Statistics and Possible Sources of Aviation Turbulence over South Korea

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ABSTRACT

The characteristics of aviation turbulence over South Korea during the recent five years (2003–08, excluding 2005) are investigated using pilot reports (PIREPs) accumulated by the Korea Aviation Meteorological Agency (KAMA). Among the total of 8449 PIREPs, 4607 (54.53%), 1646 (19.48%), 248 (2.94%), 7 (0.08%), and 1941 (22.97%) correspond to the turbulence categories of null, light, moderate, severe, and missing, respectively. In terms of temporal variations, the annual total number of turbulence events increased from 2003 to 2008, and the seasonal frequency is the highest in the spring. With regard to spatial distributions, reported turbulence encounters are dominant along the prevailing flight routes, but are locally higher over the west coast, Jeju Island, and the Sobaek and Taebaek mountains. The turbulence events in these regions vary by season. To examine the regional differences and possible sources of the observed turbulence, lightning flash data, Regional Data Assimilation and Prediction System (RDAPS) analysis data with a 30-km horizontal grid spacing provided by the Korean Meteorological Administration (KMA), and a digital elevation model (DEM) dataset with a 30-s resolution, are additionally used. Convectively induced turbulence (CIT) and clear-air turbulence (CAT) events comprised 11% and 89% of the total 255 moderate or greater (MOG)-level turbulence events, respectively. CAT events are classified as tropopause/jet stream–induced CAT (TJCAT) and mountain-wave-induced CAT (MWCAT) events. The MOG-level TJCAT and MWCAT events are responsible for 41.2% and 19.6% of the total MOG-level turbulence events, respectively. The CIT events in summer and the TRCAT and MWCAT events in spring occur most frequently over the previously mentioned regions of South Korea, associated with specific generation mechanisms.

1. Introduction

Turbulence at aircraft scale (10–1000 m) or that directly affects aircraft is commonly referred to as aviation turbulence (Lester 1994). Aviation turbulence in the free atmosphere is a serious concern in the general aviation industry because it frequently causes occupant injuries, flight delays, fuel losses, and structural damage. It is more dangerous when it occurs unexpectedly at cruising levels, where most of the passengers and crew are unbuckled. According to the 2009 annual report of the National Transportation Safety Board (NTSB 2009), from 1996 to 2005 turbulence was the leading cause of weather-related aircraft accidents in the United States. Over South Korea, from 1957 to the present turbulence has accounted for about 24% of the aircraft accidents caused by weather, making it the largest contributor to weather-related accidents [statistics from the Aviation and Railway Accident Investigation Board (ARAIB), information online at http://www.araiib.go.kr].

Possible sources of aviation turbulence include convective systems (Pantley and Lester 1990; Lane et al. 2003), jet streams along with upper-level fronts (Dutton and Panofsky 1970; Ellrod and Knapp 1992), complex terrain (Clark et al. 2000; Doyle et al. 2005), and inertial instabilities (Koch et al. 2005; Knox et al. 2008). Even though the relationship between source and turbulence is not understood completely, temporal and spatial distributions of turbulence events can provide insights into possible turbulence sources (Lane et al. 2009). In addition, the relative frequency of the turbulence events in different areas can provide information useful for long-range aviation route planning (Wolff and Sharman 2008). Therefore, many studies involving statistical analyses of turbulence events have been carried out using diagnostic indices derived from numerical weather prediction (NWP) models and turbulence observations, including pilot reports (PIREPs) and in situ measurements. The former has the advantage of uniform coverage in all areas, but

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includes uncertainties such that predicted turbulence potential cannot represent the observed turbulence perfectly. For example, overall performances of the graphic turbulence guidance (GTG) in the United States (Sharman et al. 2006) and in Korea (Kim et al. 2009) are only about 75% and 70%, respectively, and are highly dependent upon the model configurations (e.g., resolution, parameterization, etc). On the other hand, the latter has the advantage in that it reports the locations and timings of aviation turbulence, although the observations are inherently subjective (Wolff and Sharman 2008).

The characteristics of turbulence events based on PIREPs have been reported for various regions in the world. Wolff and Sharman (2008) examined the climatology of upper-level turbulence over the contiguous United States (CONUS) using many years of PIREPs. They showed that possible sources of upper-level (18 000–60 000 ft) turbulence include mountain waves in the western region and winter-season jet streams in the northeastern regions. The relatively higher numbers of incidents over Florida, eastern Texas, and along the Gulf coast are presumably associated with convective clouds. In Greenland, turbulence events reported in PIREPs were relatively higher in the winter season from 2000 to 2006, caused mainly by mountain-wave breaking when surface cyclones produce prevailing easterlies in the lower troposphere (Lane et al. 2009). Lee and Choi (2003) investigated the spatial and temporal distributions of turbulence events over South Korea, reported in PIREPs from 1996 to 2000. They showed that these events were more frequent in the spring season, with regional differences in the seasonal and spatial distributions of the turbulence events.

