DATA FUSION ENABLES BETTER RECOGNITION OF CEILING AND VISIBILITY HAZARDS IN AVIATION

BY PAUL HERZEGH, GERRY WIENER, RICHARD BATEMAN, JAMES COWIE, AND JENNIFER BLACK

It may seem surprising that low cloud ceilings[1] and poor visibility claim the lives of more general aviation (GA) pilots and passengers than any other cause of weather-related GA accidents. But when visibility deteriorates to the point where a pilot loses the visual cues that differentiate up from down, the situation can quickly become grave. This is especially true for pilots whose proficiency extends only to visual flight, and for many instrument-rated pilots whose proficiency in instrument flight has deteriorated through lack of recent practice or other causes. These pilots generally don't *plan* to fly in low visibility conditions—they most often encounter these conditions unexpectedly along their planned flight route. At that point, their margin of safety has dropped considerably, and their best option is to escape the hazardous area and reassess their flight plans.

Overall, the most powerful strategy a potentially vulnerable pilot has in dealing with ceiling and visibility (C&V) hazards is to avoid them entirely. Doing this relies on weather-aware preflight planning, smart go/no-go decisions, and in-flight course changes when necessary. METAR reports, Airmen's Meteorological Information (AIRMETs), terminal aerodrome forecasts (TAFs), Area Forecasts, and Weather Depiction Charts comprise core materials referencing current or future C&V conditions, and pilots routinely use these and other resources directly in flight planning and indirectly through briefings available through Federal Aviation Administration (FAA) Flight Service Stations and other sources.

AFFILIATIONS: HERZEGH,* WIENER, BATEMAN,+ COWIE, AND BLACK—National Center for Atmospheric Research, Boulder, Colorado
*Retired
+CURRENT AFFILIATION: Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado
CORRESPONDING AUTHOR: Paul Herzegh, 5682 Euclid Pl., Boulder, CO 80303
E-mail: pherzegh@gmail.com

DOI:10.1175/BAMS-D-13-00111.1

A PRODUCT TO IMPROVE GA SAFETY. The question asked by the FAA some years ago was, "How do we augment the safety of GA activity where C&V hazards are present?" One direction taken was to develop a new product—a ceiling and visibility analysis (CVA)—that could improve preflight and in-flight situational awareness among pilots, dispatchers, and flight service briefers. The product was conceived to have the following characteristics:

- Skillful use of observational data to represent current conditions
- Timely updates at a rate that can effectively capture evolving conditions
- Clear, geographically referenced presentation of ceiling and visibility hazard areas

The CVA product subsequently developed by the National Center for Atmospheric Research passed a series of performance and risk analysis tests and became available for public use in July 2012.

CVA yields a real-time map of the current C&V conditions that designate the use of *visual flight rules* (VFR) and *instrument flight rules* (IFR). Recognizing the occurrence of these conditions is especially important to GA pilots. FAA regulations allow pilots flying under VFR conditions to (1) navigate and orient the aircraft by visual reference to the ground, and (2) depend upon visual cues to see and avoid obstructions and other aircraft. Under IFR conditions, a pilot's ability to fly using visual cues is significantly impaired, so FAA regulations require that pilots navigate and orient the aircraft through reference to

[1] Cloud ceiling is the height above the ground or water of the base of the lowest layer of cloud below 6,000 m (20,000 ft) covering more than half the sky. If cloud coverage is half the sky or less, ceiling is designated as "unlimited."

Table 1. Flight category as determined from ceiling and visibility.

Flight Category	Ceiling in Feet AGL		Visibility in Statute Miles
Instrument Flight Rules (IFR)	Less than 1,000	and/or	Less than 3
Visual Flight Rules (VFR)	1,000 or greater	and/or	3 or greater

aircraft instruments. The ceiling and visibility values that define VFR and IFR limits are shown in Table 1. Here, ceiling is given as feet above ground level (AGL).

