Reply to "Comments on 'Characterization of Aircraft Icing Environments with Supercooled Large Drops for Application to Commercial Aircraft Certification'"

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(Manuscript received 9 August 2012, in final form 30 January 2013)

Cober et al. (2009) and Cober and Isaac (2012) characterized aircraft icing environments that contained supercooled large drops (SLD) $> 100\,\mu$m in diameter on the basis of data collected during 134 research flights into winter storms in three geographic regions of North America. The characterization was designed to be supplemental to existing aircraft icing certification envelopes, given that existing envelopes do not explicitly incorporate SLD conditions. The U.S. Federal Aviation Administration is considering using the results from Cober et al. (2009) and Cober and Isaac (2012) as the basis for new certification regulations. Marwitz (2013) has suggested that the results of Cober and Isaac (2012) are deficient with respect to their application to the proposed new certification regulations, and he provided some criticisms. The purpose of this response is to address these criticisms.

Marwitz (2013) suggested that the use of median volume diameter (MVD) and maximum diameter (Dmax) by Cober and Isaac (2012) as part of their characterization method is invalid because MVD and Dmax are not related to performance measurement. Cober and Isaac (2012) made no attempt to measure performance degradation of the research aircraft. Rather the intent was to collect and analyze a sufficiently large dataset to characterize icing environments that included SLD at the 99% and 99.9% levels (i.e., extreme values) so that manufacturers could subsequently determine the associated performance degradation on their instruments, aircraft components, or engines. A justification for using MVD and Dmax follows.

MVD is the 50% mass diameter, and hence large MVD values (i.e., $>40\,\mu$m) specifically identify icing conditions that are outside the existing certifications standards and for which the majority of the mass is incorporated in drops that have higher collision efficiency (and corresponding performance degradation) with aircraft surfaces. Aircraft, instrument, and engine manufacturers use different combinations of MVD (or other drop diameter characteristics), temperature, and liquid water content (LWC) to evaluate performance losses primarily through their use in wind-tunnel, natural-icing, and numerical simulation experiments. Aircraft icing envelopes have been based in part on MVD since their inception in the 1950s. It is an industry standard to correlate the analysis of icing conditions against performance degradation, and MVD is one of the primary variables used for characterizing icing conditions. Notwithstanding this point, there have been numerous other proposed methods to characterize icing environments, including Newton (1978), Politovich (1996), Jeck (1996), Ashenden and Marwitz (1998), and Shah et al. (2000). Each of these incorporated some measure of the drop diameter or diameter bins to characterize icing conditions. Several of these are shown in Fig. 1 and are compared with the envelopes used by the certification authorities (Federal Aviation Administration 1999). Cober et al. (2009) considered each of these characterization methods when developing the envelopes proposed in Cober and Isaac (2012). Although the method of Newton (1978) is suggested to be the most physically based because it inherently accounts for collision efficiency, Cober et al. (2009) concluded that the method of Shah et al. (2000) was the most practical with respect to the suitability of application to certification practices. Cober and Isaac (2012) also provided characteristic drop spectra for four subsets of SLD conditions, from which any diameter-based characterization could be computed, in case any potential users wanted to use the data

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DOI: 10.1175/JAMC-D-12-0213.1

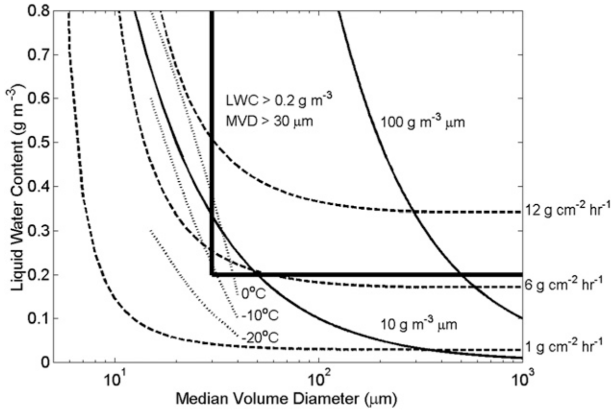

FIG. 1. Comparison of aircraft icing envelopes derived from MVD and LWC for four different methods including 1) Federal Aviation Administration (1999) envelopes as a function of temperature for 0°, −10°, and −20°C (dotted lines); 2) Newton (1978) envelopes as a function of potential accumulation for 1, 6, and 12 g cm^{-2} h^{-1} (dashed lines); 3) the Politovich (1996) envelope for severe SLD conditions (dark solid line); and 4) Ashenden and Marwitz (1998) envelopes for LWC × 80VD corresponding to values of 10 and 100 g m^{-3} μm (thin solid lines). Note that for the latter the *x* axis represents the 80VD and not the MVD so that the LWC × 80VD curves would be shifted to the left in a direct comparison with the other envelopes.

