J1.8 CLIMATOLOGIES OF UPPER-LEVEL TURBULENCE OVER THE CONTINENTAL U.S. AND OCEANS

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1. Introduction

The seasonal and geographical distribution of turbulence in the upper atmosphere is known only vaguely to some research meteorologists and airline forecasters and dispatchers. A climatology of upper-level turbulence would help in achieving a better understanding of turbulence mechanisms in the upper atmosphere. Although routine quantitative turbulence measurements are not available to produce such a climatology, qualitative turbulence information is available from daily reports provided by pilots (PIREPs) of commercial, military, and general aviation aircraft. NCAR/RAP has been archiving these reports since February 1992, giving almost 10 years of continuous information about locations and intensities of turbulence encounters. As of January 2002 this database includes over 2M turbulence PIREPs (nearly 800,000 of which are above 20,000 ft). This has been used as a proxy for quantitative turbulence information to derive climatologies of upper-level ($\geq$20,000 ft MSL) turbulence. Section 2 describes the nature of turbulence PIREPs and the data base used, as well as methods to assess the consistency of PIREPs and to remove air traffic biases. Section 3 describes results obtained to date, and these are summarized and interpreted to the extent possible in Section 4.

2. PIREPs

A fairly complete review of PIREP reporting and dissemination practices as well as errors associated with their use is given in Schwartz (1996). Briefly, voice PIREPs are received and recorded into NWS automated systems resident at either the Flight Service Stations (FSSs) or Air Route Traffic Control Centers (ARTCCs). NCAR routinely receives and archives PIREPs disseminated through the National Weather Service's (NWS) Family of Services (FOS) communication gateway. The "raw" textual PIREPs are archived, but for routine use are "decoded" to allow rapid retrieval and analysis of the most important parameters within the turbulence encounter report, (date and time, latitude and longitude, altitude, and severity). The severity of the encounter is translated from a verbal description (e.g. smooth, moderate, severe, or extreme) to an integer scale 0-8, where 0 is smooth or null, and 8 is extreme. This is of course somewhat subjective based on the pilot's knowledge and experience, but for heavier commercial aircraft that dominate upper-level traffic this subjectivity does not seem to cause appreciable difficulties in interpretation of the data. Some data checking was performed prior to use; for example, obvious duplicates were removed, and reports with one or more invalid parameters were discarded. These duplicate and bad data records were a very small percentage of the total (<1%).

A histogram of the relative number of PIREPs in each of the major turbulence intensity categories (null, light, moderate, severe) is provided in Figure 1. Due to reporting practices and air traffic biases this distribution cannot be taken as representative for upper-level turbulence as a whole. For example, based on observations using instrumented aircraft over the U. S. and the former U. S. S. R., Vinnichenko, et al. (1980) estimates only about 1% frequency of turbulent flight in the upper troposphere and lower stratosphere. Thus, in this data set the nulls and lights are probably underrepresented. The ratio of severe to moderate encounters may also be underrepresented due to reluctance of some pilots to report severe events.

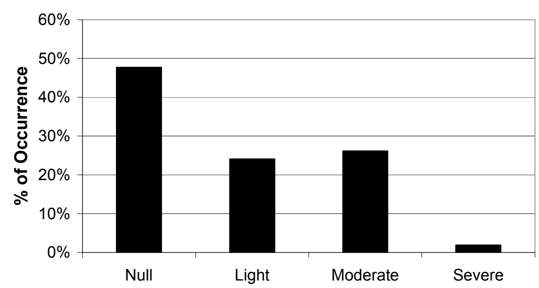

Figure 1. Distribution of PIREP intensities at altitudes $\geq$ 20,000 ft.

