Revisiting the Precipitous Terrain Classification from a Meteorological Perspective

DOMINGO MUÑOZ-ESPARZA,^a HYEYUM HAILEY SHIN,^a TEDDIE L. KELLER,^a KYOKO IKEDA,^a
ROBERT D. SHARMAN,^a MATTHIAS STEINER,^a JEFF RAWDON,^b AND GARY POKODNER^c

^a National Center for Atmospheric Research, Boulder, Colorado

^b Flight Technologies and Procedures Division, Federal Aviation Administration, Washington, D.C.

^c Weather Technology in the Cockpit Program, Federal Aviation Administration, Washington, D.C.

(Manuscript received 1 December 2020, in final form 27 July 2021)

ABSTRACT: Takeoff and landing maneuvers can be particularly hazardous at airports surrounded by complex terrain. To address this situation, the Federal Aviation Administration has developed a precipitous terrain classification as a way to impose more restrictive terrain clearances in the vicinity of complex terrain and to mitigate possible altimeter errors and pilot control problems experienced while executing instrument approach procedures. The current precipitous point value (PPV) algorithm relies on the terrain characteristics within a local area of 2 n mi (3.7 km) in radius and is therefore static in time. In this work, we investigate the role of meteorological effects leading to potential aviation hazards over complex terrain, namely, turbulence, altimeter-setting errors, and density-altitude deviations. To that end, we combine observations with high-resolution numerical weather forecasts within a $2^\circ \times 2^\circ$ region over the Rocky Mountains in Colorado containing three airports that are surrounded by precipitous terrain. Both available turbulence reports and model's turbulence forecasts show little correlation with the PPV algorithm for the region analyzed, indicating that the static terrain characteristics cannot generally be used to reliably capture hazardous low-level turbulence events. Altimeter-setting errors and density-altitude effects are also found to be only very weakly correlated with the PPV algorithm. Altimeter-setting errors contribute to hazardous conditions mainly during cold seasons, driven by synoptic weather systems, whereas density-altitude effects are on the contrary predominantly present during the spring and summer months and follow a very well-marked diurnal evolution modulated by surface radiative effects. These findings demonstrate the effectiveness of high-resolution weather forecast information in determining aviation-relevant hazardous conditions over complex terrain.

KEYWORDS: Atmosphere; Numerical weather prediction/forecasting; Mountain meteorology; Transportation meteorology

1. Introduction

Aircraft approaching or departing airports located near mountainous terrain are sometimes exposed to elevated levels of gusty winds and turbulence, making these maneuvers more challenging than at airports surrounded by relatively gentle terrain features. Some of the meteorological phenomena contributing to hazardous flying conditions near mountainous terrain include gravity waves, wakes, low-level erratic winds and rotors, and strong downslope windstorms (e.g., Blumen 1990; FAA 1997; Whiteman 2000; Smith 2018). These have the potential to impact aircraft at many levels, from near-surface to cruise altitudes, and pilots are familiar with the increased occurrence of turbulence near complex topography associated with these phenomena (e.g., Sharman and Lane 2016; Wolff and Sharman 2008). Terrain-generated waves and turbulence have been implicated in a number of aviation accidents ranging from small aircraft to jetliners (Wurtele et al. 1996; Clark et al. 2000; Parker and Lane 2013). Lee waves extending downwind of the Rocky Mountains were implicated in the crash of a Boeing 737 at the Denver International Airport (Keller et al.

2015). In addition, operations at airports located near mountainous terrain worldwide are often impacted by strong wind gusts and turbulence in the near-surface region. A few examples include the Juneau, Alaska, airport (Colman and Dierking 1992); airports on the mountainous islands of Pico and Madeira in Portuguese Macaronesia (Maruhashi et al. 2019; Belo-Pereira and Santos 2020); the Mount Pleasant Airfield downwind of the Wickham Heights mountain range in the Falkland Islands, known for severe low-level turbulence affecting air traffic (Mobbs et al. 2005); and the Hong Kong International Airport (Carruthers et al. 2014).

Another concern to pilots flying in complex terrain is both spatial and temporal changes in surface pressure, which affect altimeter settings and can lead to inaccurate altitude readings in the cockpit (e.g., Guinn et al. 2021). In conjunction with the strong gusty winds and low-level turbulence, significant surface pressure variations over short time periods have been observed during windstorms and lee-wave events (e.g., Brinkmann 1973; Neiman et al. 1988; Grubišić and Billings 2007), and can extend several kilometers horizontally downstream of the terrain (e.g., Mobbs et al. 2005; Szmyd 2016). Rapid spatiotemporal pressure variations can have a devastating consequence if altimeter settings are not updated in a timely manner, especially for landing aircraft. An example is the collision of a jetliner with trees on final approach to Bradley International Airport near Hartford, Connecticut, on 12 November 1995, which according to the National Transportation Safety Board report (NTSB 1995) had an incorrect altimeter setting as a contributing factor.

Denotes content that is immediately available upon publication as open access.

Corresponding author: Domingo Muñoz-Esparza, domingom@ucar.edu

DOI: 10.1175/JAMC-D-20-0268.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

In addition to turbulence and altimeter-setting factors, large changes in air density are another meteorological effect that can lead to hazardous situations during takeoff/landing maneuvers (e.g., Goodman and Small Griswold 2018). The density altitude, defined as pressure altitude corrected for nonstandard atmosphere temperature conditions, indicates that the local air density is equivalent to the standard atmosphere density experienced at an elevation equal to the density altitude. Thus, a sufficiently high density altitude can result in an unexpected decrease in aircraft performance, causing the aircraft's inability to produce enough lift to clear nearby obstacles or terrain. According to the Federal Aviation Administration (FAA 2010), density altitude is as often cited as weather-related cause or contributing factor in aircraft accidents as turbulence and is associated with takeoff, landing, and maneuvering. In this context, it is worth mentioning the recent study by Aguiar et al. (2017), which reported that controlled flight into terrain (CFIT)¹ and wind gusts/shear² are the most frequent accident cause or factor for general aviation aircraft operating in mountainous and high-elevation terrain environments in the United States.

To address these low-level hazards, specifically the ones related to terrain-induced altimeter errors and pilot control problems, the FAA has developed a precipitous terrain classification to provide additional buffers to instrument flight procedure minimum allowable altitudes, with those buffers increasing with more significant precipitous terrain. Note that the precipitous terrain guideline is specifically designed for Instrument Flight Rules (IFR) conditions. Therefore, ceiling and visibility effects, which are of particular relevance for small airports that cannot afford full implementations of IFR procedures, are not considered in the present work. While the current precipitous terrain classification relies solely on local terrain characteristics, there is vast evidence that weather-related effects—in particular, turbulence, altimeter-setting errors, and density-altitude differences—can contribute to hazardous conditions for aviation over complex terrain. In light of these aspects, the current work investigates the potential benefit of incorporating meteorological effects into the precipitous terrain classification. To that end, we utilize turbulence and meteorological observations combined with high-resolution weather forecasts, focused on a region covering the Rocky Mountains of Colorado. The rest of the paper is organized as follows. In section 2 a correlation analysis is performed to determine the ability of the current precipitous point value (PPV) algorithm to explain reported turbulence events for a 5-yr period. Then, meteorological observations relevant to aviation hazards are analyzed in section 3 for the same period to understand seasonal and diurnal weather effects. Model setup and validation of 1-yr high-resolution numerical weather forecasts are presented in section 4 and utilized in section 5 to complement the findings from the observation analysis and gain further insight into the meteorological aspects that influence turbulence, altimeter-setting errors, and density-altitude

differences at airports located within complex terrain regions. Section 6 is devoted to summarizing the main findings of the work.

2. The PPV algorithm and its correlation with turbulence

As already mentioned, the precipitous terrain classification provides a way for imposing more restrictive terrain clearances for aircraft approaching airports situated near complex terrain. More specifically, the revised FAA precipitous terrain method calculates a single precipitous terrain adjustment value for each flight segment/leg based on PPVs calculated for every terrain data point in the segment area employing a digital terrain database. The highest PPV in the segment area is then scaled using a factor that depends on the flight segment type, that is, final approach, nonprecision final approach, intermediate approach, and initial approach segments (FAA 2018, appendix C). The procedure to compute PPV utilizes local terrain information within a 1 n mi (1852 m) radius around the point of interest. For each point, four terrain parameters describing the characteristic features of the surrounding terrain are calculated, using all terrain points within the 1 n mi radius. The four parameters are average elevation, slope of the plane of best fit (i.e., the slope of the two-dimensional least squares plane), standard deviation from the plane of best fit, and elevation difference (98th percentile–2nd percentile). After the four parameters are scaled between 0 and 1 from their respective ranges, the weighted average is computed and then linearly scaled to obtain PPVs in the 0–250 range (see the appendix for a more complete description of the PPV formulation).

