P4.14 CLIMATOLOGICAL STUDY OF AIRCRAFT TURBULENCE VERSUS CLOUD COVER BASED ON 3 YEARS WORTH OF DATA

Jamie K.Wolff* and Robert Sharman
Research Applications Program
National Center for Atmospheric Research
Boulder, CO 80307

ABSTRACT

The relationship of positive and negative (smooth) turbulence pilot reports (PIREPs) to cloud top height and base is examined in an attempt to determine the relative frequency of turbulence in-cloud, above cloud, below cloud, and in clear air. Since PIREPs usually do not include information on whether the turbulence was encountered in or out of cloud, two different methods for determining where a PIREP was in relation to clouds are compared and presented. Three complete years of PIREPs, sounding data, and Current Icing Potential (CIP, formally known as the Integrated Icing Diagnosis Algorithm, IIDA) are included in the evaluation. The data is broken down into three altitude bands: low (surface - 10,000 ft), mid (10,000 ft - 20,000 ft), and high (20,000 ft and above), and comparisons are done seasonally as well as annually. Examination of the entire volume of air space shows that smooth turbulence reports are in clear air 20% of the time and in-cloud 40% of the time, on average. These values decrease to 15% and 25%, respectively, for moderate or greater (MOG) turbulence reports. The vertical distributions show that the majority of in-cloud turbulence occurs at mid-levels while clear air turbulence is more frequent at upper- and low-levels. In addition, the average volume of clouds versus clear air present over the CONUS is also estimated to make the comparisons more meaningful. Using two different methods it is estimated that the annually averaged cloud volume percentage is about 14% to 18%.

1. INTRODUCTION

One nagging question concerning atmospheric turbulence is the relative volume, duration, and intensities of turbulence within clouds (stratiform and cumuliform) compared to clear air. This has important consequences for such fundamental issues as the determination of global dissipation rates for use in numerical weather prediction (NWP) and general circulation (GCM) or climate models and the parameterization of turbulence in such models. It also has practical importance for the verification of turbulence forecasting systems, most of which assume the source of turbulence is related to clear-air synoptic scale features such as upper-level fronts and jet streams.

Unfortunately, in-cloud versus out-of-cloud turbulence statistics cannot be obtained directly since such observations do not currently exist. Verbal reports of turbulence encounters by aircraft (PIREPs) are a source of information about turbulence location and intensities, however, information about whether encounters were in-cloud or out-of-cloud is usually not provided. In this paper a method is proposed and preliminary results offered which uses PIREPs in conjunction with satellite derived cloud top and observations of cloud base to determine the frequency of occurrence of both in-cloud and out-of-cloud turbulence encounters. Both positive and negative (i.e., null or smooth) PIREPs are compared to cloud top and cloud base heights and classified into regions of above cloud, below cloud, in-cloud, or clear air. In this study, the cloud top and cloud base heights are determined from output of the Current Icing Potential (CIP, formerly known as the Integrated Icing Diagnosis Algorithm, IIDA; McDonough and Bernstein, 1999).

Although the derived statistics may have NWP or GCM implications, the major motivation for this work is to determine the effect of clouds on the performance of turbulence forecasting systems in general and the Graphical Turbulence Guidance (GTG, formerly known as the Integrated Turbulence Forecasting Algorithm, ITFA) in particular.

GTG was developed at the National Center for Atmospheric Research (NCAR) and is described elsewhere (Sharman et al., 2000), but is intended to predict upper-level, clear-air turbulence (CAT) using PIREPs for verification. The results from this study will help to determine

---

*Corresponding author email: jwolff@rap.ucar.edu

whether the GTG performance is negatively affected by the use of PIREPs that are actually in cloud or near cloud rather than clear air only.

2. DATA AND ANALYSIS PROCEDURES

2.1 PIREPs

For many purposes PIREPs are the only routine observations of atmospheric turbulence available. PIREPs provide latitude, longitude, altitude, time and intensity (reported on a 5 point scale: null, light, moderate, severe, or extreme) of a turbulence encounter, however, they are known to have location and timing uncertainties (e.g., Schwartz 1996), and the intensity reported is a subjective assessment by the pilot. In the future more precise measurements should become available (Cornman et al. 1995) but for now these uncertainties must by factored into the results. The database used for this study is a collection of PIREPs gathered for a 36-month period from Nov 2000-Nov 2003, which corresponds to the beginning of the CIP cloud top and cloud base dataset.

Besides location and timing uncertainties associated with PIREPs, another uncertainty is the reported altitude. The error occurs during the conversion of standard atmospheric pressure used by pilots to the actual pressure, which may be non-standard, resulting in an incorrect altitude of the report. After calculating a few cases it became apparent that errors in this conversion can account for an error in the reported altitude of more than 2000 ft. This makes it difficult to pinpoint the true aircraft altitude relative to cloud top and cloud base. In order to account for these uncertainties in this study, PIREPs that fall within 3000 ft. of the top of the cloud are classified as near top and PIREPs that fall within 3000 ft. of the base of the cloud are classified near base instead of in cloud or above/below cloud.

