Climatology of Upper-Level Turbulence over the Contiguous United States

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ABSTRACT

Climatologies of the regional, seasonal, and temporal distributions of upper-level (18 000–60 000-ft MSL) turbulence over the contiguous United States (CONUS) are constructed using pilot reports (PIREPs) of aircraft turbulence encounters. The PIREP database used contains over two million entries, and encompasses 12 complete years of data, from January 1994 through December 2005. In spite of known variability in pilot reporting practices, it was found that PIREPs are very consistent among themselves for the null and moderate-or-greater (MOG) intensity categories. Air traffic pattern biases were accounted for by considering only statistics of MOG/total report ratios. Over the CONUS, regional maxima are evident in MOG/total report ratios over mountainous regions in the west, over the south and southeast, and over the North Atlantic seaboard. Some additional investigations are presented to help to identify possible origins of the turbulence using a smaller time interval of PIREPs in comparison with archived 20-km Rapid Update Cycle (RUC) NWP model analyses, satellite and radar-based cloud-top and cloud-base analyses, and lightning flash data, as well as topography statistics.

1. Introduction

Turbulence in the free atmosphere remains a major concern for aircraft operations, causing flight delays and occupant injuries and fatalities, which, when combined, lead to economic losses typically worth millions of dollars annually. Further, turbulence is a major dissipative mechanism in the atmospheric energy budget and must be understood to develop realistic parameterizations for numerical weather prediction (NWP) and general circulation models (GCMs). Yet the mechanisms that cause turbulent eddies in the free atmosphere at the scales that affect aircraft are still not well understood. Known sources of turbulence include, but are not limited to, instabilities related to enhanced shears associated with jet streams and upper-level fronts, mountain waves, and convection. Each phenomenon is dynamic in space and time, causing turbulence episodes to be highly transient and spatially varying. In general, the examination of temporal and geographical climatological distributions of turbulence would help in achieving a better understanding of turbulence generation mechanisms and their relative strengths and frequencies of occurrence and, in particular, would help in providing long-range aviation route planning to avoid turbulence.

One approach to deriving turbulence climatologies is to use automated turbulence diagnostics applied to gridded reanalysis data or NWP output from many years. Such diagnostics are now routinely available and widely used in turbulence forecasting procedures (e.g., Ellrod and Knapp 1992; Sharman et al. 2006), some of which have been applied by Ellrod et al. (2003) to the Aviation Global Model [AVN; now the Global Forecast System (GFS)] and by Jaeger and Sprenger (2007) to the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) data to derive global upper-level turbulence climatologies. This approach has the obvious advantage of providing uniform coverage; however, it suffers from several shortcomings: 1) a major source of turbulence is from convective sources, which, because of their small scale relative to the grid spacing and the fact that most turbulence diagnostics are intended to identify clear-air turbulence (CAT) sources, are not well represented in the gridded model output; 2) NWP-based turbulence...
diagnostics are not perfect and have an overall skill as measured by probabilities of detection based on comparisons to pilot reports of turbulence of about 75% (Sharman et al. 2006); and 3) there is susceptibility to changes in observational datasets used or NWP model configurations implemented (resolution, parameterizations, etc.) to construct the gridded data over long time periods.

Another approach is to use the only routine observations of turbulence available [viz., pilot reports of turbulence encounters (PIREPs)] over many years of data to construct turbulence climatologies. This approach was used to derive climatologies of clear-air turbulence by D. Colson in a series of papers in the 1960s (Colson 1961, 1963a,b, 1969). Since that time, the use of PIREPs to infer climatological patterns of turbulence in the free atmosphere has been mostly overlooked by research meteorologists, although there have been several unpublished reports of PIREP studies of turbulence by the airlines (some of which are summarized in Nicholls 1973). Now, many years of turbulence PIREPs are archived, along with higher-resolution NWP model output, than were available for these previous studies.

This paper reexamines the use of PIREPs to infer a climatology of turbulence over the contiguous United States (CONUS). The focus is on upper-level turbulence, although some results are provided for lower levels as well. Here upper levels are defined as being within class-A airspace (http://www.faa.gov/ATpubs/AIM, chapter 3–2.2), which includes all flights between flight level (FL) 180 or 18,000 ft and FL600 or 60,000 ft (5.5–18.3 km). A flight level is a constant pressure surface that is based on the U.S. Standard Atmosphere and referenced to a worldwide sea level pressure datum (1013.25 hPa). Routing aircraft on flight levels is a convenient way to maintain proper altitude separation above terrain without requiring pilots to frequently change the altimeter setting during flight. Although the actual MSL altitude and the flight level will not generally be the same, the differences are typically small. Restricting the climatology to class-A airspace ensures that the PIREPs used in this study come from aircraft that have filed an active Instrument Flight Rules (IFR) flight plan, maintain regular radio contact with Air Traffic Control (ATC), and are equipped with an altitude-encoding transponder to provide location and altitude data to ATC (http://flighttraining.aopa.org). It also ensures that most aircraft are in the large and heavy categories (maximum certified takeoff weight greater than 41,000 lb) and, therefore, tend to report turbulence intensities consistently between aircraft.