The present study focuses on the Rocky Mountain region of Colorado, which includes three examples of airports that are surrounded by precipitous terrain areas that are known to occasionally experience approach and departure problems: Aspen/Pitkin County (KASE), Eagle County Regional (KEGE), and Leadville–Lake County (KLXV), indicated with star symbols in Fig. 1a. We implemented the PPV algorithm over a $2^\circ \times 2^\circ$ region within the Rocky Mountains that includes these three airports, centered at 39.5°N 106.5°W , as shown in Fig. 1b. For the calculation of PPV, the 1 arc s (≈ 30 m)-resolution digital elevation dataset from the Shuttle Radar Topography Mission (SRTM) Void Filled product was used (Farr et al. 2007), corresponding to the terrain map in Fig. 1a. It is evident that the selected area in Colorado is characterized by a complex orography, with extensive clusters of elevated PPV. An interesting feature is that, while the three airports are situated in locally nonprecipitous areas, the three airports are surrounded by precipitous areas that exhibit large PPV values exceeding 100 (see Fig. 1c). The region south of the Aspen airport shows PPVs reaching 250, the upper-limit value of the PPV range. Considering that high PPVs are found within 12 n mi (22 km, or 0.2°) of the three airport locations and that the final approach segment is 10 n mi (18.5 km) long (FAA 2018, their Fig. 6-2-1), the precipitous topography near the three airports could lead to hazardous turbulence encounters, depending on the specific approach route and meteorological conditions.

¹ These are likely related to altimeter-setting errors and high-density-altitude conditions, among other factors.

² Often used as a proxy for turbulence activity.

FIG. 1. (a) Terrain height (m MSL) and (b) PPV maps for the $2^\circ \times 2^\circ$ domain over the Colorado Rocky Mountains. (c) Zoomed-in views of PPV distributions centered at the three selected airports: Aspen, Eagle, and Leadville, indicated by white-outlined rectangles in (b).

To evaluate the capability of the current precipitous terrain adjustment algorithm to capture turbulence hazards related to the presence of local complex terrain, we investigated the correlation between PPV and turbulence observations. For illustrative purposes, the PPV map over the $2^\circ \times 2^\circ$ domain including turbulence observations below 20 000 ft (1 ft = 0.3 m) from 2019 is presented in Fig. 2a. The turbulence observations include verbal pilot reports (PIREPS) and in situ eddy dissipation rate (EDR) estimates available from selected commercial aircraft (Sharman et al. 2014). PIREPs are converted to EDR using the techniques outlined in Sharman et al. (2014). From their comparisons of PIREPs with in situ EDR estimates for medium-sized aircraft, the following reference EDR thresholds are used here: 0.15–0.22 is light, 0.22–0.33 is moderate, and ≥ 0.34 is severe, in units of meters to the $2/3$ power per second. This plot shows that severe turbulence events ($\text{EDR} \geq 0.34 \text{ m}^{2/3} \text{ s}^{-1}$) can occur over any locations regardless of PPV and even for zero PPV values, which do not require any terrain clearance adjustments according to the current precipitous terrain classification. To investigate and quantify the correlation between PPV and turbulence, we display all turbulence observations during the 2015–19 period

as a function of the PPV value of the underlying terrain in the scatterplot of Fig. 2b. If the PPV was a good indicator of turbulence, the data points in Fig. 2b would predominantly be clustered and following a well-defined trend. Instead, all the turbulence data points are spread across the entire PPV range with a higher probability of weaker turbulence encounters (lower EDR) that decreases quasi-linearly in logarithmic scale with increasing EDR values as shown by the right-side histogram in Fig. 2b. This is indicative of the exponential decrease of frequency of occurrence of turbulence events as the turbulence intensity becomes larger, as expected. A particular finding worth remarking on is that turbulence activity of any intensity can occur over zero PPV locations.³

There are several physical reasons for this result. First, this analysis is only looking at a limited geographical area that is almost entirely within the Rocky Mountains of Colorado. Therefore, some of the turbulence over the zero PPV locations within this plot is likely due to mountain generated

³ Note that the PPV algorithm considers that PPVs < 50 require no terrain clearance adjustment and therefore get set to PPV = 0.

FIG. 2. (a) PPV map with overlaid spatial distribution of turbulence observations over the selected $2^\circ \times 2^\circ$ domain over Colorado for 2019 (altitudes below 20 000 ft). Colors indicate the departure/destination airport for PIREPs: Aspen (magenta), Eagle (green), and Leadville (cyan), with other airports colored in gray and in situ EDR observations colored in yellow. (b) Scatterplot of PPV and turbulence observations (EDR; $\text{m}^{2/3} \text{s}^{-1}$) for the 2015–19 period. The size of each data point is proportional to EDR value, and the color indicates the data source: PIREPs transmitted to Aspen (magenta), Eagle (green), Leadville (cyan), and other (gray) airport stations, as well as in situ EDR (yellow). The top plot in (b) shows histograms of PPV (black bars; %) and EDR (orange bars; number of data points) for each PPV bin, and the rightmost plot in (b) shows a histogram of EDR (black bars; number of data points) integrated over EDR bins.

mechanisms since mountain-induced turbulence is not limited to regions directly above mountain peaks or steep slopes but can extend horizontally several kilometers away from the terrain. In particular, the approach and departure corridors for these airports were designed to traverse regions of locally smoother terrain (i.e., lower PPV values). Hence turbulence reports from landing/departing aircraft appear over low PPV values, even though the turbulence may be generated by surrounding complex terrain features. Second, most of the in situ EDR reports in this analysis are from aircraft overflying the Rocky Mountains at higher altitudes, and these aircraft generally follow specific air routes, resulting in incomplete spatial coverage of the mountainous region. These factors highlight the potential inadequacies of the current classification scheme to capture preferred areas of turbulence.

To quantify the level of correlation between turbulence and PPV, the Pearson correlation coefficient R is calculated. To calculate the correlation, eddy dissipation rate estimates from PIREPs and in situ EDR records collected over the $2^\circ \times 2^\circ$ Colorado domain for the last 5 years (1 January 2015–31 December 2019) from the surface up to 20 000 ft were used, resulting in a total of approximately 274 000 observations ($\approx 250\,000$ from in situ EDR and $\approx 24\,000$ from PIREPs). Figure 2b shows that PPV and turbulence observations have almost no correlation, with R values that are less than 0.02, regardless of observation type (PIREP or in situ EDR). This weak correlation supports the notion that static terrain properties by themselves cannot fully represent the physical mechanisms responsible for terrain-induced turbulence events; therefore other factors that affect turbulence generation, for

example, meteorological conditions, need to be taken into account to improve the precipitous terrain adjustment algorithm.

3. Climatology of meteorological conditions at three Colorado airports

In this section, hourly surface meteorological observations collected by automated weather sensors (METARs) from January 2015 through the end of 2019 are explored to understand the overall weather characteristics at the three selected precipitous terrain airports in Colorado. In particular, density altitude, altimeter setting, and wind speed/gusts are investigated since these are of direct impact to aviation.

Density altitude h_d is the pressure altitude corrected for temperature deviations from the standard atmosphere, and it is an indicator of aircraft performance. Not taking appropriate actions in high-density-altitude conditions can lead to serious safety issues and potentially accidents during takeoff and landing. Density altitude significantly influences the aerodynamic and engine performance of both fixed-wing airplanes and rotorcraft of any size. There are three factors contributing to a high-density-altitude condition: pressure (tightly related to terrain altitude), temperature, and humidity, and it is derived using the following expression (<https://www.weather.gov/media/epz/wxcalc/densityAltitude.pdf>; e.g., Goodman and Small Griswold 2018):

$$h_d = 145\,366 \left[1.0 - \left(\frac{17.326p}{T_v} \right)^{0.235} \right], \quad (1)$$

where p is the station pressure (in inches of mercury; 1 in Hg = 3386.39 Pa), T_v is the station virtual temperature (in units of

FIG. 3. (a) Climatology of monthly average diurnal cycle of density-altitude differences from airport elevation at (top) Aspen, (middle) Eagle, and (bottom) Leadville, from METAR surface observations over 2015–19. Average values are annotated in each tile. (b) Frequency of experiencing density altitude higher than 2000 ft above ground based on hourly measurements between 2015 and 2019 at a given time of the day and month for the same airports as in (a). Annotated values are frequency.

