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Aircraft Icing: In-Cloud Measurements and Sensitivity to Physical Parameterizations

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Key Points:
- In-cloud microphysics measurements were taken using aircraft under winter conditions
- The Weather Research and Forecasting model was evaluating for icing forecast with multiphysics ensemble approach
- The Morrison microphysics scheme yielded superior results, and the PBL schemes were essential in evaluating the liquid water content

Supporting Information:
- Data Set S1
- Data Set S2
- Data Set S3

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Abstract The prediction of supercooled cloud drops in the atmosphere is a basic tool for aviation safety, owing to their contact with and instant freezing on sensitive locations of the aircraft. One of the main disadvantages for predicting atmospheric icing conditions is the acquisition of observational data. In this study, we used in-cloud microphysics measurements taken during 10 flights of a C-212 research aircraft under winter conditions, during which we encountered 37 regions containing supercooled liquid water. To investigate the capability of the Weather Research and Forecasting model to detect regions containing supercooled cloud drops, we propose a multiphysics ensemble approach. We used four microphysics and two planetary boundary layer schemes. The Morrison parameterization yielded superior results, whereas the planetary boundary layer schemes were essential in evaluating the presence of liquid water content. The Goddard microphysics scheme best detected the presence of ice water content but tended to underestimate liquid water content.

1. Introduction

Icing occurs when an unheated solid structure is exposed to liquid cloud droplets at temperatures below the freezing point. This can seriously damage power lines (Thorkildson et al., 2009), wind turbines (Frohboese & Anders, 2007), and telecommunication towers (Mulherin, 1998). Supercooled liquid water (SLW) in the atmosphere is the main cause of aircraft icing. SLW can persist in a physically metastable state until coming into contact with a solid object such as an aircraft, upon which it freezes instantly and seriously threatens aircraft safety (Kind et al., 1998; Ratvasky et al., 2005). Green (2006) identified 944 icing-related aviation accidents between 1978 and 2005 in the United States.

Despite advances in aircraft anti-icing systems, atmospheric icing prediction has garnered increased attention in recent years (Thompson et al., 2017). The first algorithms derived using numerical weather prediction (NWP) models were based solely on temperature and relative humidity (Schultz & Politovich, 1992). Subsequently, numerous icing forecast algorithms were developed that were based on the use of thermodynamic profiles (Forbes et al., 1993; Thompson et al., 1997) or cloud microphysics schemes to predict the existence of SLW (Tremblay et al., 1995, 1996). However, examination of the characteristics of hydrometeors along the flight path can facilitate the construction of algorithms to evaluate risks to in-flight icing (Cober et al., 2001).

The advent of high-resolution mesoscale models produced substantial improvements in cloud microphysics schemes. It thus became possible to calculate total cloud water content for use in new prediction algorithms as an indicator of icing severity (Bernstein et al., 2005; Olofsson et al., 2003). The skill of NWP models has continued to increase in recent years because of advances in high-performance computing. This has facilitated smaller grid spacing, more advanced data assimilation techniques and improved physical parameterizations. Regmi et al. (2017) used the Weather Research and Forecasting (WRF) model to simulate weather patterns involved in a fatal aircraft accident in the foothills of western Nepal. Those authors concluded that supercooled cloud water and hail might have been the main factors leading to the deadly accident; however, a lack of weather observations prevented model validation. Nygaard et al. (2011) concluded that the spatial resolution (with grid spacing of 0.333 km) used in NWP models is a decisive factor in the correct prediction of icing at ground level. However, aircraft icing tends to occur far above the surface, precluding the need for such fine grids to correctly identify this phenomenon. Davis et al. (2014) evaluated nine WRF physics parameterization combinations for icing episodes at a wind park in Sweden. They tested three microphysics and three planetary boundary layer (PBL) schemes. Optimal results were obtained using a combination of the Thompson microphysics and version 2 of the Mellor-Yamada-Nakanishi-Niino PBL schemes.