The remainder of this paper is organized as follows: section 2 describes the PIREP data used to construct the turbulence climatology, while section 3 investigates the accuracy and consistency of the PIREP database and shows the resulting PIREP distributions both temporally and geographically. Section 4 discusses a normalization technique applied to the data to remove air traffic biases. Correlations to possible sources of atmospheric turbulence are discussed in section 5, and a summary and conclusions are provided in section 6.

2. PIREPs data description

Currently, the only routinely available observational data for aviation-scale atmospheric turbulence are PIREPs. Over the past 2 yr, automated turbulence observations have become available from in situ measurements of eddy dissipation rate (actually $\varepsilon^{1/3}$) (Cornman et al. 1995, 2004) from selected United Airlines (UAL) B737 and B757 aircraft. However, because of the limited route structure and the short time span of data currently available, these data are not appropriate to derive turbulence climatologies at the present time. In the future, as the in situ measurements expand to include other airlines and more data are accumulated, turbulence climatologies based on these eddy dissipation rate measurements can be constructed as well.

Schwartz (1996) provides a comprehensive review of the reporting requirements and dissemination practices of PIREPs. Briefly, the voice PIREPs used in this study are received and recorded into National Weather Service (NWS) automated systems resident at either the Flight Service Stations (FSSs) or Air Route Traffic Control Centers (ARTCCs). The National Center for Atmospheric Research (NCAR) has been receiving and archiving PIREPs disseminated through the NWS’s Family of Services (FOS) communication gateway continuously from February 1992 to the present. More information about the FOS is available online (http://www.nws.noaa.gov/noaaport/html/noaaport.shtml). To create this climatology, the raw textual PIREPs from 1994 to 2005 were decoded and a rudimentary quality control was performed prior to use; for example, duplicates were removed, and reports with one or more invalid parameters were discarded. For reports in climbs or descents, the mean altitude was used as a single report. The total number of PIREPs used in this study amounts to over 2.3 million, with about 630,000 in the class A altitude band over the 12-yr time period.

PIREPs provide, among other things, the time, latitude, longitude, altitude, and estimated intensity (converted to a 0–8 scale, where 0 is “smooth” (null), 2 is “light”, 4 is “moderate”, 6 is “severe”, and 8 is “extreme”) of a turbulence encounter. As pointed out by
Schwartz (1996), PIREPs are not intended to provide research-quality turbulence information, and are known to have location and timing as well as intensity uncertainties, and these must be addressed prior to use. The timing and position uncertainties were addressed in Sharman et al. (2006), where it was found that based on a 4-month comparison of PIREPs to UAL in situ turbulence measurements from the same aircraft, the median uncertainty of PIREPs was about 50 km horizontally, 200 s in time, and 70 m vertically. However, the altitude reported is actually the flight level as registered by the aircraft barometric altimeter, which may be different from the true geometric altitude since the calibration of the altimeter is based on standard atmospheric assumptions. Table 1 shows that the median differences in FL and actual MSL altitude are usually less than 350 m. These are based on 1 yr (July 2005–June 2006) of RUC20 1800 UTC analyses (~500 000 samples) for a few selected flight levels.

<table>
<thead>
<tr>
<th>FL</th>
<th>p (Pa)</th>
<th>Median MSL (ft/m)</th>
<th>Median</th>
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<tr>
<td>150</td>
<td>57 198</td>
<td>15 483/4720</td>
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<td>200</td>
<td>46 591</td>
<td>20 635/6291</td>
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<td>250</td>
<td>37 369</td>
<td>25 767/7856</td>
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<td>300</td>
<td>30 138</td>
<td>30 863/9409</td>
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<td>350</td>
<td>23 899</td>
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<td>400</td>
<td>18 814</td>
<td>40 926/12 477</td>
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<td>450</td>
<td>14 808</td>
<td>45 871/13 985</td>
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This leaves the uncertainties in the reported turbulence intensity. In interviews with commercial pilots, Bass (1999) found that the intensity values reported are usually either the peak or average intensity levels over a 1–2-min sampling interval rather than the current values. And, although the terms light, moderate, severe, and extreme have standard definitions in terms of the imposed aircraft vertical accelerations (see, e.g., Lester 1993, his Fig. 1.8), the reported intensity of a turbulence encounter is nevertheless usually a subjective estimate by the pilot. It is, therefore, dependent on the aircraft type and, to some extent, the pilot’s knowledge and experience. However, it was found that for the large and heavy aircraft that dominate class A airspace, the reported intensities are remarkably consistent between different aircraft and pilots. When PIREP intensities from aircraft in close proximity to each other (within 50 km horizontally, 500 ft vertically, and 10 min temporally) were compared, the percentage agreement was 68%, 40%, 88%, and 76% for null, light, moderate, and severe intensities, respectively. Thus, to minimize the uncertainty in the constructed climatologies of positive turbulence reports, light reports are ignored, and moderate, severe, and extreme reports are combined into a category of moderate-or-greater (MOG) intensities. This results in a percentage agreement of MOG reports of about 93%. Thus, we are satisfied that uncertainties associated with the MOG PIREP timing, location, and intensity are small enough to be used to derive meaningful climatological distributions of aircraft-scale turbulence.