Rankine, $1^\circ\text{R} = 5/9$ of 1 K), so the density altitude in feet is obtained. To analyze these weather-related effects in a climatological manner for the 5-yr period, we present the density altitude as deviations from the airport elevation (i.e., above ground level) for both average values and frequency of occurrence of exceeding a certain threshold, as a function of month versus hour of the day (Fig. 3).

Overall, average density-altitude deviation is the highest at the three airports in July (Fig. 3a), consistent with the annual trend of temperature (not shown). The minimum density-altitude deviation is experienced near sunrise, but it exceeds 1000 ft above local terrain soon afterward and reaches its maximum of 2600–2700 ft AGL at KASE and KEGE in the afternoon, when the temperature is at its maximum.

Afterward, it remains above 2000 ft AGL until sunset. Given the relatively lower temperatures at KLXV (shown later in Fig. 7), the density altitude is slightly lower relative to KASE and KEGE. However, daytime density altitude is still in the 2000s. From June through September, high-density-altitude conditions exceeding 2000 ft AGL frequently occur throughout the core of the daytime hours (Fig. 3b), particularly from midmorning to sunset (1600–0300 UTC). The 2000-ft threshold was selected as the density-altitude difference that would lead to a 6% decrease in power for a normally aspirated, fixed-pitch aircraft (FAA 1999). In the hottest hours of the day, density-altitude differences exceeding 2000 ft are experienced at least $\approx 80\%$ of the time at KASE, 90% at KEGE, and 60% at KLXV during these months. While the specific reduction of aircraft

performance depends on the actual aircraft and engine configuration, a simple rule of thumb for a naturally aspirated engine is to experience a decrease of 3.5% in horsepower per each 1000-ft increase in density altitude. This indicates that aircraft can experience $\approx 7\%$ decrease in aircraft power often during warm-weather conditions, which can in fact be more significant at Eagle, which exhibits $\approx 10\%$ – 30% frequency of exceeding 3000-ft density-altitude differences for 1900–0100 UTC during June, July, and August, and of reduced frequency at Aspen (not shown).

It is essential for aircraft flying over mountainous terrain to accurately know their altitude for both landing and avoidance of terrain obstacles during approach procedures. Aircraft altitude is determined using a barometer. Therefore, altitude is computed as a relative pressure, which needs to be adjusted according to the pressure at the airport being approached, known as the altimeter setting. The altimeter setting α_{set} provides the pressure “reduced” to mean sea level using the temperature profile of the standard atmosphere, which is representative of average conditions over the United States at 45°N latitude. The altimeter setting, usually expressed in inches of mercury, is the pressure value to which an aircraft altimeter scale is set so that it will indicate the altitude (above mean sea level) of the aircraft on the ground at the location for which the pressure value was determined, and it is calculated as (<https://www.weather.gov/media/epz/wxcalc/altimeterSetting.pdf>).

$$\alpha_{\text{set}} = (p - 0.3) \left[1.0 + \frac{8.423 \times 10^{-5} h_s}{(p - 0.3)^{0.190284}} \right]^{1.0/0.190284}, \quad (2)$$

where p is the station pressure (hPa) and h_s is the station elevation (m). Local airport altimeter settings are provided by the automated weather sensors located nearby and relayed to pilots. In the remaining discussion spatial and temporal differences in altimeter settings are converted to a height, to illustrate how altimeter changes may affect variations in aircraft altitude. The assumption used in this conversion is that for every 0.01 inch of mercury (i.e., 0.3386 hPa) there is a height difference of ~ 9.25 ft (Holmboe and Klieforth 1957).

The impact of pressure variations over time on altimeter reading is investigated using temporal tendencies of altimeter settings at the three airport stations, computed as the gradient of the altimeter setting at a given location over a 1-h time interval. These tendencies are examined to investigate the potential altitude errors associated with a lack of updates from the airport for altimeter-setting information over the last hour before landing. In particular, large negative temporal tendencies are of concern, because in these cases the altimeter would indicate that the aircraft is flying at a higher altitude than it is in reality if the pilot has not updated the altimeter setting. Overall, the mean values are within ≈ 10 ft h^{-1} throughout the year at the three locations (not shown). A relatively large decrease of 15 ft h^{-1} or more in the altitude tendency typically occurs in the cold season, particularly between 1800 and 2200 UTC, and with the maximum decrease experienced at Eagle in January. Altitude changes based on the 5th percentile of altimeter settings from all hourly data during the 5-yr period are presented in Fig. 4a. Height tendencies are often around -20 ft h^{-1} ,

but a drop to -50 ft h^{-1} is evident between 1900 and 2000 UTC in December–January. While it is less common to experience a decrease of 82 ft h^{-1} or more ($<2\%$ of the time; not shown), decreases of at least 27 ft h^{-1} occur $\approx 25\%$ – 35% of the time between 1900 and 2000 UTC in October–February at all sites (Fig. 4b), with Eagle having the highest frequency of the three airports ($\approx 40\%$ – 50%). Also, it is worth noting that, while large altitude errors exhibit a clear seasonal dependency as expected, there is in general a less marked diurnal modulation relative to density-altitude differences, although still significant. In addition to rapid changes in altimeter settings at a given airport, differences in altimeter settings between departure and arrival airports can be very hazardous if the pilot is unable to update settings. These differences may be particularly large for airports located at different elevations in mountainous regions.

Strong near-surface winds and turbulence also pose a hazard to airport approach maneuvers. To investigate these effects, climatological distributions of wind speed and wind gust⁴ from the three airport stations are shown in Fig. 5. At the three locations, the strongest winds occur during the daytime in late spring and early autumn (1800–0200 UTC, late morning/noon to near sunset), as displayed in Fig. 5a. In winter, the average wind speed is more moderate at all sites. A site-to-site comparison shows that Eagle airport experiences the calmest winds in the morning, which rapidly pick up in magnitude soon before noon, leading to the highest winds in the afternoon all-year-round in comparison with Aspen and Leadville. At all three locations, the diurnal range of wind speed is smaller in January than in July, with the largest diurnal amplitude occurring at Eagle. Correlated with higher winds, wind gusts occur the most frequently in the afternoon before sunset (1800–0000 UTC, Fig. 5b). In particular, Aspen and Eagle experience gusty winds over 50% of the time between April and September. There is a higher frequency of gusts observed at Leadville all year long around the middle of the day. It is interesting to note the presence of 10%–20% probability of gusty winds during nighttime in winter months in Leadville, which is not present at any of the other two airports, which may be indicative of mountain wave activity, that occurs together with a clear bimodal distribution of wind directions (north and northeast; not shown), likely related to local topography effects (e.g., drainage flows), and that can also contribute to these consistently observed gusty events at Leadville.

These analyses point out the differences in meteorological conditions experienced by these three precipitous terrain airports in the Rocky Mountain region of Colorado. In particular, it is relevant to highlight that despite the predominance of turbulence episodes at Aspen as indicated by the PIREPs and in situ EDR observations (Fig. 2a), Leadville exhibits a higher occurrence of gusty conditions. This could be related to the considerably lower air traffic density at Leadville, leading to fewer turbulence reports. Moreover, the METAR stations are

⁴ Wind gusts are defined as a variation of 10 kt (5.1 m s^{-1}) or more between peaks and lulls in the most recent 10-min period, with the maximum speed recorded during the 10-min period being reported as gust speed.

FIG. 4. (a) Climatology of monthly average diurnal cycle of 5th percentile of hourly tendency of aircraft altitude errors based on altimeter setting at (top) Aspen, (middle) Eagle, and (bottom) Leadville from METAR surface observations over 2015–19. Average values are annotated in each tile. (b) Frequency of observing the altimeter altitude decrease by -27 ft or more in 1 h based on measurements between 2015 and 2019 at a given time of the day and month for the same airports as in (a). Annotated values are frequency.

sparse in space, and do not provide detailed turbulence observations, so it is difficult to comprehensively assess the existence and relevance of these aviation hazards over a region surrounding the airport, and that is of most relevance when considering landing maneuvers. To complement and expand the observational findings, we carry out high-resolution numerical weather forecasts, which are described and validated in the next section.

4. High-resolution 1-km WRF modeling and validation

In this section, high-resolution simulations with the Advanced Research WRF Model (Skamarock and Klemp 2008), version 4.1.1, are presented. The WRF simulations were configured with

four domains (Fig. 6a) using one-way nesting: the outermost 27-km resolution domain covering the majority of the contiguous United States, and two intermediate domains with 9- and 3-km resolutions, and the innermost 1-km high-resolution domain covering a 1502-km² area including the three airport locations (Fig. 6b). A 1-yr period corresponding to 2019 was simulated, consisting of a suite of simulations initialized at 1200 UTC each day and run for 48 h. The first 24-h period was used for model spinup, and the second 24-h period was used for model analysis. The initial and surface boundary conditions for all four domains and the lateral boundary conditions for the outermost domain were forced by the 3-hourly North American Regional Reanalysis (NARR) at 32-km resolution (Mesinger et al. 2006).