a. Assessment of PIREPs consistencies

A natural concern with using PIREPs is the subjective nature of the intensities reported and the imprecise time and location of the reported encounter. In an attempt to assess the impact of these uncertainties on the climatological data derived from PIREPs, we compared pairs of PIREP intensities in the same immediate neighborhood (time and space). For reasonable time and space windows, the reported PIREPs intensities should be consistent. The results will of course depend on the exact values of the time and space windows: if these are too small, not enough comparisons can be made to be statistically meaningful;

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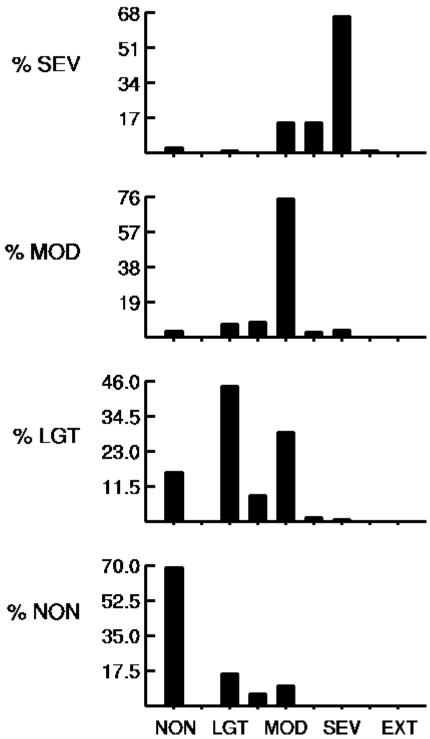

Figure 2. Percent agreement of PIREP-PIREP comparisons of reported intensities for all PIREPs pairs within 1 hr, 1000 ft, and 50 km of each other, for PIREPs at flight levels $\geq$ 20,000 ft.

if they are too large, they may be invalid because of natural turbulence variabilities. The values used here (within 1 hr in time, within 1000 ft vertically, and within 50 km horizontally) are consistent with upper-level CAT encounter data given in Vinnichenko, et al. (1980), which cites median persistence of turbulence patches to be about 6 hrs, median horizontal dimensions of 60-80km, and median thicknesses of 500-1000 m. Results of these comparisons are shown in Figure 2. Each bar in each set represents the PIREP intensity as compared to a neighboring PIREP intensity depicted as a percentage agreement in each of the major intensity categories (Null-NON, light–LGT, moderate–MOD, severe-SEV, and extreme-EXT). Overall, the agreement between neighboring PIREPs is very good, and especially so for nulls and MODs. In fact, roughly 66% of the PIREPs agree <u>exactly</u> in intensity, and if only moderate or greater (MOG) events are compared, 74% agree. Thus we are satisfied that PIREP information is consistent enough for use in deriving climatological statistics of aircraft scale turbulence.

b. Removal of air traffic biases

Any development of statistics based on turbulence PIREPs will be hampered by the strong biases associated with jet route traffic patterns and regional reporting inconsistencies. In an attempt to remove these biases, areal distributions of the ratios of MOG/TOTAL PIREPs, where MOG includes all moderate or greater intensity PIREPs and TOTAL includes turbulence reports of all intensities, were used. That this ratio does in fact remove most of the air traffic pattern and regional reporting biases can be demonstrated by comparing to available air traffic data from the Air Route Traffic Control Center (ARTCC) data bases. Air traffic overflight densities (overflights/ARTCC area) were obtained for each ARTCC region for the years 1999- 2000 and are compared in Figure 3 to PIREP densities in the same region. In this figure a set of 3 bar graphs for each ARTCC region is shown along the x-axis. Within each set, the length of the open bar is proportional to the ARTCC overflight density, the solid bar is proportional to the PIREP density, and the crosshatched bar is proportional to the ratio of MOG/TOTAL PIREPs reported above FL200. Note that the overflight densities and PIREP densities are highly variable with ARTCC region, but the MOG/TOTAL PIREP ratio is much more consistent. Hence, although the use of this ratio does not perfectly alleviate the air traffic pattern bias, it does reduce it considerably. The only disadvantage of this metric is that the ratio may become artificially large in areas where there is little traffic and therefore the total number of PIREPs is small. The cure for this is to consider only regions where the count is larger than some threshold. In the results to be presented here, statistics are not computed in regions where the total PIREP count is less than 20 within a (40 km)^2 . Except as noted, all results presented in the next section will focus on data derived from PIREPs taken only at FL $\geq$200.