3. PIREP distributions

The monthly averaged counts per day for the 12-yr period from January 1994–December 2005 for total, MOG, and severe-or-greater (SOG) PIREPs between FL180 and FL600 (5.5–18.3 km) are shown in Fig. 1. A yearly maximum during the winter months and minimum during the summer months is apparent for all years. Further, a double peak structure is evident in the winter months, with two maxima: one in December–January and another in March–April. With the excep-
tion of the spike in 1998,¹ the counts throughout the period are about the same from year to year, with a slight overall decrease in the total PIREP and an increase in the MOG PIREP counts when, presumably, there was an increase in air traffic during this time. This suggests a trend of increasing turbulence over this time period, which would be consistent with the increasing trend found by Jaeger and Sprenger (2007) based on turbulence diagnostics from an analysis of 44 yr of ERA-40 data. Although this trend is positive in both studies, a more thorough analysis is required to verify its existence since, as remarked above, both approaches have deficiencies that are difficult to quantify. Further, given that we only have 12-yr worth of PIREP data, it is difficult to assign much significance to this trend in our data. The main point here is the identification of the pronounced maxima in the winter seasons relative to the summer seasons. No attempt is made to account for this trend of increasing turbulence in our data, and only averages over the complete 12 yr of data will be used in our normalization procedures.

The average horizontal distribution of turbulence PIREPs for the 12-yr period considered for the class A airspace over the CONUS is shown in Fig. 2. In this and all subsequent figures showing areal distributions (unless otherwise noted), a spatial binning technique is used where PIREP counts over the 12 yr are collected in 40 km × 40 km cells equivalent to the grid structure used by the RUC40 NWP model (Benjamin et al. 1998). The horizontal distribution of the total (Fig. 2a) shows areas of few or no reports over parts of the Mexico border between Texas and New Mexico, southern central New Mexico, eastern Arizona, and parts of California, Nevada, and southern Oregon. These coincide with military operating areas (MOAs) or other military bases where air traffic is prohibited or restricted (see http://sua.faa.gov/ for lists and maps). Figure 2 shows the densest areas of reports in both the total and MOG counts occurring over parts of the Ohio Valley region, the Colorado Rockies, and the Pacific Northwest. These may be due to higher relative incidences of turbulence encounters, but also to some extent, to air traffic patterns and perhaps regional, temporal, and airline-specific inconsistencies in PIREP reporting practices. Further, it must be realized that this represents an overall underestimate of the actual turbulence, since pilots and dispatchers will generally try to avoid known areas of MOG turbulence. These biases must be accounted for to construct meaningful turbulence climatologies.

4. Normalization technique

When a limited record of the more precise and regular in situ measurements of atmospheric turbulence (Cornman et al. 1995, 2004) was used, Sharman et al. (2006) found that the incidence of MOG turbulence encountered by commercial aircraft at upper levels along standard jet routes was less than 1%. However, because of biases in reporting practices, the turbulence intensity distribution within the PIREP database is much different than this. For all flights within the class-A airspace during the 12-yr period, 34% of the total turbulence reports were null, 22% light, 41% moderate, and 3% severe. Thus the nulls are grossly underreported relative to the positives. To get a more realistic relative measure of the actual turbulence frequency in the atmosphere, a normalization technique

¹ As pointed out by an anonymous reviewer, it may be more than a coincidence that 1998 was also one of the strongest El Niño years on record (e.g., McPhaden 1999), which would be expected to lead to stronger jet streams than normal and perhaps to higher incidences of turbulence (Ellrod et al. 2003).
must be applied to account for air traffic patterns and pilot reporting biases.

In an attempt to remove the air traffic bias from the turbulence frequency maps, MOG turbulence reports were normalized by the total number of PIREPs (MOG/total). The volume-averaged MOG/total result for class-A airspace over the CONUS is 0.39, while the MOG/total for all altitudes (surface to FL600) over the CONUS is 0.32. These are taken to represent the MOG/total background values. Relative to the background value of 0.39, Fig. 3 shows the horizontal distribution for the class-A airspace of the MOG/total value for the 12-yr study period for each 40 km grid cell. In this and subsequent similar figures, the total number of PIREPs was required to be ≥15 per grid cell to alleviate the problem of having artificially large ratios over regions where the overall traffic density is light. A three-point smoother was also applied to all the horizontal distributions. Figure 3 shows higher incidences of MOG/total in the Pacific Northwest, over the Sierra Nevada and Rocky Mountains, along the Gulf Coast, and over the upper midwest extending eastward to the northeastern seaboard. The areas in red are at least 1.5 times as high as the class-A background MOG/total volume-averaged value. The areas in blue and purple are areas of MOG/total ratios less than the volume average. Areas in white have less than the required 15 total reports to plot. As mentioned earlier, some of these areas correspond to prohibited and/or restricted airspace. Note the very sharp gradients over most of the mountainous areas, indicating highly localized regions of favored turbulence generation.