2.2 Cloud top/base Fields

The complete process by which the cloud top and cloud base heights are determined is detailed in McDonough and Bernstein (1999). To briefly summarize, the cloud top height product is created by first binning all GOES-8 IR pixels within each RUC NWP model (Benjamin et al. 2004) interpolated to 40 km horizontal resolution. If the pixels in the bin are more than 40% cloudy, then the coldest IR measured cloud top temperature is compared to the RUC temperature sounding and the cloud top height is determined by interpolating the temperature in the column. The cloud base is determined by identifying the height of the lowest cloud base from nearby surface observations, or METARs, and mapping them to the RUC gridpoints. Both the cloud top and cloud base heights are determined hourly and are based on observations taken near the top of the hour.

A few shortcomings are apparent in this process. Clouds can exist in multiple layers. This is very difficult to detect with an automated system and may lead to over-estimates of cloud depth. Another problem is that if there is an inversion in the column at or above the highest cloud tops, then the cloud top height may be overestimated. An inversion can result in the cloud top height being placed up to 2000 ft. higher than the actual cloud top height. This usually occurs at lower levels and near the tropopause. However, PIREPs that fall within 3000 ft. of the cloud top are already being classified as unknown which helps compensate for this possible error. Also, cloud identification can be particularly difficult within the solar terminator causing some clouds to be missed.

3. RESULTS

Over the three-year study period, nearly 650,000 PIREPs were compared to cloud cover derived from CIP when both data sets were available. The time window of comparisons is limited to PIREPs occurring within one half hour of the CIP valid time. The reported turbulence intensities are binned into two categories: nulls and moderate or greater (MOG) reports. Reports of light are discarded since they tend to be ambiguous. These two categories are counted for all altitudes and the distributions examined by month, season and year. The seasons are broken into “summer” (April – September) and “winter” (October – March).

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

- Above: PIREP > 3,000 ft. above the CIP cloud top
- Below: PIREP > 3,000 ft. below the cloud base
- In cloud: PIREP from 3,000 ft. above the cloud base to 3,000 ft. below the cloud top
- Near top: within 3,000 ft. of the cloud top
- Near base: within 3,000 ft. of the cloud

base
- Clear air: No clouds apparent in the entire depth of the atmosphere at the latitude, longitude, and time of the PIREP

3.1 PIREP/Cloud Comparison for all altitudes

Figure 1 shows the percentage of reported smooth (null) PIREPs relative to total PIREPs of all intensities (ignoring light intensity reports which tends to be ambiguous) within each cloud category. Figure 2 shows the percentage of reported MOG PIREPs relative to total PIREPs within each cloud category. For all altitudes, the percentage of null PIREPs that are in any of the cloud categories are 55% - 65% while the MOG percentages are 35% - 45%. Overall, there is little substantial difference in either nulls or MOG percentages across the cloud categories and the percentage of nulls to MOGs on the average across all categories is about 60% to 40%. These ratios are consistent with those found by Sharman et al. (2002) in a study of clear-air turbulence climatologies, and simply reflects the reporting practices of the pilots. It does not correctly reflect the actual distribution of turbulence intensities in the free atmosphere, where the air is predominantly nonturbulent at aircraft scales (Frehlich and Sharman 2004).

Figure 3 shows the percentage of nulls relative to TOTAL PIREPs of all intensities in all cloud categories and Figure 4 shows the percentage of MOGs relative to TOTAL PIREPs in all cloud categories. Note that the majority of PIREPs, both null and MOG, are in-cloud for all altitudes. In addition, there are more nulls than MOGs within cloud. In both cases the percentages of PIREPs that are definitely above or below cloud is a small portion of the total, but when taken with those near the cloud top or base they could become more substantial. Without a more careful analysis of the PIREP altitude it is not possible to combine these at this time. Interestingly, the percentage of in-cloud PIREPs is not very seasonally dependent.

The categories of above cloud, below cloud and clear air may technically all be considered as clear air. Combining these categories, and discarding the near cloud top and near cloud base categories results in Figures 5 and 6. Nulls are more frequent than MOGs for all seasons, both in-cloud and in clear air. Also, for all seasons, the percentage of PIREPs of all intensities is greater in-cloud than in clear air, i.e., there are more reports, both of null and MOG, in-cloud than in clear air.

Figures 7 and 8 show the percentage of PIREPs reported in different cloud depths for all altitudes, derived from cloud top and cloud base data, for both null and MOG reports during the summer and winter seasons. For both seasons, as the cloud depth increases, the percentage of null reports decreases and the percentage of MOG reports increases. This implies turbulence tends to be higher in deeper clouds, as is intuitively expected.