Several existing databases included the reports of pilots who were affected by icing during flight (Bolgiani et al., 2018). However, the vast majority of aircraft are not equipped with icing sensors, so pilots must determine ice accretion by visual inspection. Moreover, such accretion depends on technical characteristics of the aircraft and its anti-icing mechanisms, making it difficult to ascertain SLW concentrations that produce icing. For this reason, data collection field campaigns using research aircraft to measure in situ SLW and frozen water content are very important to improve numerical model verification. Owing to the high cost of research flights and the complexity of flight plans in icing conditions, limited data are available from only a few such flight campaigns in North America and Europe (Cober & Isaac, 2012; Hauf & Schröder, 2006; Politovich, 1989). Thus, there are few available databases of in-cloud measurements (Gultepe & Isaac, 2007; Herman & Heymsfield, 2003).

The aim of the present work was to evaluate the WRF mesoscale model in the detection and prediction of atmospheric regions containing SLW. We first designed an eight-member multiphysics ensemble, which was applied to 37 events in which SLW was detected. We subsequently validated this ensemble using a microphysics database. We thus determined the sensitivity of the physical parameterizations in detecting SLW and the ideal combination to identify and predict SLW.

2. Experimental Design and Methodology

2.1. Experimental Design

The in situ observations were collected during the TECOAGUA and METEORISK field campaigns by instruments mounted on a C-212-200 aircraft belonging to the National Institute for Aerospace Technology. These projects took place over the Iberian Peninsula during the winters of 2011–2017 and were focused on microphysical conditions that might generate icing in winter clouds. The vast majority of the clouds sampled were stratiform, and the aircraft collected data during at least one constant-altitude flight within cloud. In-cloud measurements were made using the Cloud Aerosol and Precipitation Spectrometer (CAPS; Baumgardner et al., 2001). This probe is capable of measuring hydrometeor concentration and size (distinguishing their phase), aerosols, liquid water content (LWC), temperature, relative humidity, and vapor density, among other variables. Ten flights with aircraft icing conditions and SLW were examined. Using CAPS images in which hydrometers could be seen (Figure 1), we selected 37 sections containing observed SLW. In these 37 sections analyzed, the LWC was observed in regions with temperatures below the freezing level; therefore, under these conditions, the LWC is equivalent to icing risk.

2.2. Numerical Simulation: WRF Model

NWP models have been widely used to analyze in-cloud icing conditions (Fernández-González et al., 2014; Reisner et al., 1998). In the present study, we used version 3.9.1 of the WRF model (Skamarock & Klemp, 2008) to evaluate its sensitivity to microphysics and PBL parameterizations.

Initial and boundary conditions were from National Centers for Environmental Prediction Global Forecast System analyses, with 1° horizontal grid spacing. Three nested domains were designed, following a two-way nesting strategy. Horizontal resolution of the domains was 27, 9, and 3 km, respectively. Vertical resolution was set to 54 sigma levels, using high resolution in lower layers where SLW is most common.

The selected parameterization schemes were as follows: Dudhia (1989) for shortwave radiation; the Rapid Radiative Transfer model (Mlawer et al., 1997) for longwave radiation; Eta surface layer described by Janjic (1996), and Noah Land Surface Model (Chen & Dudhia, 2001), which is a four-layer soil temperature and moisture model with canopy moisture and snow cover estimation. This configuration was based on the results of studies treating winter situations (Fernández-González et al., 2015; Evans et al., 2012; Yuan et al., 2012). The effectiveness of cumulus parameterizations has been demonstrated using low-resolution models when resolutions better than 10–15 km were not needed (Arakawa, 2004). We thus used the Kain-Fritsch cumulus scheme (Kain, 2004) for the outer domain only.

