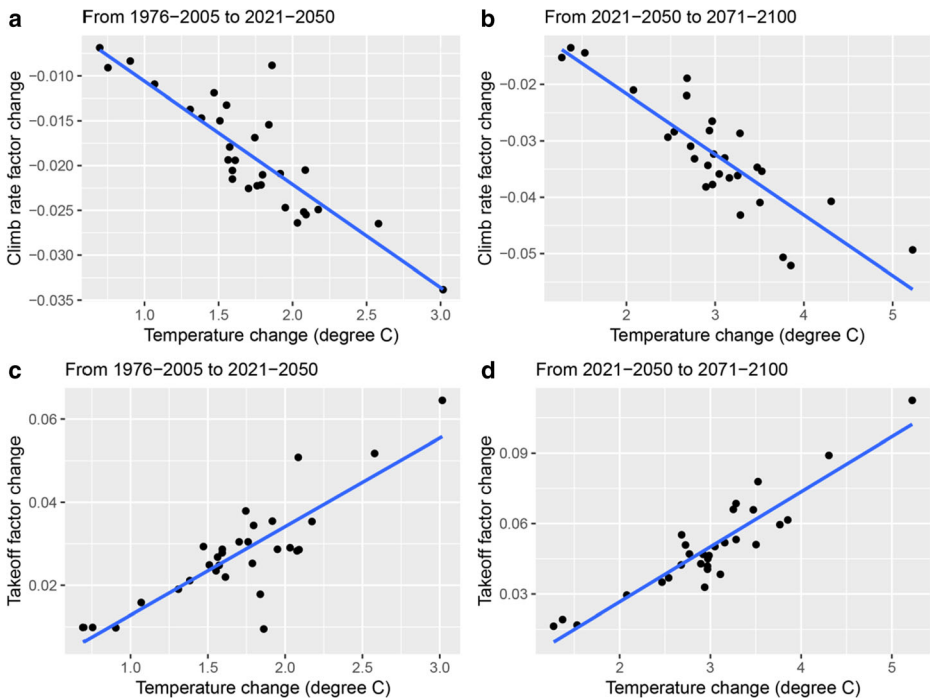
Fig. 3 Relationships between climb rate factor change, takeoff factor change, and temperature change. The linear relationship (blue line) between temperature change and both climb rate factor change, takeoff factor change is strongly significant ($p < 0.001$). Climb rate factor change is negatively correlated with temperature change from 1976–2005 to 2021–2050 (**a**), and from 2021–2050 to 2071–2100 (**b**). Takeoff rate factor change is positively correlated with temperature change from 1976–2005 to 2021–2050 (**c**), and from 2021–2050 to 2071–2100 (**d**)

3.4 Increasing Boeing 737-800 takeoff distance

Consistent with previous results, changes in the temperature and pressure altitude lead to increase in the takeoff distance of Boeing 737-800 aircraft. As the maximum takeoff weight of a Boeing 737-800 is 79,016 kg (Coffel and Horton 2015), we assume that a typical flight has a takeoff weight of 70,000 kg. We then further calculate the takeoff distance required based on this weight assumption according to the inferred changes in pressure altitude and temperature (Boeing 2013). Fig. 4 shows that the takeoff performance of the same type of aircraft varies strongly among airports. This is expected, as the locations and altitudes of airports are different. At Amsterdam (AMS, Netherland), the mean takeoff distance during summer for a Boeing 737-800 during the historical period (1976–2005), the mid-century (2021–2050), and the late-century (2071–2100) is 1781 m, 1793 m, and 1811 m, respectively. At Las Vegas (LAS, USA), the mean takeoff distance for a Boeing 737-800 in summer during the historical period, the mid-century, and the late-century is 2219 m, 2289 m, and 2408 m, respectively. At Guiyang (KWE, China), the mean takeoff distance required for a Boeing 737-800 in summer during the historical period, the mid-century, and the late-century is 2361 m, 2368 m, and 2382 m, respectively.