3.2 PIREP/Cloud Comparison above 20,000 ft.

The current version of GTG forecasts CAT only, with terrain induced and convectively induced turbulence planned for future updates of the algorithm. The GTG CAT forecasting algorithm includes a number of turbulence diagnostics, each scored and weighted depending on evaluations against PIREPs, all of which are assumed to be in clear air. Thus it is of some interest to determine the proportion of PIREPs above 20,000 ft that are actually in cloud. The comparison of the percentage of reported null PIREPs relative to total PIREPs of all intensities, again ignoring the light reports, within each cloud category for PIREPs above 20,000 ft. is shown in Figure 9. This comparison differs from Figure 1 for all altitudes in a few ways. All of the categories have a lower percentage than the first comparison except for the clear air, which is about the same. This means that for the comparison of MOG PIREPs relative to total PIREPs within each cloud category (Fig. 10) all of the categories have a higher percentage than the first comparison, again, with the exception of the clear air category. It also differs in the fact that the distribution is not uniform between the categories as it was for all altitudes.

The percentage of nulls and MOGs relative to TOTAL PIREPS of all intensities and in all cloud categories is again examined in Figures 11 and 12 for PIREPs above 20,000 ft. Unlike the distributions for all altitudes, the majority of PIREPs above 20,000 ft., both null and MOG, are in clear air. There are slightly more null reports than MOG reports in clear air as well. However, there is still a very low seasonal dependence in this study.

When looking at the combination of above, below and clear into one category, Figs. 13 and 14 are the result. There is a large difference between the clear air and in-cloud percentages for both the null and MOG reports. Clear air accounts for about 40% of both the null and

MOG PIREPs with null reports in-cloud accounting for only 5% and MOG reports in-cloud 15%. This suggests that clear-air turbulence encounters are more prevalent at upper levels than at mid levels.

3.3 Cloud Volume Percentage

The percentages of in-cloud reports versus out-of-cloud reports are likely to be an underestimate when one considers the fact that clear air makes up a much larger percentage of the total volume of air over the continental United States than clouds on the average. Two measures of that percentage were computed and compared. The first was calculated using the CIP cloud base/top fields, the same source for the cloud information discussed above, from the years 2000 through 2002. The cloud top information was cut off at 45,000 ft because the RUC does not have much data above this level. The percentage of cloud volume by month computed from the CIP output is shown in Figure 15. The yearly average of cloud volume percentage was about 18%, and ranged from a low of about 15% in September to a high of about 21% in February. This is consistent with the notion of the presence of long-lived wide-spread stratiform clouds often seen in the winter versus the fewer, smaller clouds common in the summer.

The second method used to compute the cloud volume percentage was to look at soundings archived between 1997 and 2001 at 72 sites across the continental United Stages. Each sounding was read in and, again, cut off at 45,000 ft. to match the previous CIP method. The average percentage at all the sites is a measure of the average cloud depth. Assuming this representative of the entire continental U.S., this percentage may approximate the cloud volume as well. This method is sensitive to the relative humidity threshold chosen to identify regions of clouds. Three computations were made with relative humidity thresholds set at 84%, 87%, and 90%. Figure 16 shows the results of cloud volume percentage for each RH threshold. The amount of clouds ranged from 14% of the total volume with the RH threshold set at 90% up to 18% with the RH threshold set at 84%.

The results from the sounding method show a slightly lower cloud volume percentage then the CIP method. This may be due to the fact that the sounding method can better recognize cloud layers and so it does not misidentify areas of clear air in between two cloud layers as one large, continuous cloud layer like the CIP method would. Another reason may be due to the fact that the CIP method is model driven while the sounding method is observationally driven. In spite of this, the percentages are very close and an average cloud volume percentage of about 17% is a good approximation.

3.4 Vertical Distributions

It is also interesting to examine the vertical distribution of PIREPs in both clear air and cloud. The clear air distribution (Fig. 17), exhibits two maxima, one at low levels and another at upper levels. This is seen in the actual number of PIREPs as well as in the MOG/Total ratio, which gives a better sense of turbulence frequency. The lower maximum is probably to convective boundary layer turbulence and perhaps to convective storm outflow boundary layer turbulence while the upper maximum is more likely due to jet stream shears and upper-level frontal turbulence. The in-cloud distribution (Fig. 18) shows a maximum in the number of PIREP counts of null and MOG at low levels, but the MOG/Total ratio has a maximum at mid and upper levels, implying more turbulence encounters associated with deep clouds. Figure 19 shows the fraction of MOG PIREPs in-cloud and in clear air on the same graph. In clear air, turbulence is most frequent at upper and low levels while the mid-level turbulence is more often in-cloud.

3.5 Horizontal Distributions

Finally, the horizontal distribution of the PIREP and cloud climatology was examined. The distributions were computed from in-cloud versus out-of-cloud data for over the 3 year study for all altitudes gridded on the RUC domain. At least 20 PIREPs per gridpoint over the 3 year study period was required for the MOG/Total ratio to be calculated and plotted. In Figure 20a the horizontal distribution for all altitudes for PIREPs in clear air is shown for the entire data set. The peak over the Colorado Rockies in the MOG/Total ratios is obvious. When this is broken down by season there is a larger area with higher peaks during the winter season (Fig. 20b) versus the summer season (Fig. 20c). This is consistent with the increased incident of CAT during the winter months.