Geographically, Korea and eastern Asia have significant potential for turbulence events because the strongest jet stream in the world exists there (Jaeger and Sprenger 2007; Koch et al. 2006). Moreover, since complex terrain covers more than 70% of the Korean Peninsula, the prevailing westerlies can generate a wide spectrum of mountain waves. Given the significant increase in air transportation over Korea and eastern Asia during the past decade, the characteristics of aviation turbulence in this region should be investigated. This would provide invaluable information to pilots, dispatchers, and forecasters to maintain air flight safety and to reduce the amount of unexpected damage from aviation turbulence.

The remainder of this paper is organized as follows. In section 2, the PIREP data used in this study are described. In section 3, temporal and spatial distributions of the PIREP data are examined. In section 4, possible sources of the observed turbulence events are investigated using lightning flash data, Regional Data Assimilation and Prediction System (RDAPS) analysis data with a 30-km horizontal grid resolution, and a digital elevation model (DEM) dataset with a 30-s resolution. A summary and discussion of the results are provided in section 5.

2. Pilot reports (PIREPs)

Currently, PIREPs are the only routinely available observations of turbulence from aircraft in South Korea. The PIREPs used in this study were collected using the following steps. First, pilots in commercial aircraft flying over the Incheon Flight Information Region (FIR; Fig. 1) routinely and occasionally report the existence of turbulence to the Korea Air Traffic Control Center (KATCC) through regular voice radio contact. These PIREPs include several pieces of information such as location, flight level, type of aircraft, wind speed and direction, and the turbulence (and/or icing) level and intensity [null (NIL), light (LGT), moderate (MOD), severe (SEV), or extreme (EXT)]. Some pilots additionally report weather conditions such as visibility and cloud cover as well as the extent of the turbulence level. Second, the air traffic controller documents the information in the PIREPs. Finally, the raw text of these PIREPs is transmitted to the Korea Aviation Meteorological Agency (KAMA) and accumulated in their database. In this study, a total of 8449 PIREPs during the 5 yr from 2003 to 2008 (excluding 2005 due to the lack of raw data) are used after applying quality
controls such as removing duplicates and discarding PIREPs that did not include both location and flight level.

As pointed out by Schwartz (1996), potential uncertainties in the PIREP data, such as turbulence intensity and location, should be examined before investigating turbulence statistics. The turbulence intensity reported in a PIREP tends to be determined by the pilot’s experience, and the locations recorded sometimes differ by more than 10s or 100s of kilometers from the actual locations of the turbulence observed by in situ measurements (Cornman et al. 2004). To evaluate these uncertainties, we compared reported intensities with the intensities observed in PIREPs located within 50 km horizontally, 500 ft vertically, and 10 min temporally, following the method proposed by Sharman et al. (2006). It was found that the percentages of total agreement for the NIL- and LGT-level events during the present research period were about 98% (55 cases) and 61% (23 cases), respectively. No MOD events and only one SEV event could be selected due to the small sample size. However, when the ranges and time windows are extended to 1000 ft vertically and 20 min, respectively, the percentage of total agreement for five MOD-level events was 80%. In general, only a few examples of coexisting turbulence were detected, because most pilots tend to avoid precautioned locations where significant turbulence events have been reported within a certain range and time window. This may cause an underestimation of the actual number of turbulence events in all statistical research of turbulence that use PIREPs (Wolff and Sharman 2008). Nevertheless, total agreement for the NIL-, LGT-, and MOD-level events in the present study is likely sufficient to ignore the uncertainties in turbulence intensity and location, especially when compared with those in CONUS (Wolff and Sharman 2008) of 68%, 40%, and 88% for NIL-, LGT-, and MOD-level events, respectively. It is worth noting that the number of cases considered in this study is much smaller than those in the previous work by Wolff and Sharman (2008). Hence, direct comparison of the agreement between South Korea and CONUS PIREP data may not be reliable. Also, turbulence intensities reported in PIREPs within the same range and time windows can differ depending on the aircraft type and size. The aircrafts providing PIREP data in the present study are heavy and large types of commercial airliners, such as the Boeing and Airbus series.

3. Turbulence statistics

Table 1 shows the numbers and percentages of the PIREP data over South Korea from 2003 to 2008 corresponding to the NIL, LGT, MOD, SEV, and missing categories. Missing PIREPs correspond to PIREPs that lack turbulence information. Of 8449 PIREPs, 1646, 248, and 7 were LGT-, MOD-, and SEV-level events, respectively. In the previous statistical analysis of PIREPs over South Korea, 4709 PIREPs obtained during the 5 yr from 1996 to 2000 yielded 477, 100, and 3 LGT-, MOD-, and SEV-level events, respectively (Lee and Choi 2003). Compared with the previous research by Lee and Choi (2003), the absolute numbers of all types of turbulence events analyzed in this study are higher and the relative portions of all severity levels are also higher (19.48% versus 10.13%, 2.94% versus 2.12%, and 0.08% versus 0.07% for LGT-, MOD-, and SEV-level events, respectively).