HARNESSING METARS. The primary ceiling and visibility observations used in CVA are taken from approximately 1,650 METAR sites across the contiguous United States (CONUS) and in the U.S.–Canada and U.S.–Mexico border regions. One user group, helicopter emergency medical service (HEMS) pilots, voiced a particularly stringent need for up-to-the-minute information to aid quick assessment of weather conditions at the time of an emergency call. HEMS deployment decisions are made in a matter of minutes. To meet that requirement and the needs of others, CVA METAR observations are updated every 5 min. This ensures that CVA will reflect the intermittent "special" observations that are triggered by significant changes in ceiling or visibility, as well as the mandatory METAR reports generated by each station near the top of the hour. After each 5-min update, ceiling and visibility are interpolated to the 5-km National Digital Forecast Database (NDFD) grid using nearest-neighbor interpolation. Tests of several interpolation methods (including linear, natural neighbor, and Kriging methods) showed that nearest-neighbor interpolation introduces less error into the CVA analysis than other methods.

Since ceiling is measured with respect to ground level, the interpolation of ceiling must account for the elevation of the reporting METAR station and the variation of terrain height between stations. We assume that an observed ceiling height expressed in feet above mean sea level (MSL) does not vary horizontally. Thus, an interpolated value of ceiling at a point away from its nearest METAR is taken to be the difference between ceiling height MSL and terrain height at that point. Any negative value of interpolated ceiling height is treated as 0 ft AGL. In contrast to ceiling, the interpolation of visibility is straightforward. The visibility value reported at a given METAR is applied directly to each of the grid points that meet the nearest-neighbor criterion. For both ceiling and visibility, when an observation is missing from a given METAR site, the affected grid points are filled by nearest-neighbor interpolation from the next-nearest METAR site.

The interpolation process described here in effect "stretches" limited-area METAR observations across the broader domain between stations and accounts for terrain effects on ceiling height. The resulting fields help to visualize the *likely* conditions at range from METARs. However, the reliability of these fields degrades as distance from a METAR site increases. Thus, users should apply cautious practical judgment in considering the representativeness of the product as distance from a METAR site increases.

GOES SATELLITE CLOUD DETECTION. There are broad areas within the CONUS that are not represented by METAR observations due to wide spacing of observing sites. It is desirable to augment observations in these regions however possible. CVA uses GOES-East and GOES-West cloud-detection capabilities to discriminate between cloudy regions (where a ceiling may exist below 12,000 ft AGL) and cloud-free regions (where no ceiling exists). The latter indication (no ceiling) is used in CVA to limit the interpolation of observed ceilings across the regions between METAR sites.

GOES-based cloud detection for CVA is accomplished through a processing technique developed at NASA's Global Hydrology and Climate Center. The method uses data from the 3.9-μm and 11-μm GOES satellite channels to carry out a series of threshold and pixel-to-pixel comparison tests applied to the data for each pixel in the scene. To help accommodate naturally occurring spatial and temporal variability in surface temperature and surface emission characteristics, the comparison thresholds are optimized for each hour, day, and pixel location though automated processing of a continuously updating 20-day composite background reference dataset.

GOES cloud mask data provide an opportunity to specify clear (no ceiling) conditions in regions where METAR coverage is missing. However, it is well known that real-time satellite cloud products can fail to detect very low clouds or thin clouds in the

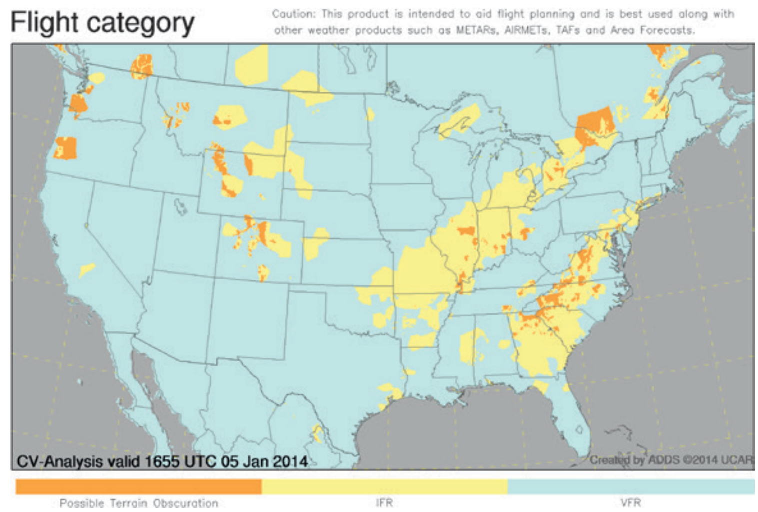

Fig. 1. CONUS-wide CVA flight category display based on current observations at 1655 UTC on 5 Jan 2014. IFR and VFR regions are defined according to the ceiling and visibility limits shown in Table 1. Regions where terrain may be obscured are shown in orange and correspond to estimated ceiling values less than 200 ft AGL.

day–night terminator region and at night. Thus, it is important that we verify that a cloud mask is representative before using it to augment METAR information. Since cloud conditions are always changing, verification is done through comparison tests between each current GOES cloud mask and the corresponding METAR data within its domain.