The horizontal distribution for all altitudes of in-cloud PIREPs with the same filter as described above applied to the MOG/Total ratio is shown in Fig. 21. Here the distribution is more regional, i.e. not wide spread (Fig. 21a). The main areas are the Ohio Valley, Florida coast, southeast Texas, Colorado Rockies and the west coast. Breaking this down by season it is seen that most of the in-cloud turbulence is again occurring in the winter (Fig. 21b). This may be due to convection in the southern portions and possibly stronger winter storms in the Ohio Valley.

4. SUMMARY

Based on these results and of those in Sharman et al. (2002), the distribution of PIREP intensities, when looking at all altitudes, is roughly 60% null and 40% MOG, in both clear air and in-cloud; there is no difference in the ratio of nulls to MOGs whether in-cloud or out-of-cloud. Also for all altitudes, the percentages of both null and MOG reports are always greater in-cloud than out-of-cloud, and those percentages do not change much with season. When concentrating on just the in-cloud reports the percentage of MOG PIREPs increases with increasing cloud depth.

When the PIREP altitude are restricted to 20,000 ft. and above the distribution of PIREP intensities is still about 60% null and 40% MOG for clear air, but is about 25% null and 75% MOG for in-cloud. However, the percentage of total null and MOG reports in clear air is much greater than in-cloud. It is possible that since commercial aircraft, which make up a great majority of the PIREPs, are able to get above clouds this may be skewing the results to give more clear air reports.

It was also shown that the vertical distribution of normalized PIREPs indicates clear-air turbulence sources are dominant at low levels and upper levels, while in-cloud encounters seem to dominate the mid-level reports.

However, there are several factors which may affect these results and these have to be assessed before firm conclusions can be derived. For example, if multiple cloud layers exist, some PIREPs currently being classified as “in-cloud” could fall into the “clear-air” category. However, in the summer these effects should be small, and the fact that the data are similar in summer and winter suggests that the effect may always be small, however, this needs further investigation.

In any event, the percentages of in-cloud reports versus out-of-cloud reports is likely to be an underestimate when one considers the fact that the percentage of volume of clear air at any given time over the continental United States is much greater than the percentage of volume of clouds. The percentage of cloud volume from the two different methods presented here averaged about 17%.

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

REFERENCES

Benjamin, S.G., G.A. Grell, J.M. Brown, T.G. Smirnova, and R. Bleck, 2004: Mesoscale weather prediction with the RUC hybrid isentropic-terrain-following coordinate model. *Mon. Wea. Rev.*, **132,** 473-494.

Cornman, L. B., C. S. Morse, and G. Cunning, 1995: Real-time estimation of atmospheric turbulence severity from in-situ aircraft measurements. *J. Aircraft*, **32**, 171-177.

Frehlich, R. and R. Sharman, 2004: Estimates of turbulence from numerical weather prediction model output with applications to turbulence diagnosis and data assimilation. *Mon. Wea. Rev.*, in press.

McDonough, F., B.C. Bernstein 1999: Combining satellite, radar, and surface observations with model data to create a better aircraft icing diagnosis. *8th Conf. on Aviation, Range and Aerospace Meteorology*, AMS, Dallas, TX 467-471.

Sharman, R., G. Wiener, B. Brown 2000: Description and verification of the NCAR Integrated Turbulence Forecasting Algorithm (ITFA). 38th Aerospace Sciences Meeting and Exhibit, Reno, NV AIAA 00-0493.

Sharman, R., J.K. Wolff, T. Fowler, B. Brown 2002: Climatologies of upper level turbulence over the continental U. S. and Oceans. *10th Conf on Aviation, Range, and Aerospace Meteorology*, AMS, Portland, OR.

Schwartz, B., 1996: The quantitative use of PIREPs in developing aviation weather guidance products. *Wea. Forecasting*, **11**, 372-384.

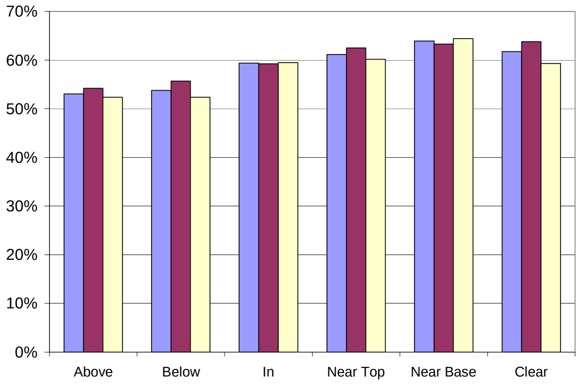

*Figure 1. **Percentage of null turbulence in each cloud category: blue, whole year; pink, summer season; yellow, winter season.***

