1. INTRODUCTION

Winter weather hazards pose a serious threat to the aviation industry. In-flight icing and low ceilings are among the more dangerous of these hazards to aircraft. Such hazards could be avoided by taking alternate routes or by taking precautions if the cloud conditions conducive to those hazards are suspected. Cloud climatologies yield useful information by describing such cloud conditions in general around the continental U.S. for a given period of time. In past studies, cloud climatologies were compiled using satellite data (Rossow and Schiffer 1991) and surface observations (Hahn et al. 1982, 1984; Warren et al. 1986, 1988). However, these studies lacked pertinent information regarding the existence of multiple cloud layers. Satellite studies reveal no information about cloud bases or multiple cloud layers, while surface observers often have obscured views of upper cloud decks and provide no information about cloud tops.

Using a method developed in AWS (1979) and later modified in Wang and Rossow (1995), rawinsonde observations (RAOBs) may be used to estimate cloud vertical structure based on the relative humidity (RH) recorded. This RAOB data provides important information that could be used to mitigate the risk of flying in these hazardous conditions and enhance air flight safety. This study presents a climatology of wintertime cloud base heights and temperatures, number of cloud layers, and cloud base distributions over the continental U.S. for the period 1985-1990 as inferred from RAOBs. Section 2 describes the data set and analysis methods used. In section 3, the results of this analysis are presented.

2. DATA AND ANALYSIS METHODS

We used rawinsonde data collected from 58 surface observing sites collocated with RAOB launching stations for the years 1985-1990. Station dates and times reporting one-tenth or more cloud cover at 1100 or 2300 UTC (the actual time of launch) were retrieved. Only data from the months November through March were used. For each RAOB, cloud layers were identified according to the revised RAOBs analysis method.

Rawinsondes report temperature, RH with respect to water, mean sea level (MSL) height, wind speed and wind direction. These variables are reported as a function of pressure. There are several problems connected with using RAOBs as a data source. These problems are documented in Elliott and Gaffen (1991), Gaffen et al. (1991), and Schwartz and Doswell (1991).

Some of the more important problems with the data used in this study were changes in instrumentation, inconsistencies within rawinsonde observations, and problematic archival methods.

An important factor in our decision to use RAOBs only after 1965 was for sake of uniformity of sensors. A new housing for a new carbon hygrometer used in the RAOBs was introduced in 1965. However, the new housing caused the RAOB to underestimate daytime RH. This underestimation plays a minor role in our climatology because the soundings in our dataset have observation times in the early morning and evening hours. After 1972, this bias from the new housing was corrected.

The data were checked for consistency by the National Climatic Data Center (NCDC) and hydrostatic balance checks were performed on the observations. NCDC's method of calculating the data introduced an additional problem. Every instance of relative humidity below 99% was recorded as a 0°C dewpoint depression before 1973 (Schwartz and Doswell 1991). However, this practice has only a minimal effect on our study as our study emphasizes information received at high RH.

There was also a potential problem with cutoff values at RH greater than 99% (Potts 1980). However, because the revised RAOBs method is flexible with its cutoff ranges of RH in determining possible locations of clouds, this problem is obviated.

The revised RAOBs analysis method used in Wang and Rossow (1995), was used to evaluate cloudy layers by sudden jumps in RH. These jumps are positive when identifying the base of the cloud, negative when identifying the top of the cloud, and must exceed numerical RH thresholds within the sounding for the layer to be considered a cloud. Additionally, each layer must have a minimum RH of 94% and at least one level

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FIG. 1. Climatological wintertime median cloud base heights across the continental U.S. for the years 1955-1990 (m AGL).
in the layer with an RH of 87% or greater. For any level within the sounding containing temperatures less than 0°C, the RH with respect to ice is used instead of the RH with respect to water.

After using the revised RAOBs analysis method to identify cloud layers within the sounding, ten cities representing a wide-range of climates were selected for further examination on the basis of climatological variety and the number of available RAOBs.