Comparisons are carried out over the region within a 10-km radius of each METAR site and are repeated for each CVA 5-min update. We require that each cloud mask grid point that falls within the test region shows cloudy conditions if the corresponding METAR reports a ceiling. If this criterion is met, then cloudy pixels throughout the nearest-neighbor domain of the METAR are assigned a terrain-adjusted ceiling height, while clear pixels are assigned an "unlimited" ceiling. If the test criterion is not met, the cloud mask is disqualified from use within the nearest neighbor domain of the corresponding METAR and each pixel within that domain is assigned a terrain-adjusted ceiling height. This represents a relatively stringent test for agreement between METAR observations and the cloud mask, and failure of the test indicates either faulty cloud detection by the satellite or, possibly, broken cloud conditions. Since even broken cloud can yield an aviation ceiling, there is good justification to assign a ceiling height within the nearest-neighbor domain if the test criterion is not met.

CEILING, VISIBILITY, AND FLIGHT CATEGORY DISPLAYS. CVA was constructed using a simple display format to provide easy recognition of the regions where observational data indicate the possible presence of IFR, VFR, and obscured terrain conditions. All CVA displays for the current initiation time and the preceding two hours can be accessed at www.aviationweather.gov/adds/cv. For users who wish to archive data or render their own displays, CVA data in GRIB2 format are available from the National Weather Service (NWS) via NOAAPort (for subscribers) and via FTP from the National Weather Service Telecommunications Gateway.

Figure 1 presents a CONUS-wide view of CVA's flight category display. This can be used to survey the "big picture"—are there any current observations pointing to IFR conditions or obscured terrain in or near a planned or current region of operation? For complementary information, a user can view corresponding CONUS displays of ceiling and visibility as well as more detailed displays focused on 18 smaller regions within the CONUS. Corresponding images taken from CVA regional displays are shown in Fig. 2. CVA's ceiling, visibility, and flight category data are also viewable in the context of interactive geographic information system (GIS) data via the experimental Helicopter Emergency Medical Services (HEMS) Tool (http://weather.aero/tools/desktopapps/hemstool). This tool was specifically designed to show weather conditions for short-distance and low-altitude flights that are common for the HEMS community. As explained in FAA National Policy Notice N8000.333 (http://weather.aero/assets/4db27660/docs/HEMS_FAA_DOC.pdf), the tool can be used by HEMS operators in VFR operations for no-go decisions only.

VALIDATING CVA PERFORMANCE. By design, CVA correctly replicates the observed values of ceiling and visibility for grid points corresponding to METAR sites. However, in the regions *between* METAR sites, CVA produces an estimate of the conditions present using processing steps such as nearest-neighbor interpolation and, for ceiling, terrain height correction and satellite-based cloud masking.

The NOAA Global Systems Division conducted a quantitative assessment of CVA specifically to assess