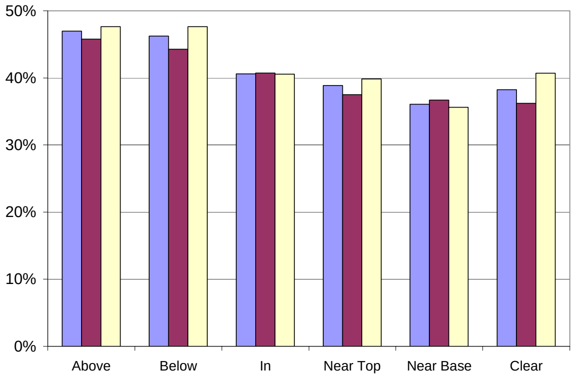

*Figure 2. **Same as Figure 1 but for MOG turbulence.***

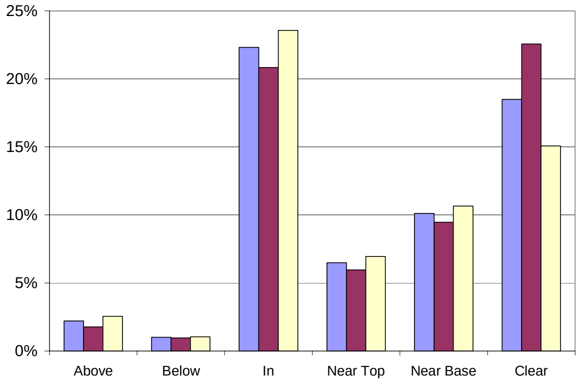

*Figure 3**. Percentage of total null turbulence for all cloud categories: blue, whole year; pink, summer season; yellow, winter season**.*

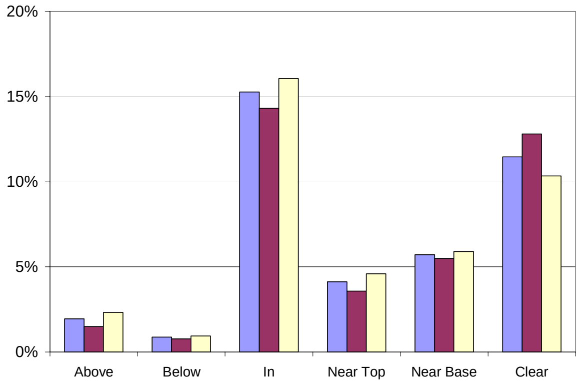

*Figure 4**. Same as Figure 3 but for MOG turbulence.***

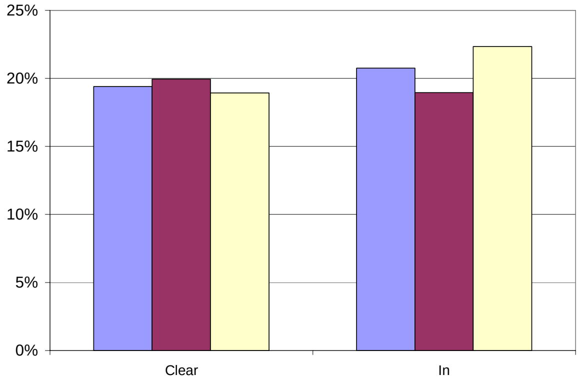

***Figure 5.** Percentage of total null turbulence for clear air and in-cloud categories: blue, whole year; pink, summer season: yellow. winter season.*

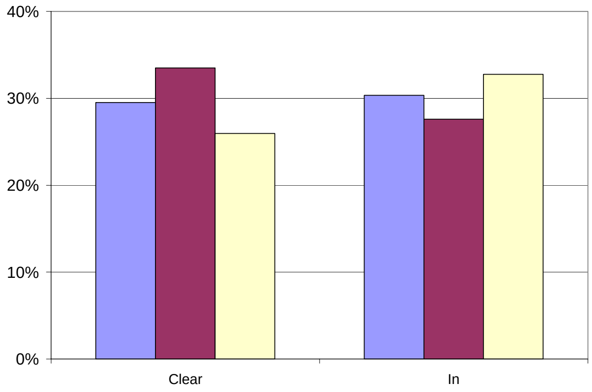

*Figure 6. **Same as figure 5 but for MOG turbulence.***

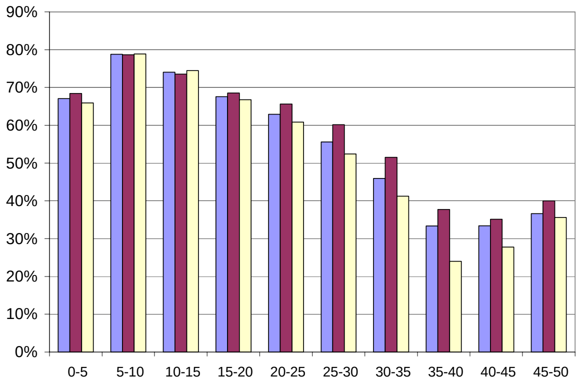

Figure 7. ***Percentage of null turbulence compared to cloud depth measured in thousands of ft.: gray, summer season; white, winter season.***