Figure 4 shows the horizontal distribution of the yearly averaged standard deviation (one sigma) from the 12-yr average horizontal distribution shown in Fig. 3. The greatest variability occurs over the Cascades, Colorado Rockies, and the Ohio Valley region. For the western region, even if the −1 sigma value is used, there is still a greater incidence of turbulence when compared to the class-A background value. If the +1 sigma value is used, there is up to 2 times more turbulence than the background value. In the Ohio Valley region, −1 sigma brings the MOG/total values close to the class-A background value. With the exception of these areas, much of the MOG/total results shown in Fig. 3 appear to be quite stable with a standard deviation less than 0.15. The normalized MOG/total ratio for ratios ≥1 is also plotted by season in Fig. 5. A broader area of higher MOG/total ratios occurs during the winter months of October–March compared to the summer months, in particular July–September. This is likely related to the jet stream moving south and the mean tropopause height decreasing during the winter months. There is also evidence of turbulence related to wintertime convection along the Gulf Coast region. During the spring months, turbulence frequency over the south decreases while it increases over the Ohio Valley region. The summer months show the lowest overall MOG/total ratios, consistent with Fig. 1.

The 12-yr average vertical distributions from the surface to 14 km (FL460) of the total and MOG PIREP counts, as well as the MOG/total ratio at each flight level divided by the globally-averaged MOG/total ratio for all altitudes (0.32), are shown in Fig. 6. The ±1 standard deviation values of the yearly averaged MOG/total distributions are also shown. An average of adjacent flight levels was computed to smooth the data. Although the MOG and total counts of PIREPs exhibit a maximum around 3 km, the MOG/total ratio has
Maxima near the surface and around 8–12 km. Because of the larger number of reports near the surface, the spread of the standard deviation is very small there. The variation starts to increase at about 4 km and reaches a maximum between 10 and 11 km of about ±0.5; however, the maximum in the MOG/total vertical distribution between 8 and 12 km is robust. If this distribution is stratified by season (not shown), as the horizontal distributions shown in Fig. 5 suggest, the profile for the summer months of July–September is significantly decreased at all levels, while the highest MOG/total ratios occur during the months of January to March. Qualitatively, the maximum MOG/total ratio at upper levels shown in Fig. 5 agrees well with vertical distributions of turbulence encounter frequencies shown in Steiner (1966, his Fig. 1) and Vinnichenko et al. (1980, their Fig. 9.3) and vertical distributions of the grid-based turbulence diagnostics presented in the Jæger and Sprenger (2007, their Figs. 2, 3) study. However, this distribution does not agree with a 4-yr climatological vertical distribution of turbulence intensity (eddy dissipation rate, $\varepsilon$) derived from a radar profiler (Nastrom and Eaton 1997), which shows an upper-level minimum of log($\varepsilon$) at about 9–10-km elevation. There may be several reasons for these seemingly inconsistent results. First, the distributions shown here (and those of Steiner and Vinnichenko) are presented as basically MOG turbulence frequency distributions averaged over the entire CONUS domain, whereas the radar climatology provides a median turbulence intensity distribution at a single site, making direct comparisons difficult. Second, the inference of $\varepsilon$ from the radar measured spectral widths involves a number of somewhat controversial assumptions (see, e.g., Hocking 1992, 1996) about the nature of (stably stratified) atmospheric turbulence at upper levels, which may cast some doubt on the interpretation of the radar-derived results.

5. Sources of turbulence

Much empirical evidence exists documenting higher occurrences of turbulence in the vicinity of jet streams and upper-level fronts, near the tropopause, over mountainous regions, and in or near cloud, especially convective cloud (e.g., Hopkins 1977; Lester 1993; Chandler 1987). Many of these occurrences are in clear air away from convective sources, and are therefore labeled as CAT. The relation of these favored areas to
actual turbulence generation mechanisms (instabilities) is still an active area of research, but certainly Kelvin–Helmholtz (KH) instabilities (e.g., Dutton and Panofsky 1970) and the breaking of gravity waves generated by a variety of mechanisms (e.g., Nastrom and Fritts 1992; Fritts and Nastrom 1992) are major sources. In this section the relationship of turbulence occurrence as inferred from the horizontal and vertical distributions of the MOG/total PIREP ratios to larger-scale identifiable characteristics (viz., jet stream/upper-level frontal systems, the tropopause, mountainous terrain, and cloud) will be examined in more detail.