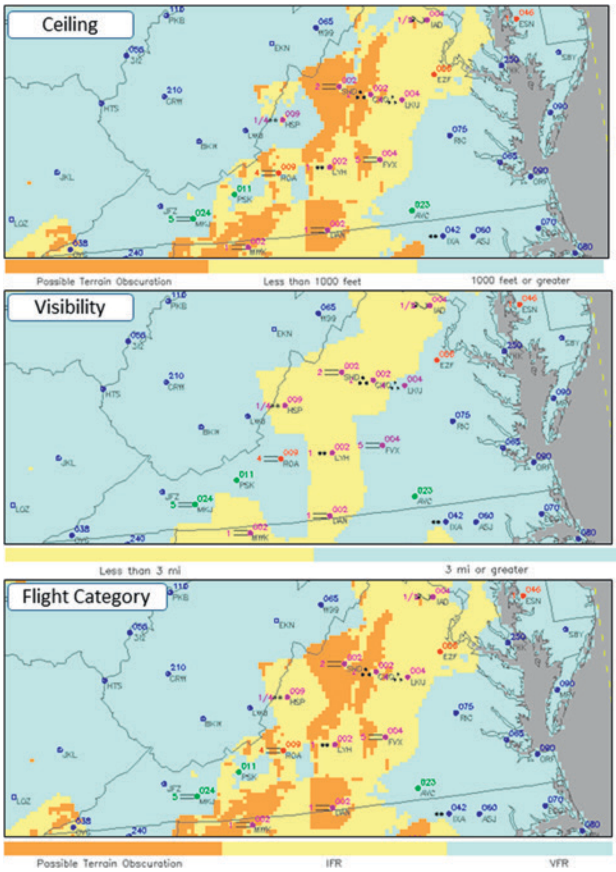

FIG. 2. Images taken from CVA regional displays covering mid-Atlantic states at 1655 UTC on 5 Jan 2014. Ceiling and visibility values that correspond to IFR conditions are shown in yellow and orange. Abbreviated station plots show ceiling in hundreds of feet at upper right, present weather at left, and visibility in miles at left.

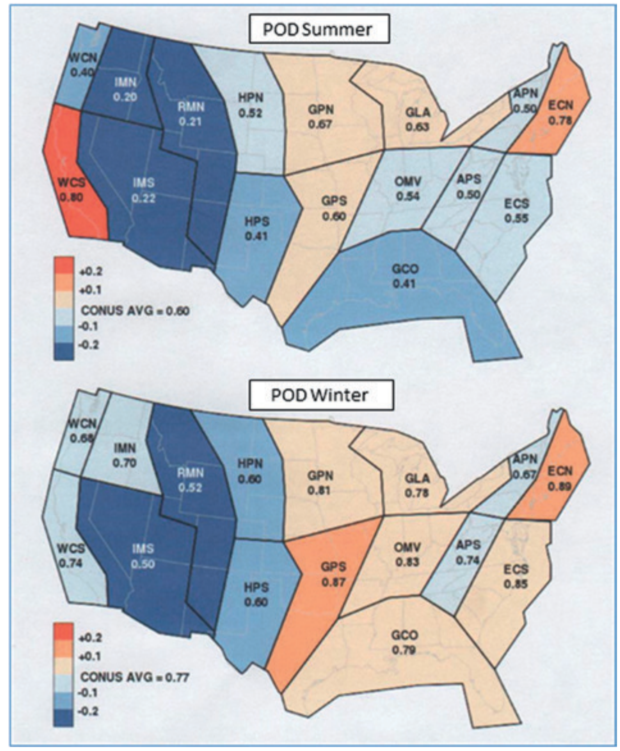

FIG. 3. Probability of detection (POD) for CVA reporting of IFR events for the areas between METAR sites in 16 CONUS regions for summer and winter. Higher values of POD denote better performance. Regions where POD values are greater than or less than the CONUS average are colored in red or blue shades, respectively, as shown at lower left. In all regions except the West Coast South (WCS), POD is markedly higher in winter than in summer. The summer maximum for POD in WCS is due to the frequent, widespread occurrence of marine stratus. Other regions are designated as follows, where N and S refer to North and South: West Coast North (WCN), Intermountain (IMN and IMS), Rocky Mountains (RMN), High Plains (HPN and HPS), Great Plains (GPN and GPS), Great Lakes Area (GLA), Ohio-Mississippi Valley (OMV), Gulf Coast (GCO), Appalachian Mountains (APN and APS), and East Coast (ECN and ECS). [Figs. 3–5 adapted from the NOAA report by Loughe et al. listed under "For Further Reading."]

its skill in reporting IFR events at points populated by nearest-neighbor interpolation between METAR sites.[2] To do this, the study looked at performance metrics for CVA values at target METAR sites that had been withheld from the processing used to derive CVA fields. The CVA values at these target sites resulted purely from the CVA algorithm and its use of the nearest METAR observations. Thus, the actual measurements made at the target sites played no role in the CVA product and could be used for independent validation.

The study compared measures of skill at points populated by interpolation for winter versus summer and for different regions of the CONUS. CONUS-wide, the study found a higher probability of detection (POD) of IFR events in the winter (0.77) than in the summer (0.60). The study also found a better (lower) false alarm ratio (FAR) in the winter than in the summer (0.22 versus 0.31). Note that FAR answers the question, "What fraction of indicated IFR alerts actually did not occur?"