3a. Yearly and seasonal distributions

To investigate annual variations in the turbulence frequencies from 2003 to 2008, the annual total of PIREPs (including missing PIREPs), and light or greater (LOG)- and moderate or greater (MOG)-level events, are presented in Fig. 2. Relative percentages normalized by the total number of PIREPs for each year also are presented, as this can reduce air traffic bias in the PIREP data (Wolff and Sharman 2008; Lane et al. 2009). Although annual counts of the total and LOG- and MOG-level events differ from year to year, the numbers of LOG- and MOG-level events show a definitely increasing trend during the 5-yr period. In particular, the 68 MOG-level events reported in 2008 are more than twice the number reported in 2003 (32 MOG-level events). This increasing pattern is also shown in the relative percentages of both the LOG- and MOG-level events, except for the LOG-level events in 2007. The relative percentages of the LOG- (MOG)-level events increased from 28.92% (2%) in 2003 to 40.68% (6.51%) in 2008.

To investigate a possible reason for this increasing pattern, the jet stream frequencies among the LOG- and MOG-level turbulence events are examined using the RDAPS analysis data with a 30-km horizontal grid spacing. If horizontal wind speeds greater than 40 m s⁻¹ are found near a LOG- or MOG-level turbulence event, then the event is regarded as being related to the jet stream.

Table 1. Numbers and percentages corresponding to the NIL, LGT, MOD, SEV, and missing categories of aviation turbulence obtained from PIREPs over South Korea from 2003 to 2008, excluding 2005.

<table>
<thead>
<tr>
<th>Turbulence intensity</th>
<th>No.</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIL</td>
<td>4607</td>
<td>54.53</td>
</tr>
<tr>
<td>LGT</td>
<td>1646</td>
<td>19.48</td>
</tr>
<tr>
<td>MOD</td>
<td>248</td>
<td>2.94</td>
</tr>
<tr>
<td>SEV</td>
<td>7</td>
<td>0.08</td>
</tr>
<tr>
<td>Missing</td>
<td>1941</td>
<td>22.97</td>
</tr>
<tr>
<td>Total</td>
<td>8449</td>
<td>100.0</td>
</tr>
</tbody>
</table>
The frequencies and relative percentages normalized by total PIREPs within a given year generally increased from 2003 [LOG (104/1603; 6.5%), MOG (9/1603; 0.6%)] to 2008 [LOG (159/1597; 10%), MOG (27/1597; 1.7%)], implying that atmospheric conditions over South Korea likely were more conducive for generating turbulence in 2008 than they were in 2003. Although unavoidable uncertainties in the PIREP data still remain, this suggests that forecasting of aviation turbulence over South Korea becomes more important.

Figure 3 shows seasonal variations in the LOG- and MOG-level events. In Fig. 3, the first and second maximum frequencies of the LOG-level events appear in the spring and winter seasons, respectively, consistent with the results obtained by Lee and Choi (2003). For relative percentages normalized by the total number of PIREPs within each season (solid line), the LOG-level events also occur most frequently in the spring and winter seasons. Although more detailed synoptic analyses are required to explain this seasonal variation, enhanced vertical wind shear below or above the jet stream causes aviation turbulence more frequently during the winter and spring seasons (e.g., Dutton and Panofsky 1970; Ellrod and Knapp 1992). This seasonal effect is likely due to the prevailing westerlies in these seasons, which are climatologically greater than those in the summer and fall.

For the MOG-level events (Fig. 3), the first maximum frequency occurs in the spring months, while the second maximum frequency occurs in the summer months, in contrast to the LOG-level events shown in Fig. 3. Moreover, the relative percentages of the MOG-level events in the summer and fall months are higher than those in the winter months. Given that convective clouds associated with the monsoon system and typhoons frequently pass through the Korean Peninsula in the summer and fall, the higher frequencies of the MOG-level events in these seasons likely are related to the presence of convective systems (e.g., Pantley and Lester 1990; Lane et al. 2003). The relationship between the observed turbulence and possible sources will be examined in section 4.

b. Vertical and horizontal distributions

To understand the vertical distributions of the observed turbulence over South Korea, all LOG- and MOG-level events for the entire study period are sorted into 5000-ft bins, from flight level (FL) 0 to FL500 (50 000 ft). Average annual counts for each bin are shown in Fig. 4. To quantify the height dependency of the turbulence intensity, the relative percentages of the LOG- and MOG-level events normalized by the total numbers of PIREPs within a given altitude are also depicted in Fig. 4. When a turbulence altitude is reported in a PIREP as a range (e.g., 30 000–34 000 ft), a mean altitude (e.g., 32 000 ft) is used to construct the vertical distribution shown in Fig. 4. Note that the flight levels shown in Fig. 4 were converted from pressure levels measured by a barometer in the commercial aircraft to the heights using standard atmospheric assumptions (Sharman et al. 2006). In Fig. 4, the maximum frequencies of both the LOG- and MOG-level events appear between the flight levels of 20 000 and 25 000 ft ($z \approx 6.1$–7.6 km), the predominant flight levels
for domestic airliners over South Korea. The relative percentages of the LOG- and MOG-level events above 20,000 ft are consistently about 4% and 30%, respectively, implying that the height dependency of the turbulence intensity over South Korea during this period is not significant.