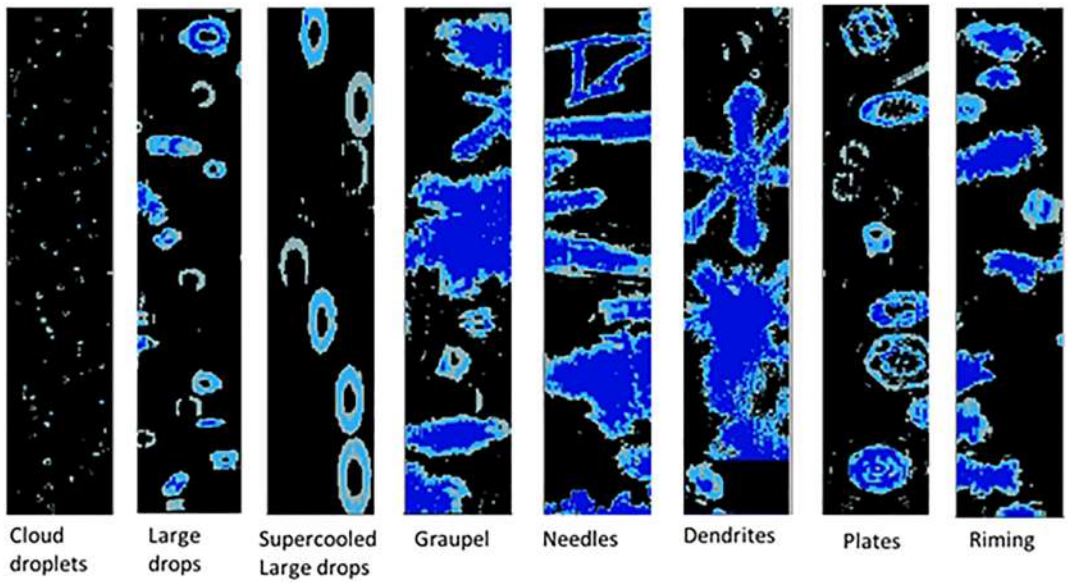

Figure 1. Hydrometeors identified using Cloud Aerosol and Precipitation Spectrometer.

Four microphysics schemes were tested: the single-moment six-class Goddard microphysics (Tao et al., 2009), Morrison six-class double-moment (Morrison et al., 2009), Thompson six-class microphysics (Thompson et al., 2008), and WRF single-moment six-class (WSM6; Hong & Lim, 2006). PBL processes were described by the Mellor-Yamada-Janjic (MYJ; Janjic, 2001) and Yonsei University (YSU; Hong et al., 2006) parameterization schemes. These schemes have been used extensively in various sensitivity studies for winter phenomena (Evans et al., 2012; Fernández-González et al., 2015; Yuan et al., 2012). However, the ability of these schemes in predicting SLW has not been tested using ground truth databases.

2.3. Model Verification

Owing to the strong spatial variability of LWC, we first conducted qualitative validation of the ensemble. For the 37 selected sections, we ascertained the presence or absence of LWC and ice water content (IWC) using each of the eight ensemble members. Using the obtained data, we constructed contingency tables and calculated the following skill scores: False Alarm Ratio (FAR); Probability Of Hits (POH); Frequency Of Mistakes (FOM), and Probability Of Detection (POD).

The results allowed us to determine which model configuration could best predict the presence or absence of liquid water and water in solid form. However, icing risk is also influenced by LWC concentration, so we also performed a quantitative verification. In each section, maximum LWC, under freezing conditions, was extracted for both the observations obtained using CAPS and each of the eight ensembles. Validation was carried out individually for each of the 10 flight days, and we calculated the bias, mean absolute error (MAE), and root-mean-square error (RMSE). Because the LWC varied substantially among the days, the indexes were standardized by dividing each by daily averages. In this way, we could compare the results among the 10 days. Icing risk is also temperature dependent, but temperature is usually accurately forecasted by the models.