FIG. 5. (a) Climatology of monthly average diurnal cycle of wind speed at (top) Aspen, (middle) Eagle, and (bottom) Leadville from METAR surface observations over 2015–19. Average values are annotated in each tile. (b) Frequency of observed wind gust activity between 2015 and 2019 at a given time of the day and month for the same airports as in (a). Annotated values are total number of wind gust events.

Physical parameterizations used in the WRF simulations include the longwave and shortwave RRTMG model (Iacono et al. 2008), Grell–Freitas cumulus parameterization (Grell et al. 2014, only used in the outer 27- and 9-km domains), and the Thompson microphysics scheme (Thompson et al. 2008). The unified Noah scheme was used for the land surface coupling (Chen and Dudhia 2001), and the surface-layer parameterization option is based on the Monin–Obukhov similarity theory (Jiménez et al. 2012). Subgrid turbulence effects were parameterized using the Shin–Hong planetary boundary layer (PBL) scheme (Shin and Hong 2015), which can handle partly resolved turbulence structures because of its scale-aware formulation. The vertical coordinate was discretized using 75 grid points in all domains, with finest vertical resolutions within the lowest 2 km, $\Delta z \approx 10\text{--}135$ m (42 vertical

levels), to ensure proper representation of gradients in the atmospheric boundary layer.

To evaluate the ability of the WRF simulations to reproduce the actual conditions over this specific region of Colorado, the performance of the high-resolution weather simulations was evaluated at climatological scales first by comparing the annual and monthly climatologies with the near-surface observations. Among the 58 METAR stations available in Colorado (Fig. 6b), 58, 43, and 7 stations are located in the 9-, 3-, and 1-km simulation domains, respectively. The climatological statistics were calculated from hourly time series, for both observations and simulations. Figure 7 shows model verification results, in terms of annual climatology of near-surface wind speed at 10 m AGL and near-surface temperature at 2 m AGL. Overall, the WRF

FIG. 6. (a) Model domains for the WRF simulations. (b) Contour map of terrain height (m MSL) used in the WRF simulations for the area corresponding to the entire state of Colorado, with METAR station elevations indicated by circles. In (b), the three airport locations are marked with a colored annulus: Aspen (magenta), Eagle (green), and Leadville (cyan).

simulations realistically capture the spatial distributions of annual-mean near-surface winds (Figs. 7a–c) and temperature (Figs. 7d–f), including the existing sharp gradients around the mountain ridges. Monthly variations of daily mean wind speed and temperature errors confirm that these near-surface variables are well modeled by the kilometer-scale WRF simulations regardless of month or season, with mean absolute errors not exceeding 1 m s^{-1} and 2 K, especially in the case of the 1-km simulations (not shown).

Additional quantification of the horizontal model grid resolution impacts on forecast skill are provided by the Taylor diagrams shown in Fig. 8, comparing the skill of WRF in predicting 10-m wind speed and 2-m temperature at the three airport locations between the 9-km (d02) and 1-km (d04) domains. The Taylor diagram provides an efficient way of summarizing the statistical performance of a forecast according to three metrics: correlation, root-mean-square (RMS) error and ratio of the variances (Taylor 2001). Consistent with the annual comparisons from Fig. 7, wind speed exhibits larger errors and reduced correlations than the temperature predictions. Wind speed forecasts at Eagle present the largest correlation levels of ≈ 0.6 . This is expected from the reduced terrain complexity surrounding that area (see Figs. 1a and 12), as well as the increased errors for Leadville and Aspen. Decreasing the grid spacing leads to increased correlation and reduced wind speed

errors at Eagle, and improved variability closely matching that of the observations is found at Aspen. In contrast, Leadville presents a decrease in model skill for 10-m wind speed for the 1-km grid, also occurring at the only location where the terrain height is lower than in reality, emphasizing the challenges of local effects in complex terrain. Temperature predictions indicate a consistent slight improvement by the 1-km domain, enhancing variability, increasing correlation, and decreasing RMS errors, attributed to the reduced terrain height errors in the higher-resolution domain. Skill of temperature predictions is consistently higher than for wind speed, with smaller relative errors and significantly higher correlations (≈ 0.95 for the annual signal). It is interesting to mention that the annual metrics in this case are improved relative to the monthly estimates, indicative of an augmented skill of the model in representing seasonal versus diurnal and day-to-day patterns.

We further evaluate the performance of 1-km WRF simulations in reproducing the local diurnal weather characteristics at the three precipitous terrain airport stations. Observed and simulated monthly mean diurnal variations for January and July 2019 are compared in Fig. 9. The diurnal variations of wind at these stations are well captured by the 1-km simulations, including characteristic features at different airport stations. The high-resolution simulations are found to accurately reproduce the signature of seasonal effects on the diurnal evolution of winds and temperature, as shown by the much weaker diurnal-cycle amplitudes for temperature and especially winds during January 2019, which is consistent with the METAR observations (Fig. 9a). Examples of other features include the two local peaks in the wind speed evolution found at Aspen in July, one at ≈ 1500 LT and the other one at ≈ 0000 LT, and the relatively large amplitude of the diurnal cycle found at Eagle in comparison with Aspen and Leadville (Fig. 9b). The diurnal variations of temperature are well simulated in terms of the diurnal cycle phase, but nighttime temperatures are slightly overestimated at all three stations. This systematic overestimation of nighttime temperature by the model is at least partly due to the limitation of boundary layer turbulence parameterizations, which cannot simulate the turbulence intermittency in the nocturnal stable boundary layer. However, in the context of weather forecasting for aviation, nighttime conditions are of less importance due to the reduced air traffic density at these hours of the day. These results demonstrate the ability of high-resolution weather simulations to adequately reproduce both the spatial distribution of meteorological conditions and their evolution over seasonal and diurnal time scales over complex terrain, and they are used in the next section to gain further insight into the specific aviation hazards of relevance to the precipitous terrain classification.

5. Suitability of high-resolution numerical weather prediction models to inform aviation hazards over complex terrain

In this section, we employ the 1-km WRF simulations to examine three aspects relevant to mountain flying, namely, turbulence, altimeter-setting errors, and density altitude, and

FIG. 7. Horizontal maps of annual-mean climatology comparing WRF simulations (filled contours) and METAR observations (colored circles), with corresponding scatterplots, for (a)–(c) near-surface wind speed at 10-m AGL ($m s^{-1}$) and (d)–(f) near-surface temperature at 2-m AGL (K): (top) daily mean, (middle) maximum, and (bottom) minimum. In the scatterplots, the colors indicate the corresponding WRF domain that includes the surface stations: d02 (9 km; gray), d03 (3 km; black), and d04 (1 km; red).

to assess the capability of the current static precipitous terrain algorithm to account for these three weather-related aspects. Note that, as already mentioned, the precipitous terrain algorithm was conceived to compensate for altimeter errors

and pilot control problems in complex terrain regions by providing additional buffers to instrument flight procedure minimum allowable altitudes. However, and although not specifically designed to account for density-altitude effects,

FIG. 8. Taylor diagrams for (a) 10-m wind speed and (b) 2-m temperature for the 9-km (d02) and 1-km (d04) domains at the three airport locations during 2019. The terrain height difference Δh_t for each of the domains with respect to the METAR terrain elevation is indicated in the legend. The larger-size, black-outlined symbols correspond to the combined full year, and the smaller-size symbols represent each individual month.

(a) January 2019

(b) July 2019

FIG. 9. Monthly mean diurnal variations (solid lines) of 10-m wind speed (m s^{-1} ; top plot of each group) and 2-m temperature (K; bottom plot of each group) for (a) January and (b) July 2019 at the three airport stations: (left) Aspen, (center) Eagle, and (right) Leadville. Observations are shown with black lines, and WRF 1-km simulations are shown with red lines. Spread across the month is indicated by the boxes and whiskers.

we additionally investigate the correlation of the PPV algorithm with density-altitude differences since these can further amplify hazardous effects induced by turbulence and altimeter-setting errors by reducing aircraft maneuverability.