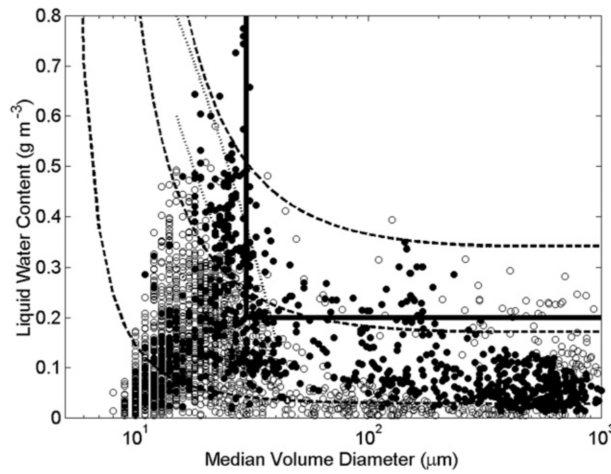

FIG. 2. Comparison of three of the four icing envelopes shown in Fig. 1 with 2444 SLD icing environments observed at 3-km resolution and reported by Cober and Isaac (2012). Data points for which the LWC × 80VD values are between 10 and 100 g m^{-3} μm, corresponding to the envelopes of Ashenden and Marwitz (1998), are shown as filled circles.

to derive their own characterization method. The identification of Dmax was a convenient parameter for separating the observed freezing-drizzle and freezing-rain conditions. Sensitivity studies showed that there would have been no significant difference in the proposed envelopes of Cober and Isaac (2012) had they chosen to use another parameter such as 95% mass diameter or 80% mass diameter (80VD) to segregate rain and drizzle conditions. This result is demonstrated in Fig. 2 in which all of the data (freezing-rain and freezing-drizzle conditions) are shown together. As was discussed by Cober and Isaac (2012), the data form a continuum and are well bounded by the Newton (1978) envelope of approximately 12 g cm^{-2} h^{-1}. Cober and Isaac (2012) showed that their freezing-rain and freezing-drizzle envelopes also bounded the observed data. Cober and Isaac (2012) did not use LWC × 80VD, use of which is suggested by Ashenden and Marwitz (1998), because this parameter was only compared with aircraft performance for one aircraft type and is not necessarily transferable to other aircraft air foils.

Marwitz (2013) suggested that the results of Cober and Isaac (2012) account only for freezing-rain and freezing-drizzle conditions and do not incorporate SLD conditions associated with severe supercooled drizzle drop (SCDD) environments. Figure 2 shows the 3-km-averaged data of Cober and Isaac (2012) in comparison with the icing envelopes shown in Fig. 1. Ashenden and Marwitz (1998) computed the LWC × 80VD values for several icing conditions and suggested that values between 10 and 100 g m^{-3} μm had the largest performance degradation on their Super King Air aircraft. Data points in Fig. 2 with LWC × 80VD values between 10 and 100 g m^{-3} μm are shown as solid dots. A significant number (37%) of the SLD data points observed by Cober and Isaac (2012) fall into the high-performance-degradation category assessed by Ashenden and Marwitz (1998).

Marwitz (2013) references other articles, including Ashenden and Marwitz (1998), in which the observed icing conditions were more severe than those presented by Cober and Isaac (2012). These other observations were averaged together, and the resulting data point, when compared with the results of Cober and Isaac (2012), is well above their 99% LWC envelope. Although, by definition, natural icing conditions that are above a 99% or 99.9% engineering standard or envelope must exist, the comparison that Marwitz (2013) provides is problematic for several reasons. Cober et al. (2009) identified four criteria that needed to be satisfied before data could be included in their analysis: 1) there had to be an independent SLD LWC measurement that was based on a hot-wire instrument and was not based on derivation from a drop spectrum, 2) there had to be an acceptable measurement of the SLD drop spectrum that was based on good-quality 2D images for drops > 100 μm in diameter, 3) the cloud phase of each SLD observation had to be accurately assessed so that liquid-phase conditions could be clearly identified for the analysis, and 4) observations that were biased by ice crystals needed to be identified and corrected or removed so that the forward-scattering spectrometer probe (FSSP) measurements were not contaminated by ice crystals and ice crystals were not inadvertently included in analysis of the 2D spectra. Cober et al. (2001a) presented a quantified method to ensure that these criteria were met. When developing the database to be used for the analysis of icing envelopes including 99% and 99.9% LWC values, Cober et al. (2009) considered including observations such as those presented by Ashenden and Marwitz (1998). However, Ashenden and Marwitz (1998) did not have independent measurements of the LWC and drop spectrum, did not have an instrument capable of directly measuring LWC at large drop sizes, and did not present a quantified method for identifying cloud phase or for ensuring that ice crystals or other artifacts were not influencing their FSSP, 1D, or 2D drop spectra. For these reasons, there was insufficient confidence in the accuracy of the Ashenden and Marwitz (1998) LWC values, and hence their data were not used in the analysis of Cober and Isaac (2012). Marwitz (2013) does not provide an error estimate for the LWC value of the data point that he compares with the results of Cober and Isaac (2012). Since Ashenden and Marwitz (1998) computed the LWC of their icing events from FSSP, 1D, and 2D probes, the errors without ice crystals or other artifacts potentially biasing the 1D and 2D probes are at best $\pm$ 43% (Cober et al. 2001b; Strapp et al. 2003) and, with possible ice crystal or artifact contamination of the 1D and 2D spectra, are likely larger. Last, the single data point suggested by Marwitz (2013) is an average of several data points, each of which has a different horizontal length scale. The average data point is compared with an envelope from Cober and Isaac (2012) that is valid for a horizontal length scale of 30 km. The length scales for the Marwitz (2013) data should have been normalized before they were averaged together, as is common practice, because it is well known that LWC values change with horizontal length scale (Federal Aviation Administration 1999; Cober and Isaac 2012).

In summary, the points raised by Marwitz (2013) have all been addressed. The methods and analysis presented by Cober and Isaac (2012) were fully endorsed and reviewed by icing certification experts on the Aviation Rulemaking Advisory Committee (ARAC) Ice Protection Harmonization Working Group (IPHWG), even after being made fully aware of the work of Marwitz and colleagues.

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