To identify the horizontal distributions of aviation turbulence over South Korea, frequencies for the total and LOG- and MOG-level events are accumulated in horizontal grid boxes of 30 km × 30 km, the same horizontal resolution as RDAPS. Results are shown in Fig. 5. Note that the domains in Fig. 5 and all subsequent figures are the subdomains of the RDAPS focused on the Korean Peninsula. As expected, turbulence events are dominant along the prevailing flight routes over South Korea, although local maxima occur along the routes. According to the aviation statistics from the Korea Airport Corporation (KAC; information online at http://kac.airport.co.kr), there are three dominant domestic flight routes in the Korea FIR (see Fig. 1): the routes from Seoul to Jeju, Seoul to Busan, and Jeju to Busan. In addition to these major air routes, a flight route from Seoul to Gangneung is additionally important, because international airliners from Korea to Japan or to the United States usually use this flight route. Along these dominant flight routes, the relatively higher frequencies of both the LOG- and MOG-level events occur near the west coast, Jeju Island, and the Sobaek and Taebaek mountains.

To better understand the regional patterns of aviation turbulence, horizontal distributions of the LOG-level events for each season are presented in Fig. 6. As the accumulated turbulence events in each grid box are normalized by the total number of PIREPs within a box for a given season, air traffic changes over different seasons and areas are also considered. In addition, any grid box with less than 10 PIREPs was ignored to avoid artificially large values of the relative percentages due to the lack of sufficient samples (Wolff and Sharman 2008).

In Fig. 6, the overall percentages in the winter and spring seasons are higher than those in the summer and fall seasons, which is consistent with the results of the seasonal variation shown in Fig. 3a. The aforementioned four regions with relatively higher frequencies in Fig. 5 have different turbulence frequencies in each season. In the winter (Fig. 6a), turbulence events occur more frequently along the west coast region of South Korea, especially near Gunsan, Incheon, and northeast of Jeju Island. In the spring season (Fig. 6b), the maximum turbulence frequency is located near Gangneung on the lee side of the Taebaek mountains, with a relatively higher frequency near Gwangju in the southwest coastal region of South Korea. In the summer (Fig. 6c) and fall seasons (Fig. 6d), areas of relatively higher turbulence frequencies are located near the southwest coast, and the Sobaek and Taebaek mountains, although their frequencies are not as large as those in winter and spring. Possible sources of the observed turbulence during these seasons include convective systems, the jet stream, and mountain waves. Details of each will be examined in section 4.

The MOG-level turbulence results in Fig. 7 are similar to those in Fig. 6, except for the relatively higher frequencies near Jeju Island in winter and spring, and the low frequencies near the Taebaek mountains in summer and near the Sobaek mountains in fall. As can be expected from the seasonal variations in the MOG-level turbulence shown in Fig. 3, the overall percentages of the MOG-level turbulence frequencies in spring and summer are higher than those in winter and fall.

4. Possible sources of turbulence

In this section, possible sources of the observed turbulence events are investigated using lightning flash data, the RDAPS analysis data with a 30-km horizontal grid spacing provided by the KMA, and the DEM dataset with a 30-s resolution.

a. Convective system

Convective systems are important sources of aviation turbulence. Turbulence events related to a convective system, referred to as convectively induced turbulence (CIT), are classified into two categories, in-cloud and out-of-cloud CIT events, depending on their location (Lane et al. 2003). Generation mechanisms for these turbulence events include strong variations in upward and downward motions within a small horizontal distance in a cloud boundary (in-cloud convective instability), the enhancement of vertical
wind shear due to flow deformation near a cloud boundary (Grabowski and Clark 1991), and breaking of convectively induced gravity waves out of a cloud boundary (Lane et al. 2003; Lane and Sharman 2008). According to a study of severe turbulence events that caused accidents in the United States, conducted by Kaplan et al. (2005a), 86% of the turbulence events were located horizontally within 100 km of well-organized convective clouds. In the present study, lightning flash data accumulated by the KMA were used to isolate CIT events from aviation turbulence reported in the current PIREPs. Since 2001, the KMA has established 17 observation sites to detect cloud-to-ground (CG) and cloud-to-cloud (CC) lightning over South Korea. In the present study, turbulence reported within 100 km spatially and ±40 min temporally of any CG and CC lightning activities was regarded as CIT. This classification method is the same as that used by Sharman et al. (2006) and Kim et al. (2009), who evaluated the clear-air turbulence (CAT) forecasting system over the CONUS and South Korea, respectively, and Wolff and Sharman (2008), who investigated the correlation between turbulence and lightning over the CONUS. After extracting CIT events, the remaining turbulence events were regarded as CAT events.