3. Results

We first determined the vertical distribution of LWC and IWC, together with isotherms, along the aircraft path for the 10 fights (Figure 2). The representations correspond to average values of the eight ensemble members. As seen in the figure, all 10 flights were during winter conditions, with a freezing level between 1000 and 2000 msl. Temperature of the sampled regions was between −5 and −15 °C, where any liquid water can be considered SLW. In several of the events, large regions of SLW were evident, which predominated over the ice phase (Figures 2a, 2e, 2f, and 2g). Conditions for icing were very favorable in these events because the hydrometeors were in liquid phase; they can remain in this phase for long periods in the

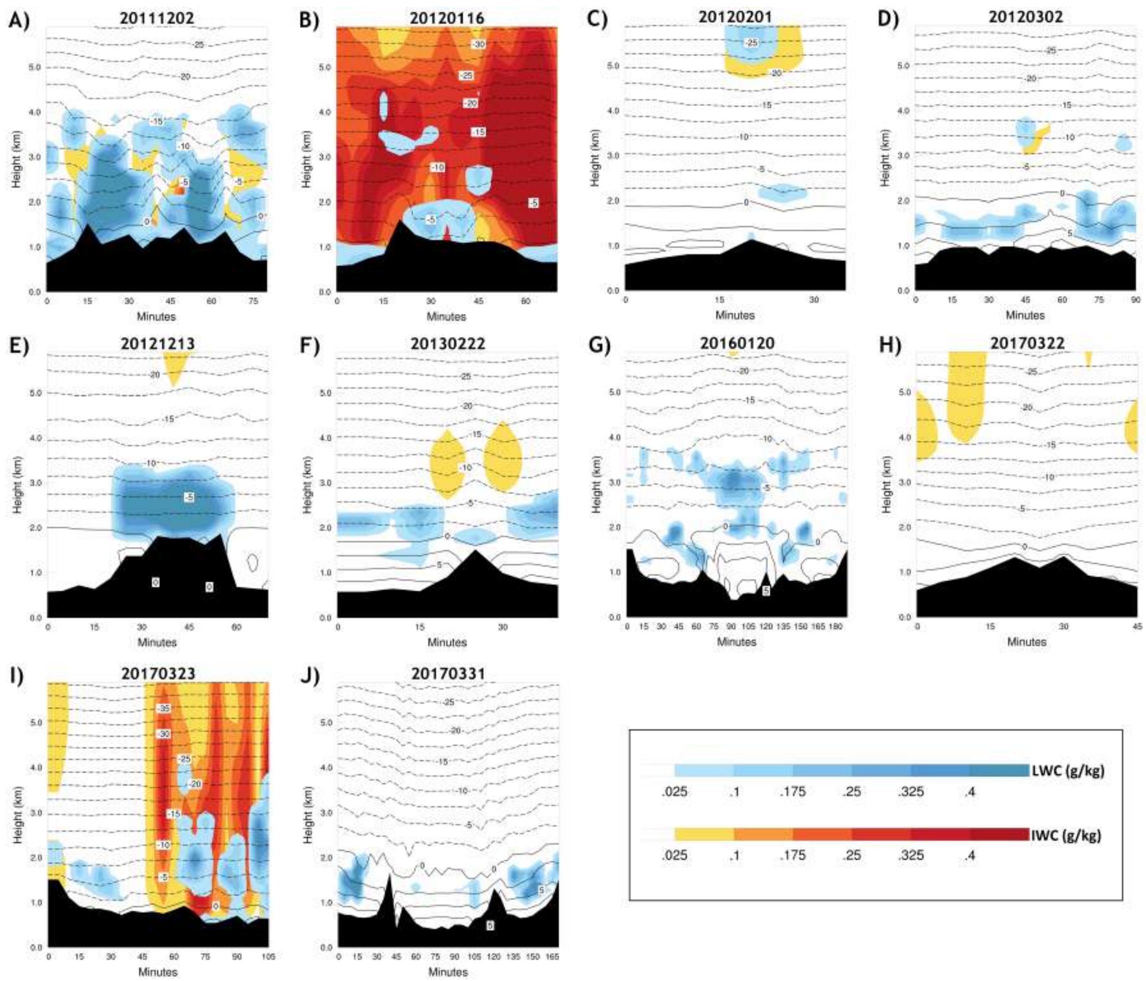

Figure 2. Average vertical profiles of eight ensemble members for C-212 tracks for 10 case studies (A-J): Liquid water content (g/kg; cold color table); ice water content (g/kg; warm color table); temperature (°C; black contours).

absence of ice (Rosenfeld & Woodley, 2000). This situation is typical of clouds with low cloud tops and temperatures that are sufficiently cold to activate freezing nuclei. In other events, the ensemble average shows a predominance of solid phase for the hydrometeors (Figures 2b and 2i) in clouds with large vertical development; the liquid phase was only present as small pockets around the cloud bases. In these situations, the clouds indicate a mixed phase in which liquid droplets feed the growth of ice crystals via evaporation.