[2] This study, listed under "For Further Reading," references CVA via its previous designation, NCVA. The study also references a confidence field that is not implemented in the product today.

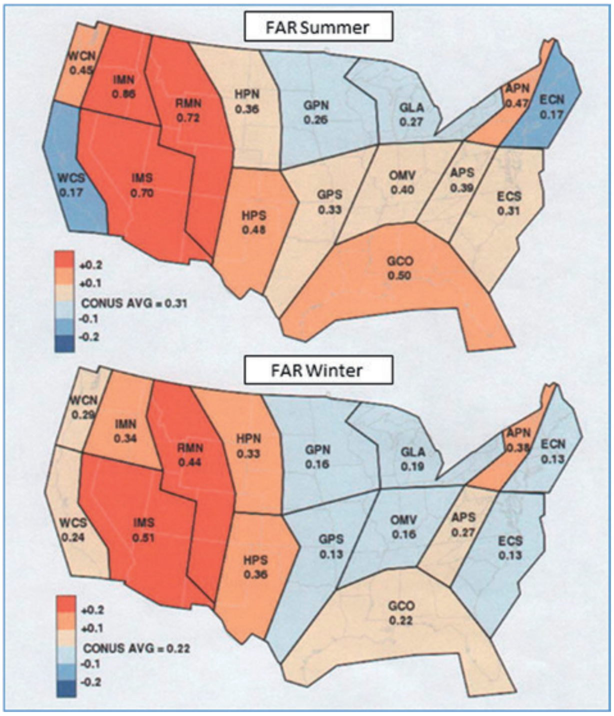

Fig. 4. As in Fig. 3, but for false alarm ratio (FAR) for CVA reporting of IFR events for the areas between METAR sites. Lower values of FAR denote better performance. In all regions except the West Coast South (WCS), FAR is markedly lower in winter than in summer. The summer minimum for FAR in WCS is due to the frequent, widespread occurrence of marine stratus.

A comparison of winter versus summer performance for 16 regions within the CONUS is given in Figs. 3 and 4. In every region except one (West Coast South), both POD and FAR indicate better performance in winter compared to summer. The winter performance advantage is consistent with the fact that midlatitude synoptic-scale cloud systems are widespread, long-lived, prolific producers of IFR conditions and are most robust and frequent in the winter. These factors increase the winter season frequency of widespread IFR events that may impact many contiguous METAR sites at one time. When that is the case, the variability of conditions between METARs is reduced, and nearest-neighbor interpolation has improved likelihood for success. For the same reason, close spacing between METARs also helps yield skillful nearest-neighbor interpolation.

In contrast, summer season cloud systems are frequently smaller in scale and more short-lived than their winter counterparts and produce IFR events that are correspondingly less widespread. As a result, summer season IFR events typically impact fewer contiguous METAR sites than winter events. In this situation, the variability of conditions between METARS is increased, and nearest-neighbor interpolation skill declines.

As cited in the NOAA study, it is summer (not winter) that brings the most frequent and widespread IFR conditions to the coastal regions in California. These conditions come in the form of low-level marine stratus clouds that have formed over cool coastal waters and have advected on shore. While marine stratus occurs along the California coast throughout the year, it is nearly a daily occurrence during the summer season. Its frequent, widespread occurrence diminishes the variability of IFR conditions and thus enhances the skill of nearest-neighbor interpolation, and this leads to better CVA performance during summer than during winter in California.

The NOAA study also found considerable variability in CVA skill from region to region within the CONUS. Figure 5 shows POD and FAR for 16 regions within the CONUS for summer and winter seasons combined. Much of the eastern half of the United States shows above-average POD and below average FAR, while farther west the High Plains, Rocky Mountain, and Intermountain regions show reduced performance yielding below average POD and above average FAR.