The numbers and percentages of CIT and CAT events corresponding to individual intensities over South Korea from 2003 to 2008 are given in Table 2, which shows that 152 (1494) and 28 (227) are LGT- and MOG-level CIT (CAT) events, respectively. Table 1 shows 1646 (255) LGT- (MOG)-level turbulence events, so the relative amounts of the LGT- (MOG)-level CIT and CAT events among the LGT- (MOG)-level turbulence events are about 9.2% (11%) and 90.8% (89%), respectively. The relative portions of the LGT- (MOG)-level CIT events among the total number of CIT events is 20.74% (3.82%), which is slightly higher than that of the LGT- (19.36%) [MOG (2.94%)]-level CAT events among the total CAT events.

Figure 8 shows the monthly variations in the LGT- and MOG-level CIT events. As expected, CIT events occur more frequently in the summer than in any other season. The maximum occurrence is in August, when well-developed convective systems are dominant over Korea, driven either by thermally forced or large-scale convergent flow. To account for monthly air traffic changes, the relative percentages of the LGT- and MOG-level CIT events normalized by the total number of PIREPs within a given month are shown as dashed and solid lines, respectively, in Fig. 8. These relative percentages of both the LGT- and MOG-level CIT events are also highest in August, at about 9.44% and 2.04%, respectively.

Other noticeable results are seen in Fig. 8. First, a relatively high number of turbulence events also appear in September, when typhoon activity directly or indirectly affects the Korean Peninsula. Second, relatively large frequencies of CIT events occur in the spring season when well-organized convective systems pass through the Korean Peninsula along with occasionally developed low pressure systems. Although actual frequencies of CIT events may be underestimated because pilots usually try to avoid previously identified convective systems, the overall features of the seasonal variations are similar to
those obtained by Wolff and Sharman (2008, Fig. 19). In the spatial distribution of CIT events in South Korea (not shown), the highest frequencies of CIT events occur in the areas of the southwest coast, Jeju Island, and the So-Baek mountain region.

b. Tropopause/jet stream

A large portion of CAT events can be explained by the Kelvin–Helmholtz instability, which is generated when the dimensionless local Richardson number \( \text{Ri} = \frac{N^2}{VWS^2} \).
where $N$ and VWS are the Brunt–Väisälä frequency and vertical wind shear, respectively) is below 0.25 (Dutton and Panofsky 1970). This instability frequently occurs above or below a strong jet stream accompanied by an upper-level front (Ellrod and Knapp 1992). Due to this upper-level frontogenesis, the dynamic tropopause is folded down into the midtroposphere. According to previous studies, CAT events frequently occur near this tropopause region (Koch et al. 2005) and are important not only for aviation safety but also for the stratosphere–troposphere exchange (STE) of chemical constituents (Shapiro 1980). To isolate CAT events occurring near
the tropopause region that is associated with the jet stream, RDAPS analysis data with 30-km horizontal grid spacing produced at 0000 and 1200 UTC were used to calculate the dynamic tropopause height [2 potential vorticity units (PVU)]. CAT events located near the 2-PVU level, within ±1 km vertically and ±6 h temporally, were regarded as being related to the tropopause/jet stream region. Hereafter, these CAT events are referred to as TJCAT (tropopause/jet stream–induced CAT) events. This method is the same as that used by Wolff and Sharman (2008).

In the tropopause/jet stream along with the upper-level front structures, CAT encounters are also associated with inertial instability and geostrophic adjustment (Knox 1997). In rotating flow, any existence of an absolute rotation opposite to the earth’s rotation is immediately corrected and stabilized to new balance through the inertial instability, as the flows spontaneously emit the gravity waves (Holton 2004). Kaplan et al. (2005b) proposed the North Carolina State University turbulence index 2 (NCSU2), which is the cross product between the vertical vorticity and Montgomery streamfunction on an isentropic surface, to diagnose severe turbulence in a strong ageostrophic flow. Kaplan et al. (2006) showed that the NCSU2 index is maximized in a region where the ageostrophically induced strong gradient of the streamwise vertical vorticity and the pressure gradient force is orthogonal in a supergradient flow regime, in contrast to the geostrophic flow where the pressure gradient force and vorticity gradient vectors are parallel. This finally transits to the horizontal vortex tubes (HVTs; Clark et al. 2000) and causes localized turbulence. Recently, Knox et al. (2008) proposed a turbulence index based on the Lighthill–Ford theory (LHF) of spontaneous imbalance and emission of the inertia–gravity waves that locally modify the environmental Richardson number.