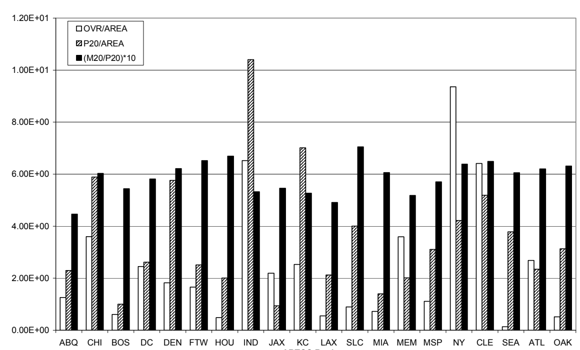

Figure 3. ARTCC overflight density (open bars), PIREP density (hatched bars) and MOG/TOTAL percentage (solid bars) in each ARTCC region.

3. Results

The yearly average vertical distribution of TOTAL, MOG and MOG/TOTAL PIREPs is shown in Figure 4. Although there is a maximum in the total PIREPs above about 25,000 ft, the MOG distribution is fairly flat, and the MOG/TOTAL distribution does show the expected

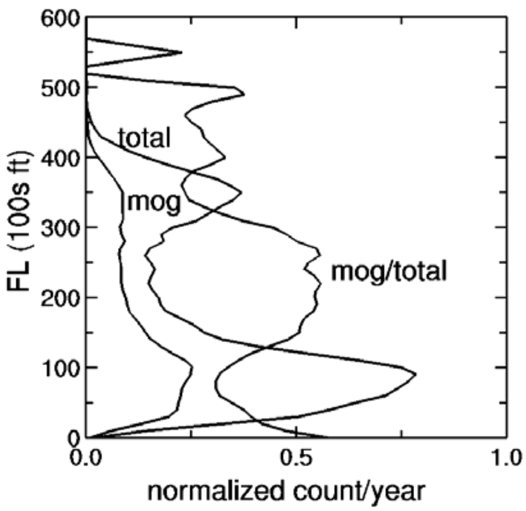

Figure 4. Altitude distribution of TOTAL, MOGs, and MOG/TOTAL PIREPs.

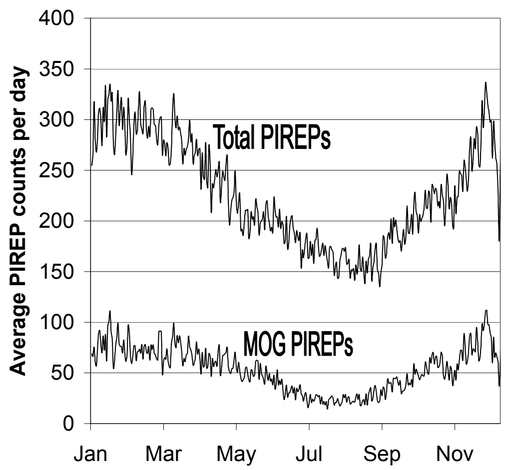

Figure 5. Average counts per day of TOTAL PIREPs and MOG PIREPs.

increase at upper levels, above about 15,000 ft. Figure 5 shows the seasonal distribution of TOTAL and MOG PIREPs. The curves are the 10-year average TOTAL and MOG counts for each day of the year (1-365). Both the TOTAL and MOGs show a maximum in the winter, especially in December, and a minimum in July-August.