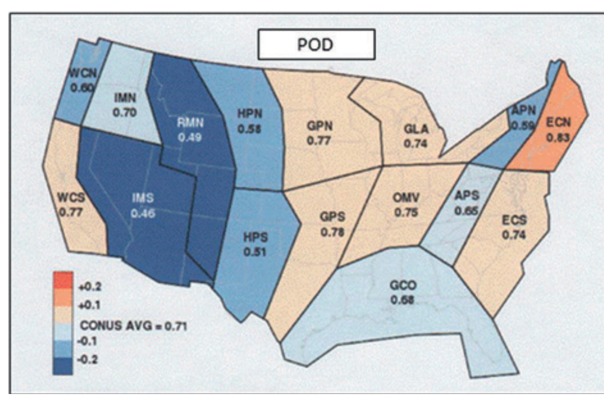

Fig. 5. As in Fig. 3, but for POD and FAR for summer and winter combined. Higher values of POD and lower values of FAR denote better performance. In general, the eastern half of the United States yields higher POD and lower FAR than the western half. As seen in Figs. 3 and 4, below-average performance in the GCO region results from reduced performance during the summer convective regime. Below-average performance in APN and APS is the case year-round, and is likely due to mountainous terrain and above-average nearest-neighbor METAR spacing.

Like the winter versus summer validation discussed above, the overall tendency for more skillful CVA performance in the East than in the West is consistent with CVA's sensitivity to the nearest-neighbor spacing of METARs. Figure 6 shows that the eastern half of the CONUS is more densely populated by METAR sites than the western half. This east-west contrast in nearest-neighbor METAR spacing is even greater when the dense METAR population in California is excluded. In that case, the western CONUS nearest-neighbor METAR spacing climbs to an average of 60 km and a median of 56 km in comparison to the east CONUS mean of 34 km and median of 31 km. As discussed above, the skill of nearest-neighbor interpolation suffers as the spatial resolution of the METAR network declines, and the reduced skill in the West seen in Fig. 5 is consistent with that.

The METAR network in California shown in Fig. 6 yields comparatively good mean and median nearest-neighbor METAR spacing of 29 km and 18 km, respectively. We can expect that this METAR spacing advantage works in concert with the frequent occurrence of marine stratus to yield the improved summer season IFR reporting skill seen for the West Coast South region in Fig. 5.

A second notable feature in Fig. 5 is the reduced interpolation skill shown in the Gulf Coast region. As shown by Figs. 3 and 4, this is primarily the result of reduced skill during the summer season, which produces a dominantly diurnal convective regime. As discussed above, nearest-neighbor interpolation skill is expected to suffer when IFR conditions are especially variable in time and geographic distribution, as is the case in a convective regime.

Also of interest in Fig. 5 is the reduced interpolation skill shown in the Northern and Southern Appalachian regions. This feature is found to persist in both summer and winter. The Appalachian regions are centered over low mountainous terrain where ceiling and visibility conditions are known to be localized and variable. The mean and median nearest-neighbor METAR spacing in the lower performing North Appalachian region are 46 km and 39 km, respectively. In the somewhat better performing South Appalachian region, these spacing figures are 42 km and 39 km, respectively. The reduced skill seen in these regions is consistent with the above-average METAR spacing in place there.

While the NOAA study shows that CVA demonstrates skill in detecting IFR conditions between METAR sites, it doesn't tell us whether pilots find