The numbers and percentages of TJCAT events corresponding to individual intensities over South Korea from 2003 to 2008 are shown in Table 3, where the numbers of the LGT- and MOG-level TJCAT events are 603 and 105, respectively. Considering that the number of the LGT- (MOG)-level CAT events in Table 2 is 1494 (227), the relative portion of the LGT- (MOG)-level TJCAT events among the total number of LGT- (MOG)-level CAT events is about 40.4% (46.3%). The relative portions of the LGT- and MOG-level TJCAT events among the total number of TJCAT events are 17.97% and 3.13%, respectively.

Figure 9 shows the monthly variations in the LGT- and MOG-level TJCAT events. In Fig. 9, TJCAT events are shown to occur the most frequently in winter and spring seasons, and the maximum relative percentages of the LGT- and MOG-level TJCAT events among the total number of PIREPs within a given month are about 15.6% in February and 3.9% in March, respectively. Considering that TJCAT events most frequently occur at the flight levels of 25 000–30 000 ft ($z = 7.6–9.1$ km), these seasonal patterns are likely due to the seasonal variations in the dynamic tropopause height over the Korean Peninsula, where the mean dynamic tropopause heights are higher in the summer and fall ($z = 12–13$ km) than in the winter and spring ($z = 9–10$ km) (Lee 2008). Moreover, the monthly variation shown in Fig. 9 is similar to that of the relative frequency of the secondary tropopause measured by ozonesonde sounding at Pohang and the satellite observations over eastern Asia shown by Hwang et al. (2007, Fig. 8).

To examine the synoptic–dynamic structure for the TJCAT events, we calculate and show in Fig. 10 the differences in the composite averages between the MOG-level TJCAT and other MOG-level CAT events (TJCAT-CAT) for the horizontal wind speed (WS) at 200 hPa and vertically averaged turbulence index 1 [TI1; Eq. (9) in Ellrod and Knapp (1992)], NCSU2 [Eq. (4) in Kaplan et al.
(2006)], and Lighthill–Ford radiation [LHF; Eq. (23) in Knox et al. 2008] between 20 000 and 30 000 ft using RDAPS analysis data with 30-km horizontal grid spacing. The 95% significant confidence level is shaded in all plots in Fig. 10. Note that the seasonal frequencies in the 105 MOG-level TJCAT events [December–February (DJF), 24 (23%); March–May (MAM), 51 (48%); June–August (JJA), 13 (13%); and September–November (SON) 17 (16%)] and the other 122 MOG-level CAT events [DJF, 24 (20%); MAM, 38 (32%); JJA, 33 (26%), and SON, 27 (22%)] are not significantly different, so that the differences in the four parameters shown in Fig. 10 are not significantly dependent upon seasonal changes in atmospheric conditions. In Fig. 10a, the jet stream magnitudes over South Korea are higher during the TJCAT events than those during the other CAT events within a 95% confidence level. Of 105 TJCAT events, 86 (82%) occurred near a horizontal wind speed greater than 40 m s\(^{-1}\), which implies that the strong jet stream is dominant over South Korea during the TJCAT events. In Figs. 10b–d, the relatively larger values of the TI1, NCSU2, and LHF indices are located over South Korea for the TJCAT events within a 95% confidence level. And of the total 105 TJCAT events, 84 (80%), 76 (72%), and 79 (75%) occurred near the grid point greater than the MOG-level thresholds of TI1 [1.7 \times 10^{-6} \text{s}^{-2}; \text{Sharman et al. (2006)}], NCSU2 [10 \times 10^{-12} \text{s}^{-3}; \text{Kaplan et al. (2006)}], and LHF [1 \times 10^{-12} \text{s}^{-3}; \text{Knox et al. (2008)}] indices, respectively, in contrast to the 50 (41%), 50 (41%), and 73 (59%) of the total 122 other CAT event results. This confirms the idea that the selected TJCAT events are related to the upper-level front/jet stream and associated with shear instability, inertial instability, and geostrophic adjustment.