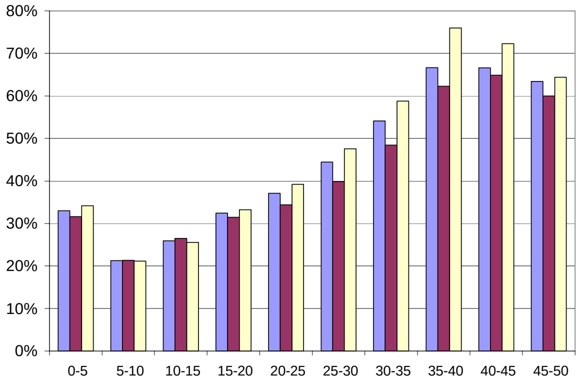

Figure 8. *Same as Figure 7 but for MOG turbulence.*

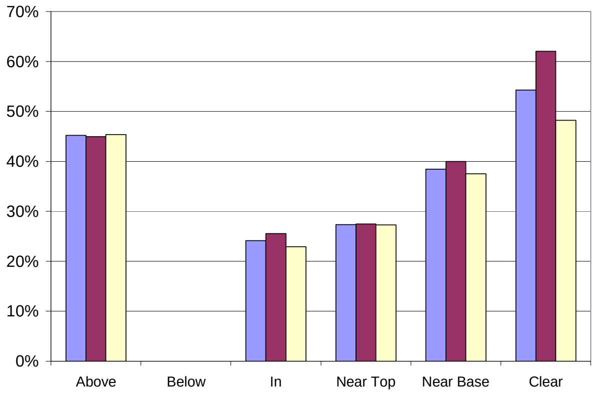

Figure 9. ***Same as Figure 1, but for above 20,000 ft.***

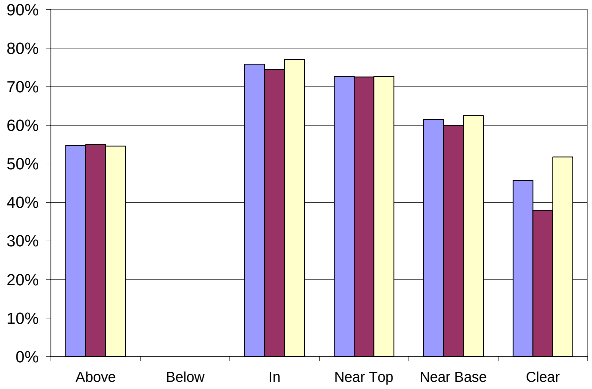

Figure 10. ***Same as Figure 2 but for above 20,000 ft.***

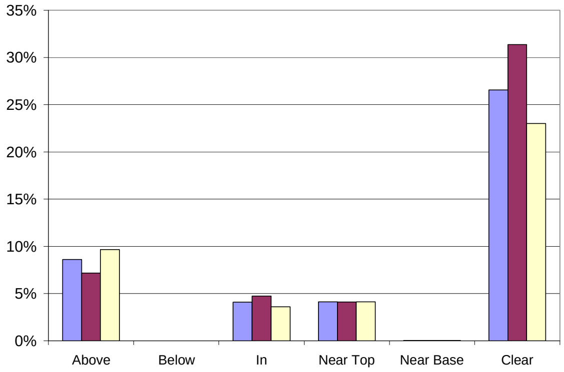

Figure 11. ***Same as Figure 3 but for above 20,000 ft.***

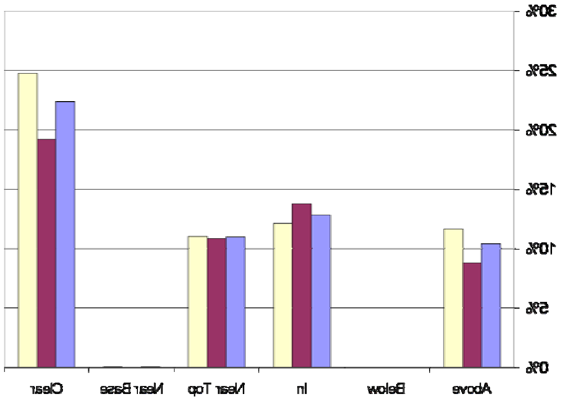

Figure 12. ***Same as Figure 4 but for above 20,000 ft.***

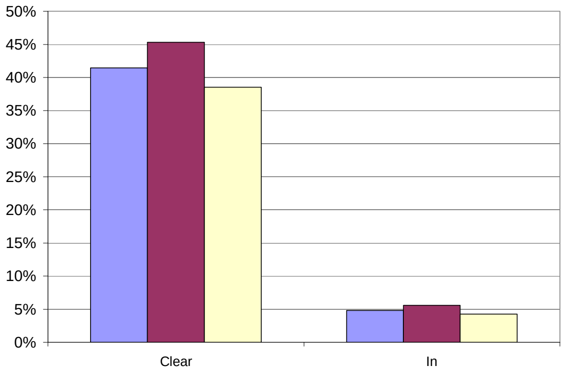