One of the main justifications for the development of an ensemble to predict icing is whether the presence of LWC or IWC is sensitive to the choice of physical parameterization scheme. As we have shown, it seems reasonable that physical schemes like microphysics and PBL are essential in forecasting various types of hydrometeors. To investigate this sensitivity, we examined the standard deviation of the eight ensemble members with respect to the vertical profiles of LWC and IWC from the aircraft trajectories (not shown). In many of the events, we found standard deviations similar in orders of magnitude to the ensemble mean. These results are consistent with the demonstrated sensitivity of the two variables to PBL and microphysical parameterizations (Fernández-González et al., 2015).

To determine conditions favorable for icing, the two most important atmospheric variables are temperature and LWC. Thus, in the 10 cases, we determined icing risk using a probability scale based on the number of ensemble members with SLW (Figure 3). It is seen that for most flight paths, the model indicated a risk of icing. For events 2 November 2011, 16 January 2012, 13 December 2012, and 20 January 2016, all

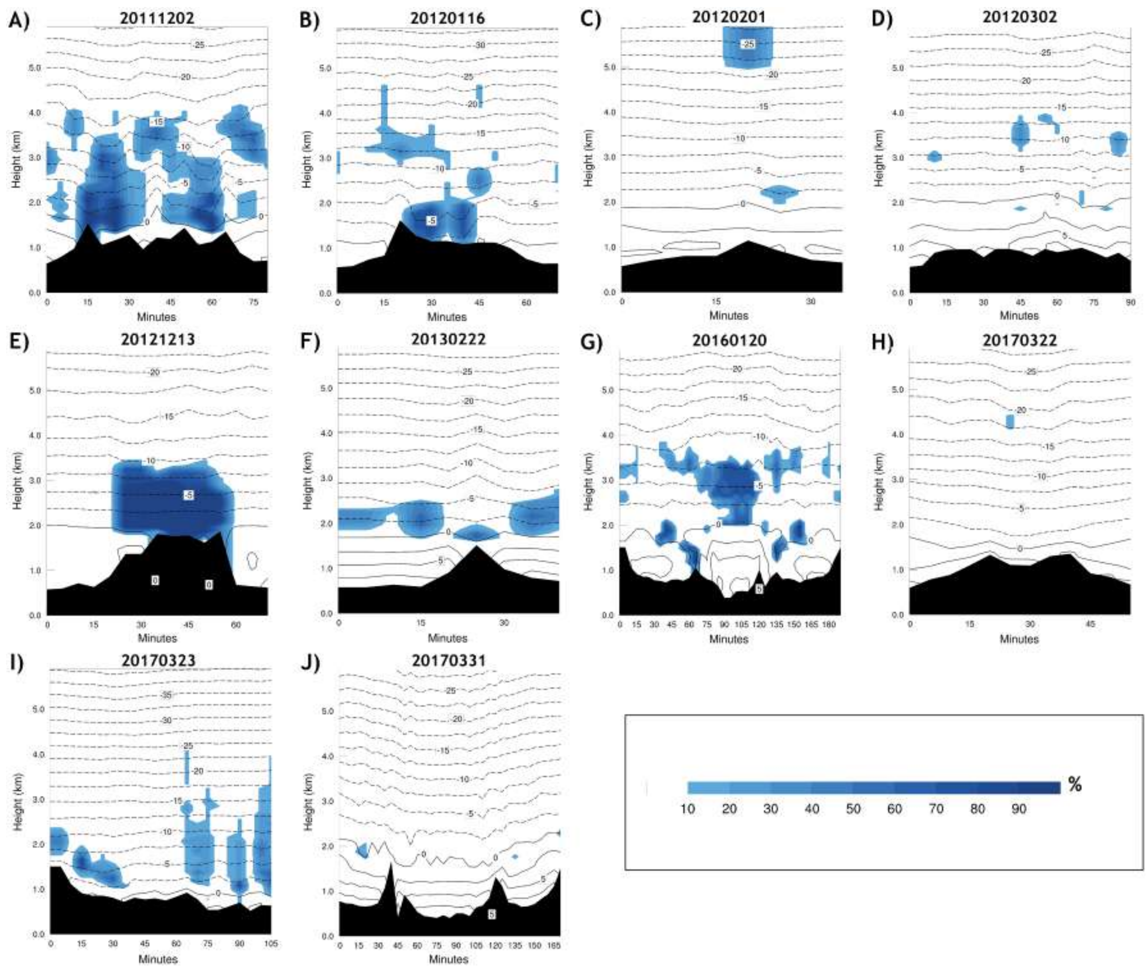

Figure 3. Supercooled liquid water probability using ensemble members for 10 case studies (A-J).

ensemble members identified conditions favorable to icing. There were discrepancies among the members for the remaining events.

A novel aspect of our study is the use of a valuable database including 37 sections containing SLW. We could thus exhaustively validate the various ensemble members according to the methods described in section 2.

Table 1 shows skill scores for validation of LWC and IWC for each of the eight ensemble members. For LWC, the small FAR for all eight members is notable, with the smallest for the Morrison and Thompson microphysics parameterizations and the PBL of the YSU scheme, for which only 5% of cases predicted by the model were not observed. For the POD, the best LWC values were obtained using the Goddard