a. Proximity to jet streams/upper-level fronts

Previous studies (e.g., Bannon 1952; Colson 1969; Reiter 1969; Chandler 1987) have shown that high-altitude turbulence is more prevalent near jet streams, with maxima favored in regions both above and below the cyclonic side of the jet core. But as pointed out in these and other studies, the jet stream and its associated upper-level front must be considered a system, both leading to locally enhanced vertical shears and reduced Richardson number (Ri), and possibly turbulence. Thus the actual cause of turbulence in the jet stream/upper-level frontal system is difficult to isolate, although local KH instabilities associated with the front (e.g., Reiter and Green 1972; Jacobi et al. 1996; Kennedy and Shapiro 1980, Muschinski 1997) and inertio-gravity wave production (mainly through frontogenetic processes), propagation, and breaking (e.g., Mastrantonio et al. 1976; Uccellini and Koch 1987; Sutherland and Peltier 1995; O’Sullivan and Dunkerton 1995; Reeder and Griffiths 1996; Guest et al. 2000; Lane et al. 2004) are plausible sources.

Koch et al. (2006) analyzed the distribution of “jet stream events” using ERA-15 data and found that the jet stream frequency over the CONUS has a maximum in the winter months over a broad band encompassing midlatitudes of the eastern half of the United States, with an absolute maximum along the East Coast (their Fig. 4). During the summer months the relative speed of the jet stream is reduced and the position shifts northward. This agrees with the distribution of the Ellrod Index (TI; Ellrod and Knapp 1992) derived by Jager and Sprenger (2007), which indicated the highest values over the east coast to the north of the mean position of the jet in both the winter and summer seasons. Thus, the relative maximum in MOG/total ratios over the eastern half of the United States in Figs. 3, 5 may be related to the increased intensity of jet streams there, especially during the winter months.

b. Proximity to tropopause

CAT is generally believed to be more prevalent in the vicinity of the tropopause (e.g., Partl 1962; Hopkins 1977; Lester 1993; Chandler 1987), especially near tropopause folds (e.g., Bannon 1952; Shapiro 1980; Wimmers and Feltz 2006). A number of theoretical studies support these observations (e.g., Reiter 1962; McHugh 2007). To determine if there is any evidence for tropopause-related turbulence in the vertical distribution of Fig. 6, the average tropopause height from RUC20 analyses valid at 1500 and 1800 UTC (corresponding to midday over CONUS and, therefore, the times of highest air traffic) for the 1-yr time period of July 2005–June 2006 was determined and compared to PIREPs within 1 km of the tropopause and within 1 h of the analysis time. For this time period this amounted to about 20 000 total PIREPs.

For this study, the tropopause height is calculated using the WMO (1957) definition, which defines the tropopause height as the “lowest level at which the lapse rate decreases to 2 K km$^{-1}$ or less, and the average lapse rate from this level to any level within the next higher 2 km does not exceed 2 K km$^{-1}$.” Only the lowest tropopause was used if multiple tropopauses existed according to this definition.

The vertical distribution of the 1-yr average MOG/
total ratio divided by the class-A volume-averaged MOG/total background value, regardless of the tropopause height, is shown in Fig. 7 (solid line) and is very similar in structure to the 12-yr average shown in Fig. 6. The vertical distribution of the ratio for PIREPs within ±1 km of the tropopause is also shown in the figure. The median value of the tropopause height for these data was about 11.6 km. The MOG/total ratio close to but above the tropopause was higher than the 1-yr average at all altitudes examined, and the MOG/total ratio close to but below the tropopause was also higher at altitudes greater than about 9 km. There is, of course, some uncertainty in these distributions associated with the nature of PIREPs; however, given the large number used (6000 within 1 km of the tropopause height) in the comparison, these results do imply that there is at least some increase in occurrence of MOG turbulence in the vicinity of the tropopause. The peak in the 1-yr average MOG/total ratio around 11-km elevation (also apparent in Fig. 6) is coincident with the median tropopause height. Since below about 11.5 km the MOG/total ratios were generally higher than above that level, the tropopause-related turbulence is apparently favored by lower tropopause heights, and by inference, larger values of the horizontal gradient of tropopause height.

c. Mountain waves

The association of increased levels of turbulence with mountainous terrain is well known (e.g., Reiter and Foltz 1967; Nicholls 1973; Lilly et al. 1972; Hopkins 1977; Lester 1993; Nastrom and Fritts 1992; Wurtele et al. 1996; Smith 2002). Qualitative connections of turbulence to mountainous regions are also given in Fahey et al. (2002). In that study and this one, the spatial distribution of turbulence associated with mountain waves is inferred from comments in the PIREPs in which the pilot specifically stated that the turbulence encounter was associated with mountain waves [mountain wave turbulence (MWT)]. Using only these reports and normalizing the MOG reports by the total PIREPs at upper levels provides the spatial distribution shown in Fig. 8. Also shown in the figure are contours of topographic height above 0.5 km. Qualitatively, good correlation of the normalized MOG pattern is apparent with topographic heights greater than about 1.5 km. This includes most of the Rocky Mountains from the Canada–Montana border south through southern New Mexico, the Wasatch Range in western Utah, and the Sierra Nevada range on the eastern California border. These favored zones in the western United States are consistent with those shown in Reiter and Foltz (1967), Calabrese (1966), Nicholls (1973), and Lee et al. (1984). The latter three studies also show favored zones over the Appalachian Mountains; however, we find that although there were also some MWT reports over the Appalachian Mountains, none above FL180 were in the MOG intensity category. A comparison to Fig. 3 indicates that a major source of turbulence over the western United States must be due to MWT.