c. Mountain waves

According to several previous studies, mountain waves are one of the important sources of CAT events. The amplitude of vertically propagating mountain waves increases with height due to decreasing air density (Hines 1960; Lindzen 1981), which leads to wave steepening, overturning, and subsequent breaking at higher altitudes (Doyle et al. 2005). Stationary mountain waves can break when they approach a critical level at which the background wind speed equals zero (Lilly 1978). To isolate CAT events related to mountain waves, possible areas of turbulence induced by mountain-wave breaking are diagnosed by mountain-induced gravity wave drag parameterization. The parameterization used in this study is based on Palmer et al. (1986) and Chun et al. (1996) using the RDAPS analysis data at 0000 and 1200 UTC. A brief description of the parameterization is as follows. First, mountain-wave stress along with the surface-level horizontal wind vector (denoted by the subscript \( s \)) is calculated by \( \tau_s = -K_0 \rho_s N_0 |h'|^2 \), where \( K_0 \) is the horizontal wave-number (1.0 \times 10^{-3} is used in this study, corresponding to a 6.28-km horizontal wavelength), \( \rho_s \) is the surface air density, \( N_0 \) is the Brunt–Väisälä frequency at the surface, \( U_s \) is the basic-state wind projected on the surface wind vector, and \( |h'|^2 \) is the subgrid-scale topography height variance. The variances in the subgrid-scale mountain height (\( |h'|^2 \)) at the grids of the RDAPS domain are derived using the DEM dataset with a 30-s resolution. Second, regions of wave breaking induced by mountain waves are determined by using the minimum Richardson number including the saturation wave stress is calculated by \( \tau_s = \frac{e_s}{2} \frac{K_0 \phi_k \epsilon_U^2}{N_0} \), where \( e_s = \frac{U_k}{\epsilon} \frac{K_0 \phi_k \epsilon_U^2}{N_0} \) the horizontal wind projected onto the surface wind and \( \epsilon = \frac{1}{\epsilon_k} \frac{K_0 \phi_k \epsilon_U^2}{N_0} \) is the horizontal wave number at a given level (denoted by the subscript \( k \)) and \( \epsilon \) is an inverse Froude number \( \epsilon = \frac{U_k}{\epsilon} \frac{K_0 \phi_k \epsilon_U^2}{N_0} \), where \( U_k \) is the horizontally projected wind on the critical level and \( \epsilon = \frac{1}{\epsilon_k} \frac{K_0 \phi_k \epsilon_U^2}{N_0} \) the horizontal wave number at a given level (denoted by the subscript \( k \)).

![Fig. 9. As in Fig. 8, but for TJCAT.](image)
is encountered in the calculation, we assumed that the gravity waves are absorbed at the critical level and then the wave stress is set to zero at and above the critical level. When $N_k = 0$, saturation stress becomes infinity, implying no wave breaking occurs, and the wave stress is assumed to be the same as that at the level below. The aforementioned steps are repeated at higher levels until the wave stress is zero or the model top is reached. When the reported CAT events are located near the grid point of the nonzero mountain-induced gravity wave drag within 30 km horizontally, 1000 ft vertically, and $6\,h$ temporally, the CAT events were regarded as being related to mountain waves. Hereinafter, CAT events related to mountain waves are referred to as mountain-wave-induced CAT (MWCAT) events. It is noted that the frequency of MWCAT events categorized in this study would tend to underestimate the percentage of MWCAT encounters, because the classification method used in this study is based on a hydrostatic assumption and, therefore, may miss some events that occurred due to the effects of wave breaking in non-hydrostatic (e.g., trapped) waves.

The numbers and percentages of MWCAT events corresponding to individual intensities over South Korea from 2003 to 2008 are shown in Table 3, where the numbers of LGT- and MOG-level MWCAT events are 273 and 50, respectively. Since there are 1494 (227) LGT- (MOG)-level CAT events in Table 2, the relative portions of the LGT- (MOG)-level MWCAT events among the total number of LGT- (MOG)-level CAT events is about 18.3% (22%). The relative portions of the LGT- and MOG-level MWCAT events among the total number of MWCAT events are 23.16% and 4.24%, respectively.
which are slightly higher than those of the LGT- (17.97%) and MOG-level (3.13%) TJCAT events among the total number of TJCAT events, respectively.

Figure 11 shows the monthly variations in the LOG- and MOG-level MWCAT events. MWCAT events occur most frequently in the spring season, and the maximum relative percentages of the LOG- and MOG-level MWCAT events among the total number of PIREPs within a given month are about 8.7% in May and 1.6% in April, respectively. This result is consistent with the relatively high percentages of turbulence frequencies over the lee side of the Taebaek mountains during the spring season, as shown in Figs. 6 and 7. The highest frequency of downslope windstorms over the lee side of the Taebaek mountains occurs in the springtime (Kim and Chung 2006; Jang and Chun 2008), lending further support to the idea that the maximum frequency of MWCAT events in this season is likely related to mountain-wave breaking.

Another noticeable result in Fig. 11 is that relatively higher frequencies appear during the summer season. The relative percentages of the LOG- and MOG-level MWCAT events among the total number of PIREPs in June and August rise to about 7.1% and 1.53%, respectively. According to the seasonal variations in the zonal mean wind in the Northern Hemisphere, the westerlies in the troposphere change to the easterlies in the lower stratosphere during the summer season. Because of this variation, the critical level for stationary mountain waves can be located near the tropopause during the summer. In addition, expansion of the northwestern Pacific high toward the Korean Peninsula occasionally cause easterlies and southeasterlies in the lower troposphere and midtroposphere, which can induce flow reversal in the troposphere and increase the potential for mountain-wave breaking over the mountainous regions of South Korea. Under these conditions, the relatively higher frequencies of MWCAT events can occur during the summer season.