3. RESULTS

Characteristics of clouds across the continental U.S. during 1965-1990 presented include cloud base heights and temperatures, number of cloud layers, and frequency of icing conditions given a cloud exists. An in-depth examination of cloud base heights and temperatures, and cloud layer distributions over ten cities is also shown and provide essential insights into the cloud characteristics over those cities.

3.1 Continental climatologies

Cloud base heights in themselves reveal little about the characteristics of clouds unless combined with topographic knowledge. For instance, a MSL cloud base height of 2000 m is quite different from an above ground level (AGL) height of 2000 m, especially over elevated terrain. To sort through these effects, the cloud base heights are shown in Fig. 1 as AGL heights of the lowest cloud base in the sounding. The median is used because it is a resistant statistic, relatively unaffected by outlying data points. However, because the median is resistant, information regarding extremely high cloud bases, such as possibly cirrus clouds, is effectively discarded. Because information about cirrus clouds has little relation to winter aviation hazards, this description of clouds is still useful in characterizing important synoptic-scale cloud features for aviation purposes.

Despite elevation being subtracted from the data, cloud base heights over the Rocky Mountain states greatly exceed surrounding states (Fig. 1). It is also revealed that drier climates, such as those found in southern Arizona and southern New Mexico produce cloud bases markedly higher than those found even over the Rocky Mountain region. Conversely, more moist, coastal climates have the lowest cloud bases—0 m, indicating a high occurrence of fog or precipitation in these areas. Great Plains states have more moderate heights, as does most of the upper eastern seaboard.

Fig. 2 displays the median cloud base temperatures. Some questions arise concerning the usefulness of the combination of humidity and temperature sensors in the computation of cloud temperature-related climatologies because of the -40°C cut-off enforced in RAOB reports. As to be shown in our distribution-based analysis of this parameter, -40°C lies well beyond the 95th percentile of cloud base temperatures for most sites, thus making this computation meaningful.

As expected, Fig. 2 shows cloud base temperatures are strongly related to climatological surface air temperature. Cities in coastal environments display greater cloud base temperatures than inland cities.

**FIG. 3.** Histogram of number of cloud layers (%). Frequencies, cumulative frequencies, percentages, and cumulative percentages are also reported.

**FIG. 4.** Frequency of icing conditions given a cloud is detected by RAOB (%). Icing conditions are defined as cloud tops between 0°C and -20°C.
Southern regions have warmer cloud base temperatures than northern regions.

Nearly 50% of the time only one cloud layer exists at any site across the U.S. (Fig. 3). This also implies that multiple cloud layers exist nearly 50% of the time. Up to 13 separate cloud layers existed in this dataset, although this was an extreme case and only occurred once. Ninety-nine percent of the time, there were five or fewer layers.

Since icing is the accretion of supercooled liquid water (SLW) onto aircraft in flight, we seek those temperature ranges in which cloud in which clouds favor the presence of SLW. Based on the climatology of Sand et al. (1984), a cloud top temperature range of 0 to -20°C was selected. Clouds with colder tops are assumed to be subject to glaciation, which can effectively decrease or eliminate the icing threat.

We found the frequency of icing conditions given the presence of a cloud in the RAoB analysis (Fig. 4). A very large percentage of clouds have some capacity for icing based on this definition, as shown in the figure. Because the prerequisite for a cloud to have SLW relies solely on the temperature at the top of the cloud, warmer climates reflect an increased number of clouds falling within the appropriate temperature threshold. Maxima in icing conditions occur over the southern U.S. and both coasts. The frequency of icing reaches a minimum over the Rocky Mountain region most likely because of the high elevations and cold cloud top temperatures achieved. Generally, the frequency of icing conditions given a cloud appears related to climatological surface air temperature.