Figure 13. ***Same as Figure 5 but for above 20,000 ft.***

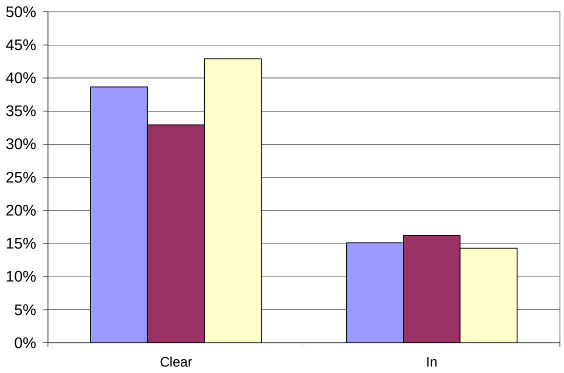

Figure 14. *Same as Figure 6 but for above 20,000 ft.*

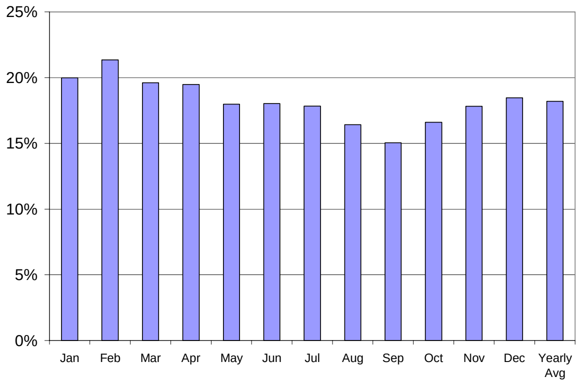

*Figure 15****. Cloud volume percentage by month and yearly average from CIP output method.***

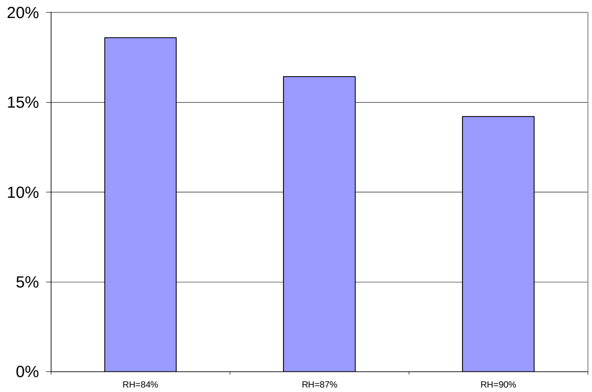

*Figure 16****. Cloud volume percentage by RH threshold from the sounding method.***

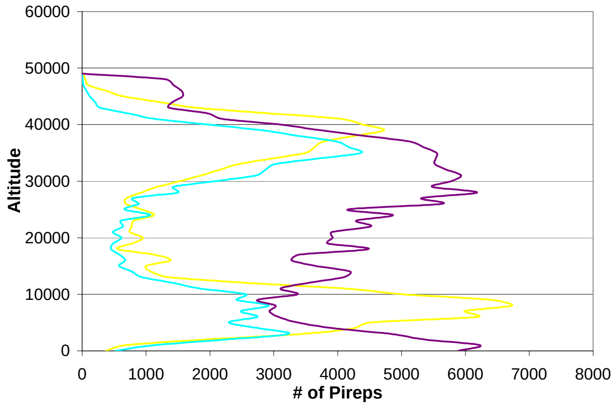

Figure 17. ***Clear air vertical distribution: yellow, Null PIREPs; blue, MOG PIREPs; purple, MOG/Total*10000.***