First, the high-resolution 1-km forecasts are used to revisit the findings from [section 2](#) related to the correlation between PPV and turbulence events found by analyzing aircraft observations. Model-derived turbulence fields have the distinct advantage of a more complete spatial and temporal coverage when compared with aircraft turbulence reports. [Figure 10a](#) shows a 2D histogram of model-derived turbulence kinetic energy [subgrid-scale (SGS) TKE; $\text{m}^2 \text{s}^{-2}$] versus PPV for heights below 1.5 km AGL. This turbulence metric is a useful surrogate to EDR, so the analysis is consistent with the one

performed using aircraft observations. Note that these probabilities, in percentage, are normalized by the number of counts in each PPV bin to avoid spurious overweighting by more frequent PPV ranges in the domain of interest. The distribution of the 2D histogram exhibits a lack of correlation between PPV and turbulence, indicated by the nearly horizontal lines of constant probability across the PPV range for each SGS TKE bin, and with a very small correlation coefficient at the three airports and over the entire $2^\circ \times 2^\circ$ Colorado domain considered herein ($R < 0.1$). This uneven PPV distribution can be seen in the upper histogram of [Fig. 10a](#), clearly depicting a predominance of lower PPV values over higher PPV values. Overall, the climatological behavior of model-derived turbulence exhibits a similar pattern to that found using the aircraft

FIG. 10. (a) A 2D histogram of PPV and model (SGS) TKE calculated over the 1-km WRF domain for heights below 1.5 km AGL. The color map indicates normalized probability (%) per each PPV bin. The top plot in (a) shows histograms of PPV for PPV bins, and the rightmost plot in (a) shows a histogram of EDR for EDR bins, similar to Fig. 2b. Model forecasts are for a full year, 2019, and sampled every 3 h. (b) Correlation coefficients between PPV and EDR observations and SGS TKE model forecasts for different seasons and a flight altitude range between 10 000 and 20 000 ft MSL. Observations correspond to a 5-yr period, and model results are for 1 year. Labels ANN, DJF, MAM, JJA, and SON refer to annual (all months), December–February, March–May, June–August, and September–November, respectively.

turbulence observations, with a higher occurrence of low turbulence events that decreases for increased turbulence levels, as displayed by the right-side histogram of Fig. 10a (consistent with the corresponding right-side histogram in Fig. 2b). In particular, it is worth emphasizing that the 0 PPV bin has a similar distribution to the high PPV bins ($PPV > 200$), indicating that PPV cannot discriminate between occurrences of various turbulence intensities even for the most disparate PPV values.

Quantification of the correlation between PPV and model turbulence is presented in Fig. 10b, similar to the earlier analysis based on turbulence observations (Fig. 2b). For all seasons and the full climatological year, the model correlation coefficients R are in very good agreement with those calculated using aircraft EDR observations in all cases, reinforcing the

notion of the inability of a PPV algorithm based on static (and local) terrain characteristics to explain or be a proxy for turbulence events (R is negative and smaller than 0.05). While subsampled on a 3-h frequency, the model forecast PDFs have 10 000 time as many instances (i.e., data samples) than the observations, since we include all locations within the 1-km domain. Further insight beyond the climatological behavior of turbulence can be gained by examining 2D histograms from model forecasts at several times of the day in different months. This analysis is presented in Fig. 11, for the months of January and July at 0000, 0600, 1200, and 1800 UTC. January displays a more uniform 2D histogram pattern across the day, with an increase of turbulence levels around local noon (1800 UTC). In contrast, during July the probability distributions exhibit a stronger dependence on the time of the day, with a more consistent and significant increase of turbulence levels throughout the core of the morning and afternoon hours (1800–0000 UTC). These particular aspects provide evidence of the important role that weather conditions play into the resulting turbulence characteristics.

Besides turbulence, altimeter-setting errors and density-altitude differences also play a critical role in leading to potentially hazardous conditions over regions nearby precipitous terrain airports. As the aircraft approaches the airport, it will be flying closer to the ground, which in turn can increase the chances of intersecting the terrain. To investigate these factors in a more specific manner, we select a region surrounding each of the three selected airports (Aspen, Eagle, and Leadville). This specific region is $30 \times 30 \text{ km}^2$ centered at each airport, as indicated by the dashed black rectangles in Fig. 12, and was selected based on the distance required to approximately descend the last 2700 ft before reaching the ground according to the simplified 3-to-1 rule-of-thumb formula for initial instrument flight rule descent planning (FAA 2017, chapters 3 and 4). Note that there are more specific procedures in approach design; however, this is sufficient for the purpose of estimating the impact of the altimeter-setting error and density-altitude effects in a general sense. The bottom panel in Fig. 12 shows the distribution of terrain differences within the aircraft descending regions for each of the three airports. These distributions convey that terrain differences are comparable to the total vertical distance to be descended ($\approx 800 \text{ m}$), which further emphasizes the proximity to the terrain that the aircraft experiences during landing at these airports located within complex terrain regions.

Analysis of time rate of change in the METAR altimeter setting at the three airport stations from section 3 showed that decreases of altimeter setting over time, converted to altitude variations, are typically of $\approx 15 \text{ ft h}^{-1}$, with slightly larger magnitude drops found at Eagle. If the aircraft receives the current altimeter-setting error prior to landing, these pressure changes over time are not a problem. However, from its working principle, it can be deduced that horizontal surface pressure gradients between the airport's weather station and the actual location of the aircraft as it approaches the landing runway can also lead to an error in the height estimated by the altimeter, which is referred to as altimeter-setting error, and may be more significant over precipitous terrain locations

FIG. 11. As in Fig. 10a, but for (left) 0000, (left center) 0600, (right center) 1200, and (right) 1800 UTC in (a) January and (b) July 2019.

characterized by large terrain variability. This aspect is examined by deriving altimeter-setting errors from model forecasts, calculated as the difference with respect to each of the airports within the descending region.

As for near-surface turbulence, altimeter-setting errors are found to be very loosely correlated with PPV at the three airports, with correlation coefficients of $R < 0.15$ in all cases, and as it can clearly be seen from the 2D histograms for the three airports presented in Fig. 13a. However, there seems to be a slight increase in probability of extreme altimeter-setting errors for larger PPV values, indicative of the role of the terrain, but still altimeter-setting errors can be small or nonexistent at these high PPV locations most of the time. Note that altimeter-setting errors will be of most concern when its magnitude is negative, resulting in the pilot flying closer to the terrain than the altimeter reading indicates. The integrated histograms shown on the right panel show that negative altimeter-setting errors of up to 200 ft can be present in the most extreme situations. Since seasonal weather characteristics can factor into altimeter-setting error, 2D histograms for the four seasons during 2019 are presented in Fig. 14. These distributions indicate a strong seasonal dependence, with the autumn and winter months presenting the most negative altimeter-setting errors (December–February and September–November, respectively), which become of reduced amplitude during the warmer months.

The statistical behavior of density-altitude difference with respect to the reference airport is presented in Fig. 13b. For density altitude, positive values indicate less dense air, which in turn reduces the aircraft lift and increases the required distance for landing, as well as decreasing aircraft performance and its ability to adjust to elevated turbulence levels as those present in the vicinity of complex terrain, among other performance impacts. Density-altitude deviations are also not correlated to PPV, as can be seen from the near-airport characteristics for Aspen, Eagle, and Leadville, all with very low correlation coefficients ($R \approx 0.005$). Interestingly, these climatological maps exhibit a bimodal distribution, with a peak for slightly negative values and another one around 1000 ft, which is

responsible for the lack of correlation between density-altitude difference and PPV. Seasonal density-altitude distributions as a function of PPV are presented in Fig. 15. From these histograms, it is evident that, in contrast to altimeter-setting errors, density-altitude variations affecting aircraft performance are more predominant during the summer and fall (June–August and September–November, respectively), consistent with the METAR reports (section 3). There is again a strong seasonal dependence in a statistical sense, with a shift in density altitude during the year, transitioning in the fall, and responsible for the bimodal distribution that appears in the annual climatology.

FIG. 12. (top) Terrain elevation within the 1-km high-resolution WRF grid. The dashed black lines indicate the area surrounding each airport corresponding to the final 2700 ft of descent. (bottom) Histograms that represent the terrain differences with respect to the elevation of each of the airports within these descending regions.

FIG. 13. The 2D histograms of PPV and (a) altimeter-setting error and (b) density-altitude difference, calculated over the $30 \times 30 \text{ km}^2$ regions surrounding (top) Aspen, (middle) Eagle, and (bottom) Leadville, as indicated in Fig. 12. The color map indicates normalized probability (%) per each PPV bin. Model forecasts are for a full year, 2019, and are sampled every 3 h.