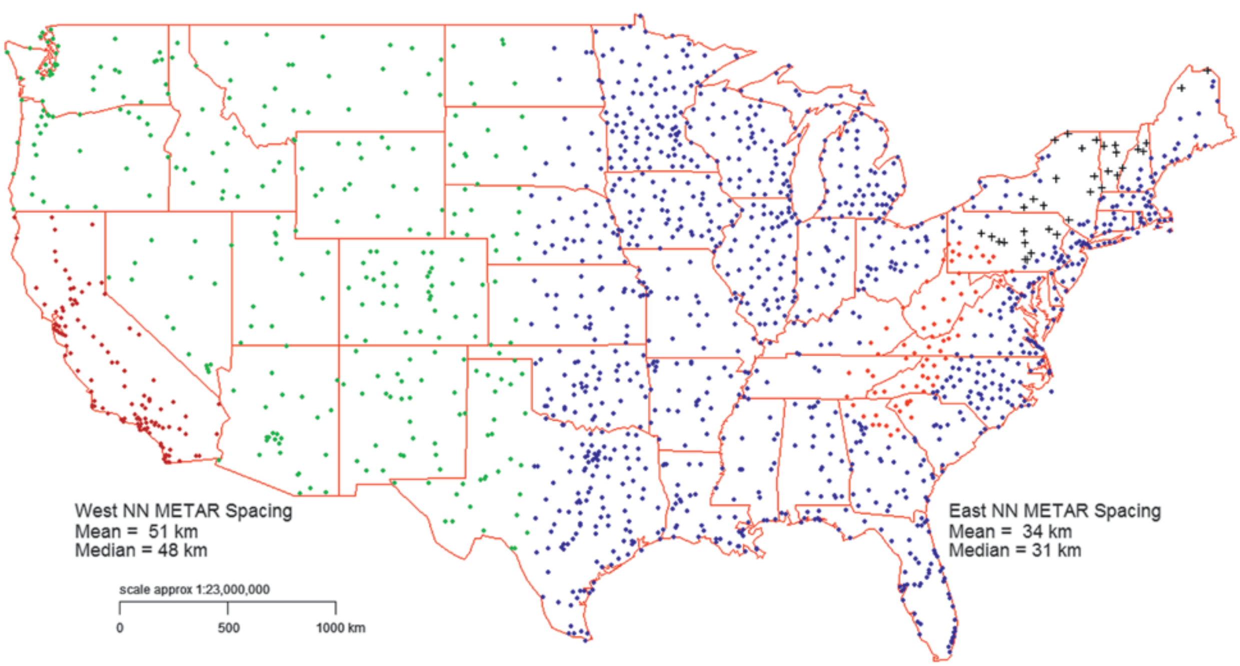

Fig. 6. METAR sites reporting ceiling and visibility observations used in the NOAA study. Eastern METAR sites are those shown in blue, plus those in the North Appalachian region (shown as +) and the South Appalachian region (shown in red). Western METAR sites are those shown in green, plus the California sites (shown in brown). Nearest-neighbor (NN) METAR spacing is shown for East and West sites.

CVA useful in flight planning. To address that question, the FAA conducted an evaluation using 20 GA pilots, 5 HEMS pilots, and 7 flight service briefers. These participants were presented with a variety of weather scenarios, each involving adverse C&V conditions, and each associated with a preplanned flight route. The participants then conducted flight planning using all the weather resources routinely available, but first without access to CVA, and then including CVA. Results from this evaluation were clear—all participants held a positive view of CVA as an aid in flight planning in hazardous C&V conditions. At the same time, they had insights that led to simplification and improvement of the product.

CONCEPTS FOR A NEXT-GENERATION PRODUCT. Experience gained developing and using CVA has led to concepts for a next-generation C&V analysis product now in development for Alaska. Two additional data sources will augment METARs and satellite data in that product:

- Forecast model data valid at analysis initiation time will be blended with satellite data and extrapolated surface data to estimate C&V conditions in gap areas where surface observations are unavailable. Initial development is making use of the hourly updated Rapid Refresh model for this purpose.
- Weather camera photos are updated every 10 min from a population of more than 750 FAA cameras across Alaska. Image-processing techniques will derive limited C&V information from these images to augment METAR observations. Many cameras offer especially critical information along important flight routes in mountainous terrain where no surface observations are available.

A proof-of-concept Alaska analysis product should become available for trial use by the NWS Alaska Aviation Weather Unit by the end of FY2015. If this trial is successful, we hope to develop a second-generation Alaska analysis product tailored for public use over the Internet.

ACKNOWLEDGMENTS. We thank Andrew F. Loughe and his coauthors for valuable discussions and use of the findings of the NOAA study report. We thank meteorologist Matt Tryhane for his valuable work early in the development cycle. This research is in response to requirements and funding by FAA. The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA.

FOR FURTHER READING

Air Safety Institute, 2012: 22nd Joseph T. Nall Report, 49 pp. [Available online at www.aopa.org/Pilot-Resources/Safety-and-Technique/Accident-Analysis/Joseph-T-Nall-Report.]

Jedlovec, G. J., S. L. Haines, and F. J. LaFontaine, 2008: Spatial and temporal varying thresholds for cloud detection in GOES imagery. *Trans. Geosci. Remote Sens.*, **46**, 1705–1717.

Loughe, A. F., B. P. Pettegrew, J. K. Henderson, J. E. Hart, S. Madine, and J. L. Mahoney, 2011: Quality assessment report: National ceiling and visibility analysis product. NOAA Tech. Memorandum OAR GSD-37. Earth System Research Laboratory, Global Systems Division.