An interesting variation is the frequency of clouds falling entirely within the range for SLW (Fig. 5). When computed, approximately 2/3 of all clouds in this climatology are in the appropriate temperature range. Minima in the distribution occur along the Gulf Coast region, the southeast, and southern California, opposing the results found in Fig. 4. There is a noticeable area of maximum icing frequency over eastern Montana, North Dakota, South Dakota, and Nebraska, with more than 50% of the clouds in this region lie entirely in the temperature range for icing.

3.2 Selected station climatologies

Through the use of boxplots and histograms of a few selected cities, insights are revealed about the cloud characteristics over those cities and cities with similar climates.

In Fig. 6, the boxplots of MSL cloud base heights for ten cities are shown. The boxes show the 25th through 75th percentiles. The center line is the median (50th percentile), and the notches are the confidence intervals on the median. The whiskers extend to the

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FIG. 5. Frequency of clouds entirely within the range for icing (%).

FIG. 6. Boxplots of cloud base heights over ten selected cities over the U.S. (m, MSL).

FIG. 7. Boxplot of wintertime cloud base temperatures for selected cities (0.1°C).
5th and 95th percentiles, and individual dots are data points residing outside these limits. The lowest observation can be considered the elevation of the station. Stations near large bodies of water such as ACY, BUF, GEG, LCH, MIA, and UIL have compact distributions with relatively low cloud base heights. BIS, however, also has low cloud bases despite being away from any large bodies of water. The northern Great Plains has frequent arctic fronts in the winter, bringing low, shallow, cold and widespread clouds over the region, which most likely explains the cloud base height distribution over BIS. The boxplot of cloud base heights at TUS, unlike the other stations, has a distinctly different distribution from the other stations. At TUS, the median and mean are both well above the elevation of the station. This is most likely indicative of the dry climate found there, as contrasted to the moist climates of BUF, GEG, LCH, MIA, and UIL.

The cloud base temperatures for the selected cities (Fig. 7) show similar findings. The stations located in relatively warm coastal climates, such as LCH and MIA have warmer cloud base temperatures. TUS, located in a warm, dry climate has cold cloud base temperatures, as also reflected in its high cloud bases. BIS and DEN have comparably cold cloud base temperatures most likely due to low surface air temperatures.

4. DISCUSSION

As a result of this climatology, areas of potential problems for aviators were identified. A strong relationship between surface air temperature and cloud base heights and temperatures is suspected. A large area of possible icing conditions was found over the areas of South Dakota, North Dakota, and eastern Montana. It was also found that 50% of the time multiple cloud layers exist, allowing one to fathom the importance of finding reliable ways to characterize these cloud conditions. Satellite and surface observations reveal data about either the base or top of cloud layers, but provide little or no information about intervening cloudless layers. Although RAOBs are sometimes deemed unreliable, they give an indication of the vertical structure and in-cloud temperature ranges and heights that satellite or surface observations are unable to give.

High-resolution, accurate numerical models are improving in cloud depiction, and their ability to identify multiple layers should be verified. "Cloud radars" (e.g. Moran et al. 1998) could be used in terminal areas for real-time cloud layer determination.

While a cloud climatology does not constitute a prediction of weather, it can be incorporated into aviation hazard prediction algorithms such as the Integrated Icing Diagnosis Algorithm (IID, McDonough and Bernstein 1998). IID extracts icing information from sensors and numerical weather models and weights the information according to its potential influence on hazardous icing conditions. As with numerical weather forecast guidance such as MOS (Model Output Statistics), climatology could be used to weight predictions more heavily to "normal" conditions with lead time.

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5. REFERENCES


McDonough, F. and B.C. Bernstein, 1998: Combining satellite, radar and surface observations with model data to create a better aircraft icing diagnosis. (Elsewhere in this preprint volume.)


Median Cloud Base Temperatures in °C

Nov thru Mar 1965 - 1990
Median Cloud Base Heights in Meters

Nov - Mar 1965 - 1990
AGL Median Cloud Base Heights in m
Nov - Mar 1965 - 1990