Up to now, we have been evaluating the impact of these weather-related effects from a climatological perspective. To illustrate the temporal and seasonal nature of these effects, we show the time evolution of density-altitude difference, altimeter-setting error and turbulence for January and July 2019 in Figs. 16 and 17, respectively. These time evolutions reveal some important features related to weather patterns. During January, Fig. 16, there is a weak diurnal signature, with meteorological evolution being dominated by synoptic weather conditions. Density altitude, as already discussed, is essentially negative during almost the entire month, resulting in less of a hazard for aviation. However, the altimeter-setting error reaches deficits of -75 ft on average, and up to -180 ft maximum during 20–29 January. These events coexist with elevated turbulence levels

at the three locations, of considerably larger magnitude over Leadville, and reaching very high levels of $\text{TKE} \approx 10 \text{ m}^2 \text{ s}^{-2}$ (approximately corresponding to $\text{EDR} \approx 0.4 \text{ m}^{2/3} \text{ s}^{-1}$; Muñoz-Esparza et al. 2018). A similar period of aviation hazard activity occurs from 5 to 8 January. However, multiday periods of safe meteorological conditions, that is, reduced turbulence and altimeter-setting errors, are also present (e.g., 9–15 January).

The time evolution for July 2019 is in stark contrast (see Fig. 17). During the summer season, meteorological conditions in this region are dominated by fair weather (i.e., relatively drier and calmer conditions), with atmospheric characteristics modulated by surface radiative effects, resulting in a regime strongly dominated by diurnal cycles that lack large-scale synoptic influence. In the warm season, altimeter-setting

(a) Aspen

(b) Eagle

(c) Leadville

FIG. 14. The 2D histograms of PPV and altimeter-setting error for the different seasons, calculated over the $30 \times 30 \text{ km}^2$ regions surrounding (a) Aspen, (b) Eagle, and (c) Leadville as indicated in Fig. 12. The color map indicates normalized probability (%) per each PPV bin. Model forecasts are for a full year, 2019, and are sampled every 3 h.

errors are less likely to pose any challenge to aircraft safety and operability near precipitous terrain airports, as seen from the positive average trend of altimeter errors at the three airports. While some instances of negative altimeter-setting error do

occur, these are very infrequent and of very low magnitude. In contrast, systematic and large density-altitude values (up to $\approx 3000 \text{ ft}$) are found during the core of the daytime hours, coincident with the largest turbulence levels (SGS TKE up to 5–

(a) Aspen

(b) Eagle

(c) Leadville

FIG. 15. As in Fig. 14, but for density-altitude difference with respect to the airport conditions.

FIG. 16. Hourly evolution of (top) density-altitude difference, (middle) altimeter-setting error, and (bottom) TKE from the high-resolution 1-km weather forecasts at the three selected airports (Aspen, Eagle, and Leadville) during January 2019. Solid lines represent the average conditions within the descending region, indicated by dashed black rectangles in Fig. 12. The shaded envelope corresponds to the 10th–90th percentiles within the respective areas.

$7 \text{ m}^2 \text{ s}^{-2}$). While there is some variability among days in July, the strong diurnal pattern dominates, with relatively less-hazardous conditions consistently occurring during the late evening and night, when turbulence essentially vanishes and density-altitude differences reach their minimum ($\approx 1000 \text{ ft}$).

Validation of the adequacy of the analyzed high-resolution weather simulations in predicting altimeter settings and density-altitude deviations at the three airports is presented in Fig. 18. Similar to the analysis of climatological characteristics of surface station data, we present errors expressed as the difference between the model with respect to the observations and averaged for the time of the day and month of the year (Fig. 18a). Altimeter setting predicted by the model tends to systematically be slightly higher, especially for Aspen and Leadville, as confirmed by the hourly evolution of the average across the three stations for the month of July, shown in Fig. 18c. Eagle does exhibit the lowest errors, in part due to the smaller difference in terrain height between the model and the observations ($\approx 20 \text{ m}$) relative to the other two airports ($\approx 30 \text{ m}$). Despite these differences, the evolution of the synoptic pressure patterns during January 2019 are very accurately reproduced (Fig. 18c). This is further supported by the corresponding Taylor diagram in Fig. 18b that indicates a very high correlation to the observations both at the monthly and annual scales (0.95–0.99), together with a very accurate reproduction of the variability. With respect to density altitude, errors follow a clearer diurnal pattern, with overpredictions during nighttime hours and underestimations during daytime, as result from the model temperature biases (note the similar pattern of the Taylor diagram). This effect can be clearly seen in Fig. 18c, where the amplitude of the diurnal evolution of density altitude is reduced in the model, but the phase is very accurately captured. Note that these weather

FIG. 17. As in Fig. 16, but for July 2019.

forecasts could be further improved by optimizing the choices and combinations of physics parameterizations, in particular the land surface model and PBL scheme (e.g., Hu et al. 2010; Zhang et al. 2013; Massey et al. 2016; Banks et al. 2016; Xiang et al. 2017), as well as by applying statistical correction/calibration methods as a postprocessing step (e.g., Glowacki 1988; Durai and Bhadrwaj 2014; Jeong and Lee 2018; Kosović et al. 2020).

6. Summary and conclusions

Meteorological conditions leading to elevated turbulence, density-altitude deviations, and altimeter-setting errors can pose additional hazards for aviation safety and operability at airports in the vicinity of complex terrain. In this work, we have evaluated the suitability of the current precipitous terrain classification (i.e., PPV algorithm), developed for approach procedures during IFR conditions and that only depends on static and local terrain features (within 1 n mi), to account for weather-related turbulence and altimeter errors. In addition to the turbulence, altimeter-setting, and density-altitude effects that we have investigated herein, there are other meteorological factor such as ceiling and visibility and strong sustained winds that can be of relevance for general aviation near complex terrain. While these meteorological factors are not directly applicable to the precipitous terrain classification (applicable to IFR landing maneuvers), they could be useful as aviation weather products over complex terrain. As terrain influences are highly localized, we focused on three airports in the Colorado Rockies: Aspen, Eagle, and Leadville, which are within areas of complex terrain, and are known to occasionally have approach and departure problems. To better understand these complexities and the limitations of the different sources of information, we carried out detailed investigations combining aircraft turbulence and surface meteorological observations together with high-resolution numerical modeling in the form of high-resolution weather forecasts.

Correlation analysis between PPV and turbulence observations (PIREPs and in situ EDR) over a $2^\circ \times 2^\circ$ domain in the

FIG. 18. (a) Climatology of monthly average diurnal cycle of altimeter-setting (converted to altitude) and density-altitude errors at (top) Aspen, (middle) Eagle, and (bottom) Leadville, from the high-resolution 1-km weather forecasts of 2019. (b) Taylor diagrams for altimeter setting and density altitude. The larger-sized, black-outlined, circles correspond to the combined full year, and smaller-size circles represent each individual month. (c) Hourly evolution of altimeter setting (January 2019) and density altitude (July 2019) corresponding to the surface observations and WRF simulations averaged across the three airport stations, and with the shaded envelope indicating the spread across the three stations.

precipitous region of Colorado during 2015–19 revealed almost no correlation between these two ($R < 0.02$). It was found that severe turbulence events, for example $EDR \geq 0.34 \text{ m}^{2/3} \text{ s}^{-1}$, can occur over any location regardless of PPV, and that turbulent events of any intensity can occur over zero-PPV points. In addition, climatological analysis of airport weather stations at the three selected airports revealed that the highest density-altitude values occur during July, consistent with the annual trend of temperature, and often exceeded 2000 ft above the airport elevation in the summer months. For hourly change of altitude readings from altimeter-setting changes, the largest drops occur during cold seasons with maximum amplitudes of

$\approx 30 \text{ ft h}^{-1}$. Eagle was found to have the highest winds and the largest frequency of gust occurrence of the three airports, while turbulence reports were more predominant at Aspen (where air traffic density is higher).

One year (2019) of WRF high-resolution weather forecasts down to 1 km of horizontal grid spacing were performed to compensate for the lack of spatial coverage in the available observations and to properly characterize the areas surrounding the airport. Validation of the model forecasts utilizing meteorological data from 58 surface weather stations over Colorado was carried out and showed good skill in reproducing the observations, providing confidence in the veracity of the

weather model. We used the validated 1-km model forecasts to gain further insight into the three weather-related factors contributing to hazardous flying conditions in complex terrain: turbulence, altimeter setting, and density altitude.

When the three weather-related factors that potentially lead to hazardous aviation conditions in complex terrain are considered altogether, our analyses of the three airport locations in Colorado, based on combining aircraft turbulence and meteorological observations with high-resolution weather forecasts, lead us to conclude the following (at least for the locations considered herein):

- 1) Turbulence can be an issue throughout the entire year, generally following a diurnal cycle, and with larger values typically present during daytime and summer months. Both simulations and observations show little correlation to PPV values, supporting the notion that the static terrain properties represented by PPV cannot be used to reliably explain or predict hazardous conditions related to low-level turbulence.
- 2) Altimeter-setting errors contribute to hazardous conditions more often during cold seasons. They are predominantly driven by synoptic weather systems characterized by multi-day modulations and are thus not present at all times. In addition, altimeter-setting errors often occur together with elevated turbulence levels and were also found to be uncorrelated with PPV values.
- 3) Density-altitude effects, in contrast, are predominantly present during the spring and summer months, and follow a very well-marked diurnal evolution, with the largest positive density-altitude differences occurring during the core of the daytime hours and modulated by surface radiative effects (fair weather conditions). As anticipated, the density-altitude difference was found to be uncorrelated with underlying PPV values.