The mean takeoff distance required for a Boeing 737-800 is less impacted from the historical period to the middle of the century than from the middle of this century to its end (Table S3).
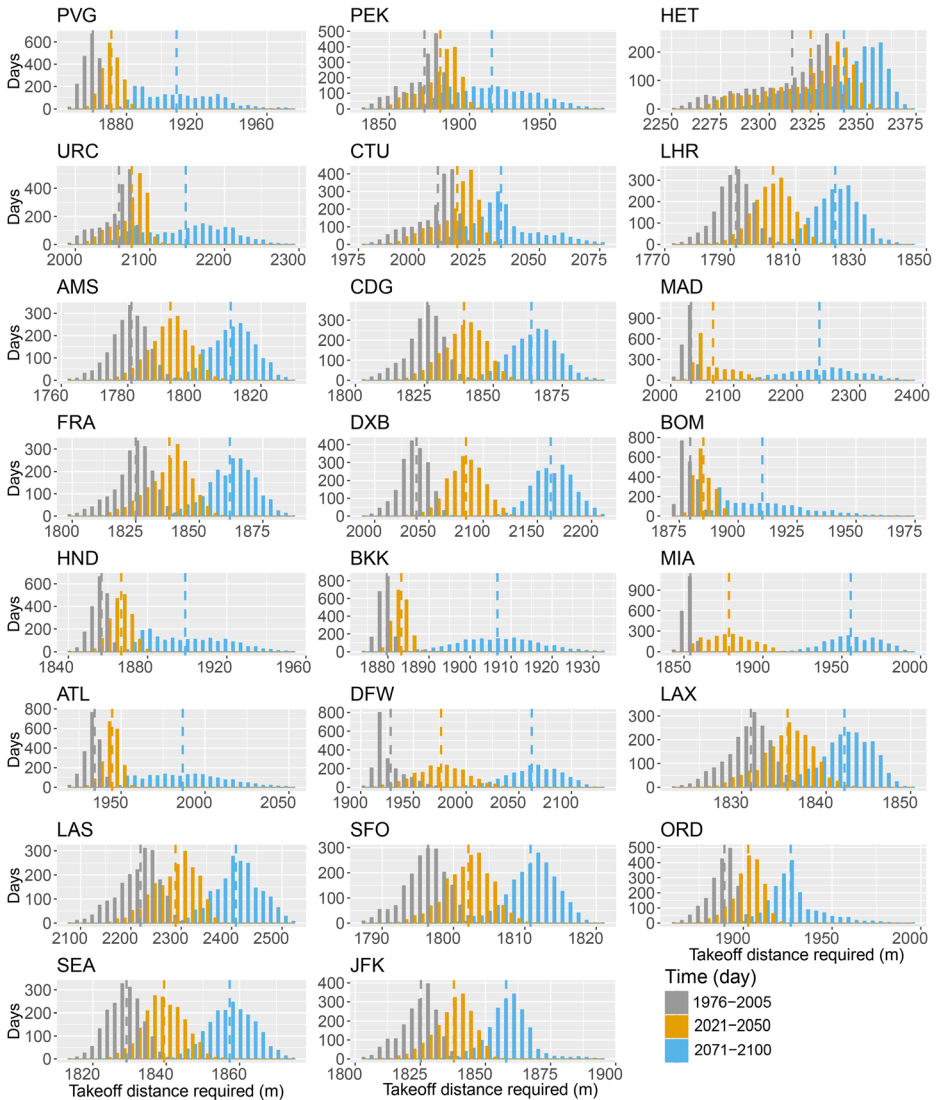
Fig. 4 Probability distributions of required takeoff distance of Boeing 737-800 aircraft in 1976–2005 (gray), 2021–2025 (yellow), and 2071–2100 (blue) at the 30 airports around the world. Dash lines represent mean values. The takeoff distances all shift toward higher values from the history to the future

Among the 30 international airports, the takeoff distance distributions from 2071 to 2100 at some airports, such as Shanghai (PVG, China), Beijing (PEK, China), Urumqi (URC, China), Chengdu (CTU, China), Madrid (MAD, Spain), Bombay (BOM, India), Tokyo (HND, Japan), Bangkok (BKK, Thailand), Miami (MIA, USA), Atlanta (ATL, USA), and Dallas (DFW, USA), are much wider than those from 1976 to 2005 or from 2021 to 2050. It means that the takeoff distance of Boeing 737-800 varies more in the future summer than it does in the past. The increased takeoff distance required ranges from 3.5 m (Bangkok, Thailand, BKK) to 69.5 m (Las Vegas, USA, LAS) from the history to the mid-century, whereas it changes greatly from 6.7 m (Los Angeles, USA, LAX) to 168.7 m (Madrid, Spain, MAD) from the mid- to late-century.

4 Discussions

Although aviation is known to be partially contributed to climate change (Stuber et al. 2006; Lee et al. 2009), the relative effects of climate change on aviation are seldom studied and are not well understood (Thompson 2016; Williams 2016). Our results quantify the effects of climate change on takeoff distance and climb rate of aircraft during summer for the first time. As mentioned previously, temperature and pressure altitude can profoundly affect aircraft takeoff performance by influencing the density of air molecules. The density affects the molecules of the air flowing around aircraft wings to generate a lift. When temperature and pressure altitude increase, takeoff distance must increase and climb rate must decrease in order to meet airline safety standards. Although our study does not show consistent trend of pressure altitude, we find significant increasing temperature and corresponding increasing takeoff distance and decreasing climb rate. These changes suggest that aircraft will need to increase takeoff distance and decrease climb rate in summer, by the mid- and late-century, relative to the historical period. A Boeing 737-800 aircraft needs additional 3.5–168.7 m of takeoff distance in future summers depending on the departure airport.

As for the Boeing 737-800, we made a takeoff weight of 70,000-kg assumption. The use of other weight makes little difference for our conclusion because we examine the change of takeoff performance from the history to the future. Taking LAS (Las Vegas, USA) for example, when the takeoff weight is 70,000 kg, the increased takeoff distance required is 69.5 m and 119.9 m from the history to mid-century and from the mid- to late-century, respectively. When the takeoff weight is 69,300 kg (1% decrease), the increased takeoff distance required is 67.0 m and 114.5 m from the history to mid-century and from the mid- to late-century, respectively.

One caveat of this research is that the Koch chart only provides approximation, although it is a good estimation tool for all kinds of aircrafts. A document such as Aerodata Performance Handbook is more accurate and specific for each type of aircraft, but it is not publicly available. In addition, we only consider takeoff distance and climb rate in this research. Other factors, such as takeoff gross weight, runway slope, and conditions, all affect takeoff performance. Except for daily temperature and pressure, other potential climate-driven changes in variables such as extreme temperatures, wind, lightning, storms, and fog could also affect aviation. Therefore, more research is needed to analyze the effects of climate change on takeoff performance, airport infrastructure, and other factors. There is no doubt that aircraft manufacturers are improving takeoff performance (Hane 2016). However, during the future design and performance evaluations of aircrafts, climate change must be taken into account in order to develop loss-reducing adaptation options (Coffel and Horton 2015).

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