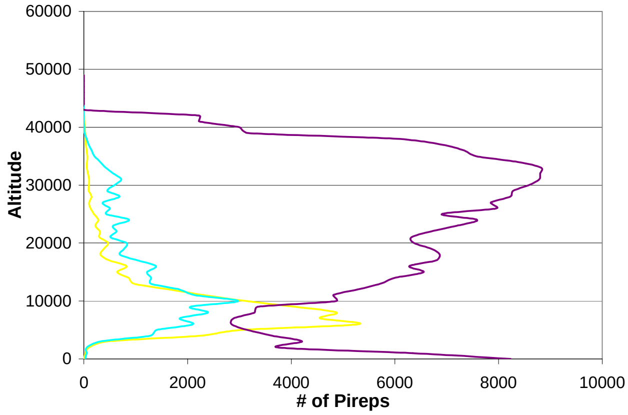

Figure 18. ***Same as Figure 17 but for in-cloud.***

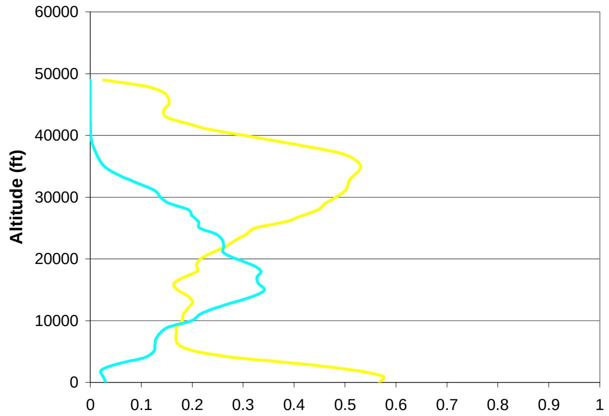

Figure 19. ***Fraction of MOG PIREPs: yellow, clear air; blue, in-cloud.***

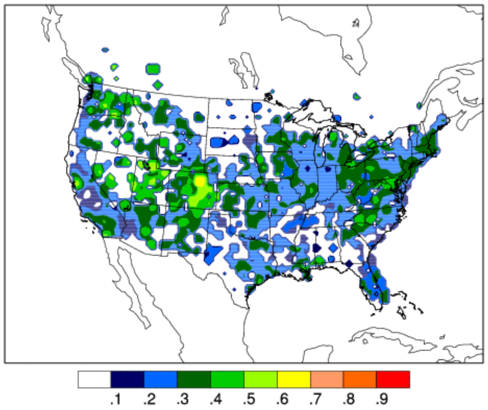

Figure 20a. ***Clear air horizontal distribution of the fraction of MOG PIREPs for the entire data set.***

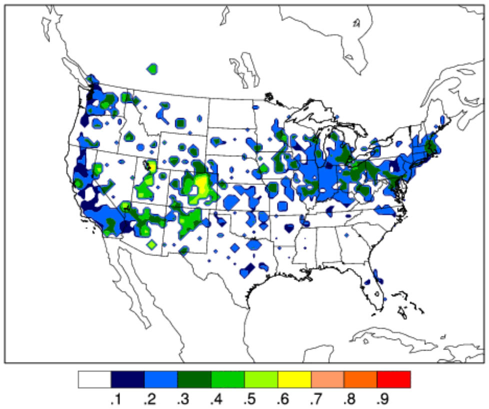

Figure 20b. ***Clear air horizontal distribution of the fraction of MOG PIREPs for summer season.***

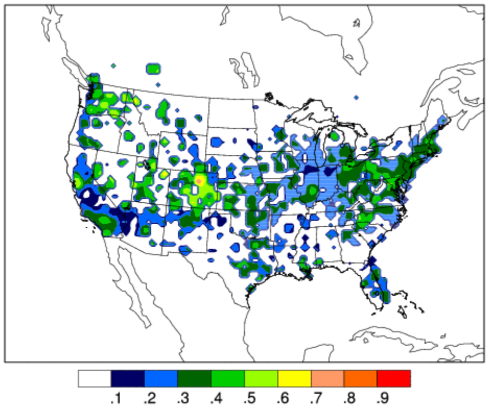

Figure 20c. ***Clear air horizontal distribution of the fraction of MOG PIREPs for winter season.***

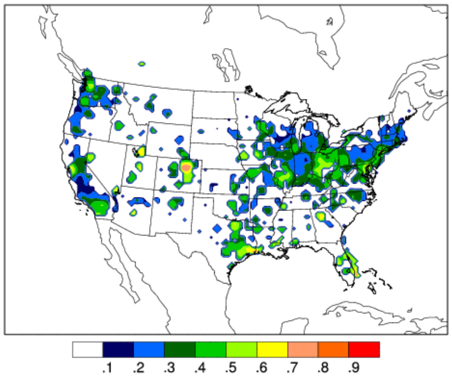

Figure 21a. ***In-cloud horizontal distribution of the fraction of MOG PIREPs for the entire data set.***

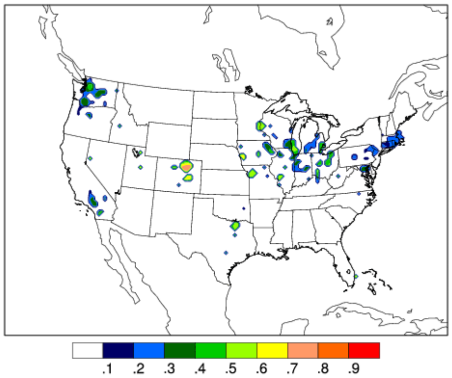

Figure 21b. ***In-cloud horizontal distribution of the fraction of MOG PIREPs for the summer season.***

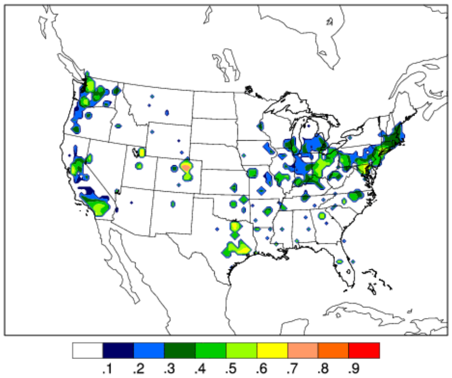

Figure 21c. ***In-cloud horizontal distribution of the fraction of MOG PIREPs for the winter season.***