All of these findings demonstrate that meteorological information can provide additional value to the existing precipitous terrain adjustments for terrain clearances, and that high-resolution numerical weather prediction forecasts, validated with observations, have the potential to provide reliable guidance about weather-related aviation hazards over complex terrain. As future efforts, we plan to investigate the transferability of the current findings to airports within other complex terrain regions in the United States, as well as to understand how representative airport-based observations are for the surrounding conditions experienced by aircraft throughout the course of their approach maneuvers. In addition, we envision the development of algorithms that account for these weather-adverse effects and application of relevant thresholds to derive a dynamic hazard product that fuses the impacts of turbulence, altimeter-setting errors, and density-altitude effects into a single combined hazard product. We expect all of these efforts to lead to a weather-informed PPV algorithm that allows a more efficient operability of the national airspace system.

Acknowledgments. This research is in response in part to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not

necessarily represent the official policy or position of the FAA. All of the WRF simulations were performed using high-performance computing support from Cheyenne (<https://doi.org/10.5065/D6RX99HX>) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation (as is NCAR itself).

APPENDIX

PPV Equations

The PPV equations from appendix C of [FAA \(2018\)](#) are summarized here. A digital terrain database (100-m or 3 arc s separation density or better) must be used for the determination of precipitous terrain $h(x, y)$. Four parameters $p_k(x, y)$ are calculated from all terrain points within 1 n mi of the geographic location being evaluated, determined as follows. First, for average elevation,

$$P_1(x, y) = \frac{\sum h(x, y)}{n}, \quad (\text{A1})$$

where n is the total number of grid points within the 1 n mi buffer region and P_1 is bounded at each location by 800 and 3200 m. The second parameter is the slope of plane of best fit:

$$P_2(x, y) = \sqrt{a^2 + b^2}, \quad (\text{A2})$$

where P_2 is bounded at each location by 0.04 and 0.15 m, and a and b are the following coefficients from the plane of best fit using least squares: $\hat{h}(x, y) = ax + by + c$. Third is standard deviation from plane of best fit:

$$P_3(x, y) = \sqrt{\frac{\sum [h(x, y) - \hat{h}(x, y)]^2}{n}}, \quad (\text{A3})$$

with P_3 limited to the range 33–165 m. The last parameter is elevation difference:

$$P_4(x, y) = h_{98p}(x, y) - h_{2p}(x, y), \quad (\text{A4})$$

where $h_{98p}(x, y)$ and $h_{2p}(x, y)$ are the 98th and 2nd percentile of the terrain distribution within the 1 n mi buffer region and P_4 is limited to the range 300–1500 m.

The second step consists of converting the specific parameters into interest values $I_k(x, y)$ by applying a linear scaling within its respective indicated range:

$$I_k(x, y) = \begin{cases} 0 & \text{for } P_k(x, y) < P_{k,\min} \\ \frac{P_k(x, y) - P_{k,\min}}{P_{k,\max} - P_{k,\min}} & \text{for } P_{k,\min} \leq P_k(x, y) < P_{k,\max} \\ 1 & \text{for } P_k(x, y) \geq P_{k,\max} \end{cases} \quad (\text{A5})$$

The third step combines the scaled parameters via their weights

$$C(x, y) = \sum_{k=1}^4 w_k I_k(x, y), \quad (\text{A6})$$

$$\text{PPV}(x, y) = \begin{cases} 0 & \text{for } C(x, y) \leq 0.2475 \\ 50 + \left[\frac{C(x, y) - 0.25}{0.5} \times 200 \right] & \text{for } 0.2475 < C(x, y) < 0.7475. \\ 250 & \text{for } C(x, y) \geq 0.7475 \end{cases} \quad (\text{A7})$$

Note that an additional correction is applied to determine the actual vertical adjustment depending on the specific flight procedure segment, but that step was not considered herein so as to keep the analysis as general as possible. The reader is referred to appendix C of FAA (2018) for the specific details of the conversion from PPV to additional vertical adjustments.

REFERENCES

- Aguilar, M., A. Stolzer, and D. D. Boyd, 2017: Rates and causes of accidents for general aviation aircraft operating in a mountainous and high elevation terrain environment. *Accid. Anal. Prev.*, **107**, 195–201, <https://doi.org/10.1016/j.aap.2017.03.017>.
- Banks, R. F., J. Tiana-Alsina, J. M. Baldasano, F. Rocadenbosch, A. Papayannis, S. Solomos, and C. G. Tzanis, 2016: Sensitivity of boundary-layer variables to PBL schemes in the WRF model based on surface meteorological observations, lidar, and radiosondes during the HygrA-CD campaign. *Atmos. Res.*, **176–177**, 185–201, <https://doi.org/10.1016/j.atmosres.2016.02.024>.
- Belo-Pereira, M., and J. A. Santos, 2020: Air-traffic restrictions at the Madeira International Airport due to adverse winds: Links to synoptic-scale patterns and orographic effects. *Atmosphere*, **11**, 1257, <https://doi.org/10.3390/atmos11111257>.
- Blumen, W., Ed., 1990: *Atmospheric Processes over Complex Terrain*. Meteor. Monogr., No. 45, Amer. Meteor. Soc., 323 pp.
- Brinkmann, W. A. R., 1973: A climatological study of strong downslope winds in the Boulder area. INSTAAR Occasional Paper 7, 228 pp., <http://instaar.colorado.edu/uploads/occasional-papers/OP07-Brinkmann-1973.pdf>.
- Carruthers, D., A. Ellis, J. Hunt, and P. Chan, 2014: Modelling of wind shear downwind of mountain ridges at Hong Kong International Airport. *Meteor. Appl.*, **21**, 94–104, <https://doi.org/10.1002/met.1350>.
- Chen, F., and J. Dudhia, 2001: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569–585, [https://doi.org/10.1175/1520-0493\(2001\)129<0569:CAALSH>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<0569:CAALSH>2.0.CO;2).
- Clark, T. L., W. D. Hall, R. M. Kerr, D. Middleton, L. Radke, F. M. Ralph, P. J. Neiman, and D. Levinson, 2000: Origins of aircraft-damaging clear-air turbulence during the 9 December 1992 Colorado downslope windstorm: Numerical simulations and comparison with observations. *J. Atmos. Sci.*, **57**, 1105–1131, [https://doi.org/10.1175/1520-0469\(2000\)057<1105:OAOADCA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2000)057<1105:OAOADCA>2.0.CO;2).
- Colman, B. R., and C. F. Dierking, 1992: The Taku wind of southeast Alaska: Its identification and prediction. *Wea. Forecasting*, **7**, 49–64, [https://doi.org/10.1175/1520-0434\(1992\)007<0049:TTWOSA>2.0.CO;2](https://doi.org/10.1175/1520-0434(1992)007<0049:TTWOSA>2.0.CO;2).
- Durai, V., and R. Bhadrwaj, 2014: Evaluation of statistical bias correction methods for numerical weather prediction model forecasts of maximum and minimum temperatures. *Nat. Hazards*, **73**, 1229–1254, <https://doi.org/10.1007/s11069-014-1136-1>.
- FAA, 1997: Hazardous mountain winds and their visual indicators. FAA Advisory Circular AC 00-57, 99 pp., https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_00-57.pdf.
- , 1999: Tips on mountain flying. FAA Aviation Safety Program, 18 pp., https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/media/tips_on_mountain_flying.pdf.
- , 2010: Weather-related aviation accident study 2003–2007. U.S. Department of Transportation FAA Doc., 71 pp., <https://www.asias.faa.gov/i/studies/2003-2007weatherrelatedaviationaccidentstudy.pdf>.
- , 2017: Instrument Procedure Handbook. U.S. Department of Transportation FAA Doc. FAA-H-8083-16B, 312 pp., https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/instrument_procedures_handbook/media/faq-h-8083-16b.pdf.
- , 2018: U.S. Standard for Terminal Instrument Procedures (TERPS). U.S. Department of Transportation FAA Order 8260.3D, 507 pp., https://www.faa.gov/documentLibrary/media/Order/Order_8260.3D_vs3.pdf.
- Farr, T. G., and Coauthors, 2007: The Shuttle Radar Topography Mission. *Rev. Geophys.*, **45**, RG2004, <https://doi.org/10.1029/2005RG000183>.
- Glowacki, T. J., 1988: Statistical corrections to dynamical model predictions. *Mon. Wea. Rev.*, **116**, 2614–2628, [https://doi.org/10.1175/1520-0493\(1988\)116<2614:SCTDMP>2.0.CO;2](https://doi.org/10.1175/1520-0493(1988)116<2614:SCTDMP>2.0.CO;2).
- Goodman, C. J., and J. D. Small Griswold, 2018: Climate impacts on density altitude and aviation operations. *J. Appl. Meteor. Climatol.*, **57**, 517–523, <https://doi.org/10.1175/JAMC-D-17-0126.1>.
- Grell, G. A., and S. R. Freitas, 2014: A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. *Atmos. Chem. Phys.*, **14**, 5233–5250, <https://doi.org/10.5194/acp-14-5233-2014>.
- Grubišić, V., and B. J. Billings, 2007: The intense lee-wave rotor event of Sierra Rotors IOP 8. *J. Atmos. Sci.*, **64**, 4178–4201, <https://doi.org/10.1175/2006JAS2008.1>.
- Guinn, T. A., D. J. Halperin, and C. G. Herbster, 2021: Climatology of estimated altimeter error due to nonstandard temperatures. *J. Appl. Meteor. Climatol.*, **60**, 377–390, <https://doi.org/10.1175/JAMC-D-20-0159.1>.
- Holmboe, J., and H. Klieforth, 1957: Pressure fields and altimeter errors. Investigations of Mountain Lee Waves and the Air Flow Over the Sierra Nevada, University of California Los Angeles Rep., 187–202, <https://apps.dtic.mil/sti/pdfs/AD0133606.pdf>.
- Hu, X.-M., J. W. Nielsen-Gammon, and F. Zhang, 2010: Evaluation of three planetary boundary layer schemes in the WRF Model. *J. Appl. Meteor. Climatol.*, **49**, 1831–1844, <https://doi.org/10.1175/2010JAMC2432.1>.
- Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins, 2008: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative

- transfer models. *J. Geophys. Res.*, **113**, D13103, <https://doi.org/10.1029/2008JD009944>.
- Jeong, J., and S.-J. Lee, 2018: A statistical parameter correction technique for WRF medium-range prediction of near-surface temperature and wind speed using generalized linear model. *Atmosphere*, **9**, 291, <https://doi.org/10.3390/atmos9080291>.
- Jiménez, P. A., J. Dudhia, J. F. González-Rouco, J. Navarro, J. P. Montávez, and E. García-Bustamante, 2012: A revised scheme for the WRF surface layer formulation. *Mon. Wea. Rev.*, **140**, 898–918, <https://doi.org/10.1175/MWR-D-11-00056.1>.
- Keller, T. L., S. B. Trier, W. D. Hall, R. D. Sharman, M. Xu, and Y. Liu, 2015: Lee waves associated with a commercial jetliner accident at Denver International Airport. *J. Appl. Meteor. Climatol.*, **54**, 1373–1392, <https://doi.org/10.1175/JAMC-D-14-0270.1>.
- Kosović, B., and Coauthors, 2020: A comprehensive wind power forecasting system integrating artificial intelligence and numerical weather prediction. *Energies*, **13**, 1372, <https://doi.org/10.3390/en13061372>.
- Maruhashi, J., P. Serrão, and M. Belo-Pereira, 2019: Analysis of mountain wave effects on a hard landing incident in Pico Aerodrome using the AROME model and airborne observations. *Atmosphere*, **10**, 350, <https://doi.org/10.3390/atmos10070350>.
- Massey, J. D., W. J. Steenburgh, J. C. Knivel, and W. Y. Cheng, 2016: Regional soil moisture biases and their influence on WRF Model temperature forecasts over the Intermountain West. *Wea. Forecasting*, **31**, 197–216, <https://doi.org/10.1175/WAF-D-15-0073.1>.
- Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.*, **87**, 343–360, <https://doi.org/10.1175/BAMS-87-3-343>.
- Mobbs, S. D., and Coauthors, 2005: Observations of downslope winds and rotors in the Falkland Islands. *Quart. J. Roy. Meteor. Soc.*, **131**, 329–351, <https://doi.org/10.1256/qj.04.51>.
- Muñoz-Esparza, D., R. D. Sharman, and J. K. Lundquist, 2018: Turbulence dissipation rate in the atmospheric boundary layer: Observations and WRF mesoscale modeling during the XPIA field campaign. *Mon. Wea. Rev.*, **146**, 351–371, <https://doi.org/10.1175/MWR-D-17-0186.1>.
- Neiman, P. J., R. Hardesty, M. Shapiro, and R. Cupp, 1988: Doppler lidar observations of a downslope windstorm. *Mon. Wea. Rev.*, **116**, 2265–2275, [https://doi.org/10.1175/1520-0493\(1988\)116<2265:DLOAD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1988)116<2265:DLOAD>2.0.CO;2).
- NTSB, 1995: Aircraft accident report: Collision with trees on final approach American Airlines flight 1572. NTSB Rep. NTSB/AAR-96/05, 136 pp., <https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR9605.pdf>.
- Parker, T. J., and T. P. Lane, 2013: Trapped mountain waves during a light aircraft accident. *Aust. Meteor. Oceanogr. J.*, **63**, 377–389, <https://doi.org/10.22499/2.6303.003>.
- Sharman, R., and T. Lane, 2016: *Aviation Turbulence: Processes, Detection, Prediction*. Springer, 523 pp.
- , L. Cornman, G. Meymaris, J. Pearson, and T. Farrar, 2014: Description and derived climatologies of automated in situ eddy-dissipation-rate reports of atmospheric turbulence. *J. Appl. Meteor. Climatol.*, **53**, 1416–1432, <https://doi.org/10.1175/JAMC-D-13-0329.1>.
- Shin, H. H., and S.-Y. Hong, 2015: Representation of the subgrid-scale turbulent transport in convective boundary layers at gray-zone resolutions. *Mon. Wea. Rev.*, **143**, 250–271, <https://doi.org/10.1175/MWR-D-14-00116.1>.
- Skamarock, W. C., and J. B. Klemp, 2008: A time-split non-hydrostatic atmospheric model for weather research and forecasting applications. *J. Comput. Phys.*, **227**, 3465–3485, <https://doi.org/10.1016/j.jcp.2007.01.037>.
- Smith, R. B., 2019: 100 years of progress on mountain meteorology research. *A Century of Progress in Atmospheric and Related Sciences: Celebrating the American Meteorological Society Centennial*, Meteor. Monogr., No. 59, Amer. Meteor. Soc., <https://doi.org/10.1175/AMSMONOGRAPH-D-18-0022.1>.
- Szmyd, J., 2016: Influence of lee waves and rotors on the near-surface flow and pressure fields in the northern foreland of the Tatra Mountains. *Meteor. Appl.*, **23**, 209–221, <https://doi.org/10.1002/met.1546>.
- Taylor, K. E., 2001: Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.*, **106**, 7183–7192, <https://doi.org/10.1029/2000JD900719>.
- Thompson, G., P. R. Field, R. M. Rasmussen, and W. D. Hall, 2008: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Mon. Wea. Rev.*, **136**, 5095–5115, <https://doi.org/10.1175/2008MWR2387.1>.
- Whiteman, C. D., 2000: *Mountain Meteorology: Fundamentals and Applications*. Oxford University Press, 368 pp.
- Wolff, J., and R. Sharman, 2008: Climatology of upper-level turbulence over the contiguous united states. *J. Appl. Meteor. Climatol.*, **47**, 2198–2214, <https://doi.org/10.1175/2008JAMC1799.1>.
- Wurtele, M., R. Sharman, and A. Datta, 1996: Atmospheric lee waves. *Annu. Rev. Fluid Mech.*, **28**, 429–476, <https://doi.org/10.1146/annurev.fl.28.010196.002241>.
- Xiang, T., E. R. Vivoni, D. J. Gochis, and G. Mascaro, 2017: On the diurnal cycle of surface energy fluxes in the North American monsoon region using the WRF-Hydro modeling system. *J. Geophys. Res.*, **122**, 9024–9049, <https://doi.org/10.1002/2017JD026472>.
- Zhang, H., Z. Pu, and X. Zhang, 2013: Examination of errors in near-surface temperature and wind from WRF numerical simulations in regions of complex terrain. *Wea. Forecasting*, **28**, 893–914, <https://doi.org/10.1175/WAF-D-12-00109.1>.