Quantitative correlations of the MOG MWT/total
PIREPs ratio to terrain statistics were also computed. The terrain statistics were computed from the National Imagery and Mapping Agency (NIMA) Digital Terrain Elevation Data (DTED) level 0 (roughly 1-km spacing), averaged over each 40 km × 40 km grid cell. The best correlations were achieved by comparing the MOG MWT PIREPs to the terrain statistics in the adjacent westward grid cell. The correlation coefficients for MOG MWT to total PIREPs ratio to the mean topographic height, variance, positive east–west slope, negative east–west slope, east–west convexity, and east–west asymmetry were 0.32, 0.24, 0.23, 0.22, 0.11, and 0.02, respectively. East–west statistics were used because most mountain ranges over the western United States are aligned mainly north–south. Note that none of these correlations are particularly high, and that the mean topographic height has the highest correlation.

The low correlations are somewhat surprising, since linear gravity wave theory predicts that the wave amplitudes should be proportional to the magnitude of the terrain slope, and some commonly used gravity wave drag parameterizations (which attempt, in part, to capture high drag states associated with gravity wave breaking) are proportional to the terrain variance (e.g., Miller and Swinbank 1989) while others are proportional to the local terrain convexity and asymmetry (e.g., Kim and Arakawa 1995).

Since most of the major mountain ranges in the CONUS are aligned mainly in the north–south direction, it would be expected that the maximum occurrence of MWT would occur with low-level wind directions from the west or east (i.e., perpendicular to the dominant ridge line orientation). Figure 9 shows the distribution of MWT-related turbulence PIREPS with the low-level wind direction (based on the maximum wind speed within 1500 m of the terrain) derived from the RUC20 1500 and 1800 UTC analyses for the 1-yr time period of July 2005–June 2006 across the western half of the CONUS domain (30° ≤ latitude ≤ 50°, −125° ≤ longitude ≤ −105°). The low-level wind direction frequency is also shown for the same time period (solid line). As expected, there is very little incidence of mountain waves or MWT for easterly wind directions (because of lower wind speeds associated with easterly winds), with a maximum incidence in the range of about 270°–300°. This agrees with the forecaster’s rule of thumb that the wind direction must be within 30° of the perpendicular to the ridge line (e.g., Lester 1993).

The annual-average distribution of MWT can be inferred from Fig. 10, which shows the percentage of MWT and MOG MWT PIREPs relative to total PIREP counts per day. Consistent with the mean jet stream increase in strength and position moving to midlatitudes in the winter (e.g., Foltz 1966), the frequency of occurrence is nearly 90% greater in winter than in summer, with overall maxima in the months of December–January.

All this suggests that MWT is a major source of upper-level turbulence over the western half of the United States. Its occurrence is favored by strong, westerly low-level winds, which are more common in the winter.
months, and over geographic regions where the mean topographic heights are greater than about 1.5 km.

d. Association with clouds

As is well known [e.g., Federal Aviation Administration (FAA) http://www.faa.gov/ATpubs/AIM, section 7–1-28], clouds are a major source of turbulence, both within the cloud and in the clear-air regions surrounding the cloud. Besides convective instabilities within the clouds (e.g., Lester 1993), the cloud itself may alter its environment leading to increased occurrences of turbulence in the clear air above (due at least in some cases to the breaking of vertically propagating gravity waves generated by convective clouds; e.g., Pantley and Lester 1990; Lane et al. 2003; Lane and Sharman 2006) or surrounding the cloud by lowering the background Richardson number (e.g., Fovell et al. 2007). However, as far as we are aware, the relative frequency of occurrence of turbulence in cloud versus clear air has not been quantified. This frequency is difficult to assess from PIREPs, since that information (clear air or in cloud) is not normally included in the reports. Thus, it is necessary to infer the frequencies by indirect means.

Here, two methods are used for this. The first compares the PIREP altitude with the cloud top and base derived from an icing analysis product at the PIREP position, while the second compares the PIREP position with National Lightning Detection Network (NLDN) lightning flash data. The icing product considers both stratiform and cumuliform clouds while the lightning data only identify intense convective clouds. Both comparisons are highly susceptible to PIREP position errors, so discriminating between turbulence in cloud versus near cloud is problematic using either method.