Contours of TOTAL and MOG/TOTAL PIREPs over the continental U. S. above 20,000 ft for all months are shown in Figure 6a,b, respectively. Gray scaled contours of topography are also shown for reference. In Fig 6a,b three large maxima are apparent; one over the Ohio Valley and two areas that line up with the central Rocky Mountain regions and the Wasatch Mountain regions. The maximum over the Ohio Valley is in part due to aggressive solicitation of PIREPs by Indianapolis Center controllers (cf. Fig 3), and in part to enhanced thunderstorm activity in that region in the spring and summer months. But this solicitation bias is largely removed in the MOG/TOTAL plot in Fig 6b. In

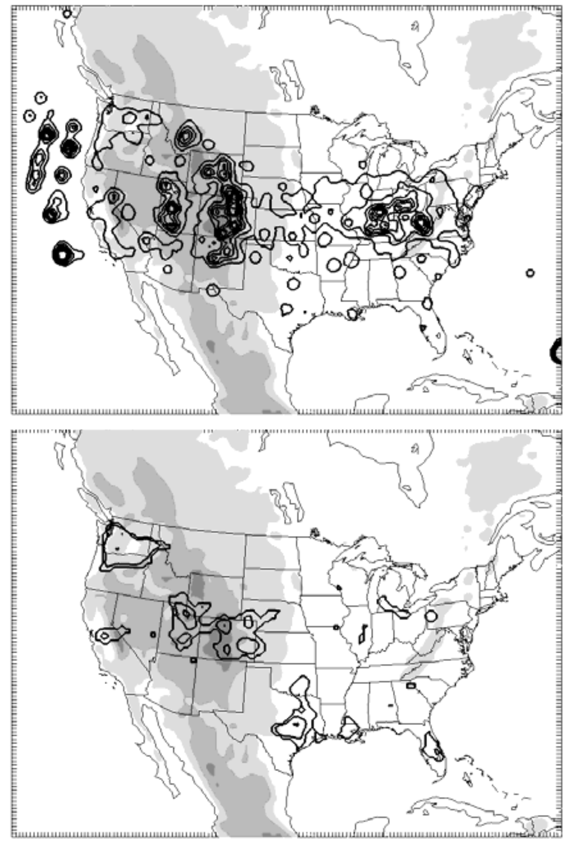

Figure 6. (a) Top, contours of PIREPs above 20,000 ft for all months. Contour interval=100. (b) Bottom, contours of MOG/TOTAL $\geq$ 0.4. Contour interval=0.1.

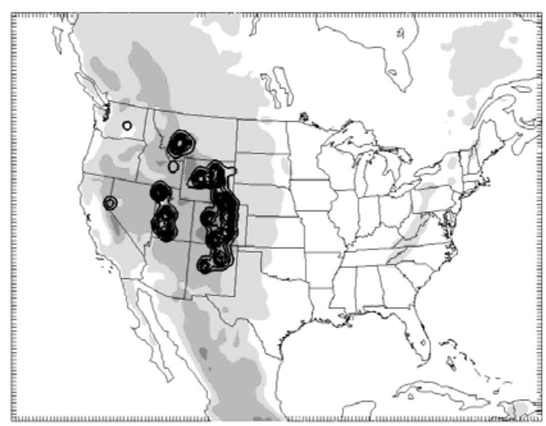

Figure 7. Contours of PIREPs indicated as being associated with mountain waves above 20,000 ft for all months. Contour interval=50.

Fig 6b the contours enclose areas where MOG/TOTAL ratio is at least 0.40 and the PIREPs count in a 40 km^2 area is at least 20. It can be seen that many of these areas coincide with mountainous regions - the Colorado Rockies, the Wasatch range in northern Utah, the

Sierra Nevada range on the eastern California border, and in the lee of the Cascades in northern Oregon and Washington. Thus these maxima are likely associated with mountain wave and consequent turbulence production. In fact, some 77,000 PIREPs even specifically mention mountain waves as being the source. Recording and contouring these derives Fig. 7. In most aspects these regions coincide with the regions in Fig 6c, although not entirely. The maxima shown in Fig. 6b in southeastern regions, including parts of Texas, Louisiana, and Florida, are probably associated with convective activity since these regions correspond to regions of enhanced thunderstorm activity (e.g., Huffines and Orville, 1999, Figs. 1,2).