Figure 12 is a Venn diagram of three generation mechanisms (convective system, tropopause–jet stream, and mountain waves) for the MOG-level turbulence events that occurred over South Korea from 2003 to 2008. The largest portion (41.2%; 105/255) of the total MOG-level turbulence events is associated with the tropopause/jet stream, while 19.6% (50/255) and 11% (28/255) of the total MOG-level turbulence events are associated with the mountain waves and convective systems, respectively. Of the total MOG-level CAT events, 19 cases (7.4%) occur simultaneously due to the tropopause/jet stream and mountain waves. In the present study, the RDAPS analysis data used are interpolated equally into a 1000-ft vertical interval, since the observed turbulence events are reported at every 1000 ft. Some variables used to categorize the CAT events are sensitive to the vertical resolution of the data, such as the Richardson number, which is determined by the vertical gradients of the wind and temperature. When the Richardson number is calculated using the coarse-resolution RDAPS data with a 2000-ft vertical interval, slightly fewer (46) MWCAT events are selected compared with those (50) based on the RDAPS data with a 1000-ft vertical resolution. This is somewhat expected, given that the higher vertical resolutions of the background wind and stability can provide the better estimation of the wave-breaking heights.

5. Summary and discussion

Characteristics of aviation turbulence over South Korea are investigated using the PIREP data accumulated by the KAMA from 2003 to 2008. Before investigating turbulence statistics, uncertainties in the PIREPs were
examined by evaluating the agreement of turbulence intensity reports with those observed in adjacent PIREPs within a certain range and time period. The uncertainties in the turbulence intensity and location in the current PIREPs were found to be negligible.

The frequencies of the LGT-, MOD-, and SEV-level turbulence events in the present study are higher than those in the previous statistical study by Lee and Choi (2003), which used PIREP data over South Korea from 1996 to 2000. In addition, increasing trends of the relative percentages of the LOG- and MOG-level turbulence frequencies are evident in the present study (2003–08), implying that turbulence forecasting over South Korea is becoming more important as air transportation has increased over Korea as well as over eastern Asia. The frequencies and relative percentages of the LOG- and MOG-level turbulence events are the highest during the spring season. In terms of spatial distributions, reported turbulence events occur most frequently along the dominant flight levels and routes, as expected, with relatively higher frequencies along those routes near the west coast, Jeju Island, and the Sobaek and Taebaek mountains. The turbulence frequencies over these regions vary by season, likely due to different source mechanisms.

To understand the generation mechanisms of the observed turbulence events, three potential sources (the convective system, tropopause/jet stream, and mountain waves) are investigated using lightning flash data, RDAPS analysis data, and the DEM dataset. The total aviation turbulence events are classified into convectively induced turbulence (CIT) and clear-air turbulence (CAT) events depending on the existence of lightning activity. The relative portions of the MOG-level CIT and CAT events among the total number of the MOG-level aviation turbulence events are 11% and 89%, respectively. As expected, CIT events are dominant in the summer due mainly to convective systems. The CAT events are classified as tropopause/jet stream–induced CAT (TJCAT) and mountain-wave-induced CAT (MWCAT) events. The relative portions of the MOG-level TJCAT and MWCAT events among the total number of the MOG-level turbulence events are 41.2% and 19.6%, respectively. TJCAT events are dominant in the winter and spring seasons due to the seasonal variations in the jet stream strength. Based on the differences in composite averages for the synoptic–dynamic structures between the TJCAT and other CAT events, the shear instability, inertial instability, and geostrophic adjustment associated with the strong jet stream are likely the generation mechanisms for the TJCAT events over South Korea. MWCAT events are dominant during the spring and summer seasons over the mountain regions of South Korea, and are related to breaking and a critical level of mountain waves, respectively.

This study extends the previous study by Lee and Choi (2003) that analyzed the spatial and temporal distributions of aviation turbulence recorded in PIREP data over South Korea from 1996 to 2000. In the present study, normalization of the turbulence frequencies is applied in all statistical results to take into account air-traffic changes over South Korea. In addition, possible sources of the turbulence events are examined using the available observations (e.g., lightning data), CAT diagnostics, and a mountain-wave drag parameterization.

Even though unavoidable uncertainties still remain in the PIREP data, these results of the turbulence events over South Korea can provide useful and invaluable information to pilots, dispatchers, and forecasters to help reduce unexpected damage from the turbulence encounters over South Korea. Constructing a more reliable climatology of the turbulence events over South Korea requires collecting PIREP data over longer periods of time. To understand more precisely the mechanisms of the turbulence events that occurred over South Korea, numerical modeling studies on the observed turbulence events under various conditions are required (e.g., Kim and Chun 2010). The current results based on observations in the Korean Peninsula under the synoptic environments over eastern Asia and local weather conditions associated with terrain and convective systems can provide useful information on research into aviation turbulence in general over other areas of the world.

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