1) Estimates from icing analysis product

The cloud-top and cloud-base height algorithm within the Current Icing Product (CIP) was utilized to locate clouds to determine whether a PIREP was in cloud, above cloud, below cloud, or in clear sky. The process by which the cloud-top and cloud-base heights are determined is detailed in Bernstein et al. (2005). For this study, a 2-yr time period from July 2004–June 2006 was used to compare over 200 000 turbulence PIREPs above FL180 (~5.5 km) with cloud cover derived from CIP, when both datasets were available. Because of uncertainties in the PIREP location, as well as the CIP-derived cloud boundaries, PIREPs that fall within 1 km of the CIP-derived cloud top or cloud base are classified as unknown and eliminated from the comparisons.

Each PIREP location (latitude, longitude, altitude) and time is compared with the nearest time of the available CIP cloud-top and cloud-base data and categorized as follows:

- above cloud: PIREP > 1 km above the CIP-derived cloud top;
- below cloud: PIREP > 1 km below the CIP-derived cloud base;
- in cloud: PIREP is between 1 km above the CIP-derived cloud base and 1 km below the CIP-derived cloud top;
- clear sky: no clouds apparent in the entire depth of the atmosphere at the latitude, longitude, and time of the PIREP.

Using these criteria, 44% of all the turbulence PIREPs were in clear sky, while 39% were above cloud and 9% were in cloud (Fig. 11). Because of the fairly high lower boundary used in this study (≥FL180) there are very few PIREPs (<1%) below cloud. About 8% were eliminated because they were too close to the cloud top or cloud base. Within the clear-sky reports, 52% were null while 48% were MOG. Similar results were seen for above-cloud encounters, with 53% of the reports being MOG. However, the percentage of MOG reports within cloud was significantly higher at 80%. This suggests that there is a correlation between cloud cover and turbulence reports, with relatively more MOG reports within cloud.

The horizontal distribution of the ratio of in-cloud MOG reports to total PIREPs is shown in Fig. 12. Higher ratios occur along the eastern seaboard, across the southern Great Lakes states, over Florida, and east-
ern Texas. When examined by season (Fig. 13), the winter months (October–March) have the greatest incidence of turbulence and account for the majority of the annual-average encounters. The Cascades, Colorado Rockies, and the southern Great Lakes states to the northern east coast also have contributions during the spring and summer months.

The in-cloud results were also examined as a function of cloud depth. As the cloud depth increases, the percentage of in-cloud null reports decreases while the percentage of in-cloud MOG reports increases to about 85% for (convective) clouds 9–12 km thick (not shown). This implies that turbulence tends to be of greater intensity in deeper clouds, as is intuitively expected.

Another way to examine the data is to look at vertical distributions of PIREPs in both clear air (including above cloud, below cloud, and clear air categories) and in cloud (Fig. 14). The 2-yr average MOG/total ratio (where “total” includes all clear-air and in-cloud reports of all intensities) is normalized by the globally averaged background turbulence value of 0.32. In clear air, there is a maximum at the lowest levels, which may be due to convective boundary layer turbulence, and another maximum at upper levels that is more likely due to classical CAT. In contrast, the in-cloud distribution shows a maximum at midlevels. A slight seasonal dependence is also apparent within these distributions—during the winter months there is a larger maxi-
mum at midlevels for in-cloud reports. This is most likely due to the relatively large-scale stratiform systems in winter when contrasted with the smaller-scale nature of convective clouds in the summer. There is also a slight increase in the MOG frequency of in-cloud reports during the summer months at upper levels, which is consistent with deeper convection during those months. And, there is a higher clear-air turbulence frequency at upper levels during the winter months, associated with an increase in both above-cloud and clear-air reports.

2) Estimates from NLDN Lightning Flash Data Correlations

Recently the use of the National Lightning Detection Network cloud-to-ground (CG) lightning flash data has become the preferred approach for inferring thunderstorm climatologies (e.g., Reap and MacGorman 1989; Changnon 1989), and therefore, for relating thunderstorms to PIREPs.

Contours of lightning flash density (flashes per kilometer squared per year) are shown in Fig. 15 for the annual average and Fig. 16 for the seasonal averages based on NLDN CG lightning flash data for the 9-yr period of 1997–2005. Figure 15 compares well with the NLDN CG lightning flash density shown in Huffines and Orville (1999, their Fig. 1) for the 8-yr period of 1989–96. Visual comparisons of the annual average to the PIREP distributions of Fig. 3 indicate that some of the turbulence encounters over the Ohio Valley region, the eastern half of Oklahoma into Texas, along the Gulf Coast, and over Florida are likely related to the increased occurrence of convection in those areas.