Assuming the MOG/TOTAL PIREP ratio also reduces the air traffic bias over oceanic regions, we have computed distributions over oceanic regions as well, based on approximately 9 years of data and approximately 1M turbulence reports. The results are shown in Figures 8a,b, again corresponding to contours of TOTAL and MOG/TOTAL PIREPs respectively. In these figures, the traffic patterns are also misleading; whereas maximum occurrences of TOTAL (and MOG) PIREPs are over the North Pacific and North Atlantic, only the North Atlantic has appreciable ratios of MOG/TOTAL PIREPs.

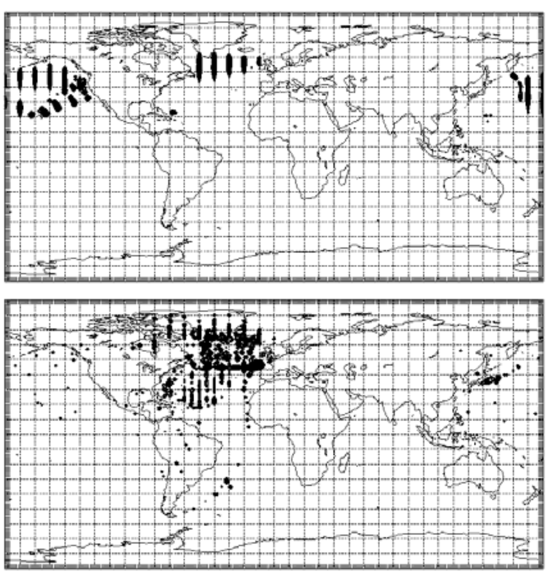

Figure 8. (a) Top, contours of TOTAL PIREPs received above 20,000 ft for all months. Contour interval=500. (b) Bottom, contours of MOG/TOTAL $\geq$ 0.1.

4. Summary and conclusions

This study has used PIREPs to construct climatologies of aircraft scale turbulence (~100s m) at upper levels ($\geq$20,000 ft) over the continental U. S. and oceans. Although PIREPs are know to contain errors in position, timing, and intensity, comparisons between PIREPs close together in space and time showed consistently reported intensities. Further, although spatial errors are important for deriving climatologies, timing errors are of no concern, and by looking at only MOG pireps, some uncertainty in intensities is reduced. By using the MOG/TOTAL ratio to derive climatologies, as opposed to the MOGs or TOTALs separately, we were able to remove most of the traffic bias.

The temporal distribution of the PIREPs showed many more PIREPs of all intensities in the winter, with the overall the maximum in December.

Based on contour plots of the MOG/TOTAL ratio over the continental U. S., the largest percentage of MOG PIREPs occurred over the mountainous areas of the western U. S., and were very likely associated with turbulence in mountain gravity waves. Secondary maxima in this quantity occur over parts of Texas, Louisiana and Florida, and since these locations agree well with lightning flash densities, it was conjectured that these were probably related to thunderstorms.

Over the oceans, again based on contour plots of MOG/TOTAL ratios, maxima occur over the North Atlantic, including the southern tip of Greenland, and although more PIREPs occur over the North Pacific, the percentage of MOGs in those reports was actually small, less than 20%.

This technique has been expanded to derive climatologies at lower altitudes, and to derive seasonal distributions as well, but those results will be presented elsewhere. Finally, to better understand the causes of the turbulence observed in the Southeast, we are comparing lightning flash data to PIREPs to see if areas of correspondence agree with the areas shown in the MOG/TOTAL contour plots.

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