To further quantify this connection, correlations between MOG PIREP counts and lightning flash data within 0.5 h and 40 km were computed with the results shown in Fig. 17 for the annual average and in Fig. 18 for the seasonal averages. In both figures the correlations were normalized by the total PIREP counts, so the contours represent a percentage of MOG PIREPs that may be related to convection. Again, correlations are strongest over the Ohio Valley region, the eastern half of Oklahoma and Texas, along the Gulf Coast, and over Florida, but amount to no more than 20% (not contoured) of the MOG PIREPs. When compared to Fig. 13, Fig. 18 suggests that the turbulence encounters associated with clouds between October and March along the Gulf Coast are typically convective while encounters farther north during the winter months are more likely associated with stratiform clouds (with little to no lightning). During the summer months the higher correlation of MOG PIREPs associated with convection moves northward along the eastern Seaboard and across the southern Great Lakes states, over the Colorado Rockies and the Cascades.

Figure 19 shows the daily averaged percentage of MOG PIREPs based on the PIREP–lightning correlations, and shows similar results, with a maximum correlation of about 7% in the summer months related to increased thunderstorm activity, and with an overall average of about 3%. This is consistent with the in-cloud correlations found using the CIP data (Fig. 11), which gave an overall average of about 9% for all cloud types (including those with and without lightning).
6. Summary and conclusions

Spatial and temporal distributions of upper-level turbulence corresponding to class-A airspace (FL180–FL600 or approximately 5.5–18.3 km MSL) as inferred from PIREPs were presented. By comparing PIREPs close together in space and time, it was found that PIREPs were very consistent among themselves in intensities reported (at least for the null and MOG categories), and PIREP position and timing uncertainties were within acceptable ranges for constructing turbulence climatologies. However, because of variable air traffic densities and pilot reporting biases that are difficult to quantify, these distributions must be interpreted as relative distributions and not as true probabilities. Factors such as whether or not the pilot decides to make a report or not, route planning, and en-route maneuvering will also affect the representativeness of the data and this is essentially impossible to remove from the PIREP dataset. Nevertheless, pronounced maxima in the winter seasons relative to the summer seasons were clearly and consistently evident with a double peak structure in the maxima during the months of December–January and March–April (Fig. 1). Further, consistent with the study of Jaeger and Sprenger (2007), a trend of increasing MOG/total ratios with time was observed, but it is impossible to assess the significance of this trend with this data. Horizontal distributions of PIREP data show preferred regional locations of higher turbulence.
MOG/total ratios (more than 1.5 times the background value) in the Pacific northwest, over the Sierra Nevada and Rocky Mountains, southeastern Texas, Florida, and the upper midwest extending eastward to the northern east coast.

Using subsets of the data in comparison with features derived from RUC NWP analyses, lightning data, cloud depth data (CIP), and other reference sources, various causes or sources of regionally and temporally dependent turbulence could be inferred. For example, the higher incidences over the northeast seem to coincide with preferred jet stream locations, and are therefore probably due to increased shears associated with jet stream/upper-level frontal systems. Higher relative incidences over Florida, eastern Texas, and along the Gulf Coast, especially during the winter months, are presumably associated with convection. Over the upper midwest and northern Ohio valley region the higher incidences are probably associated with stratiform clouds during the fall and winter months and convection during the spring and summer months. Overall, the highest MOG/total ratios were found to occur over the Colorado Rockies, because of pronounced mountain
wave activity in the winter months and thunderstorm activity in the summer months.

When examined vertically, an increase in the MOG/total ratios is evident between about 4 and 12 km, with a maximum of nearly 1.7 times the background value at 9 km. By using a subset of PIREPs compared to features derived from RUC20 NWP analyses, a higher frequency of MOG reports was observed within 1 km of the tropopause compared to the overall distribution. From the same dataset, it was shown that the major source of turbulence over the western portions of the United States was due to mountain wave–induced turbulence, with a nearly 90% higher frequency of such in the winter relative to the summer.

Using a combination of cloud-base and -top information from the CIP analyses for a subset of the PIREP data, the MOG turbulence frequencies were shown to be greater in cloud than in clear air, with 80% of all the reports in cloud being MOG. An increase in MOG frequency also occurred with increasing cloud depth, reaching 85% for cloud depths of 9–12 km. Vertically, a maximum in MOG occurrence for in-cloud reports was found to be in the 4–6-km range, while for clear air, the maximum is between 9 and 11 km. When NLDN CG flash data are used, correlations between MOG PIREPs and lightning flash data across the CONUS were as high as 20%. When looking at the annual distribution of this correlation there was a daily peak of about 7% during the summer months.

These are climatologies based on 12 yr of PIREP data, and because of this fairly lengthy dataset, these distributions should be a good representation of average conditions. However, substantial year-to-year variations are always possible (cf. Fig. 4), and this should be taken into account for aircraft route planning or other applications. In addition to strategic applications, these data may be useful in developing probabilities of upper-level turbulence for use in turbulence forecasting systems (such as the Graphical Turbulence Guidance; Sharman et al. 2006) and the development and refinement of free-atmosphere turbulence parameterizations used within GCM and NWP models.

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