and Thompson microphysics parameterizations, whereas WSM6 scheme obtained the lowest POD values, smaller than 50%. In this case, it appears that the effect of the PBL was stronger, with the YSU giving superior results to the MYJ scheme. Considering all skill scores, ensemble member 4 (Morrison microphysics and YSU PBL schemes) yielded the best results, with a FAR of 4%, POH of 96%, FOM of 33%, and POD of 67%. Combination 7 produced the poorest results, with a FAR of 22% and POD of 39%.

Although the risk of icing depends exclusively on the presence of SLW, the existence of ice crystals within a cloud reduces the LWC, because the saturation vapor pressure is lower over ice than over liquid water. For this reason, we decided to also validate IWC. Its detection is vitally important for cloud microphysics processes because it affects the balance of the remaining hydrometeors. The skill scores for IWC showed a very high FAR for all members except the Thompson microphysics and MYJ PBL schemes. However, these members had a very low POD and are therefore not effective options for predicting IWC. Combining all

Table 1
Skill Scores for Qualitative Validation of LWC and IWC

Ensemble member		1	2	3	4	5	6	7	8
Microphysics		Goddard	Goddard	Morrison	Morrison	Thompson	Thompson	WSM6	WSM6
PBL		MYJ	YSU	MYJ	YSU	MYJ	YSU	MYJ	YSU
LWC	FAR	0.1	0.08	0.05	0.04	0.05	0.05	0.22	0.15
	POH	0.9	0.92	0.95	0.96	0.95	0.95	0.78	0.85
	FOM	0.47	0.36	0.47	0.33	0.5	0.44	0.61	0.53
	POD	0.53	0.64	0.53	0.67	0.5	0.56	0.39	0.47
IWC	FAR	0.45	0.43	0.5	0.5	0.38	0.46	0.53	0.6
	POH	0.55	0.57	0.5	0.5	0.62	0.54	0.47	0.4
	FOM	0.33	0.28	0.67	0.78	0.56	0.61	0.5	0.56
	POD	0.67	0.72	0.33	0.22	0.44	0.39	0.5	0.44

resultant skill scores, the best member was 2 (Goddard microphysics and YSU PBL schemes) with a POD of 67%, although the FAR was as high as 43%.

In view of the qualitative validation results, the choices of microphysics parameterization and PBL are of utmost importance in predicting LWC and IWC. Although the results differ, the ensemble members tended to overestimate the presence of IWC to the detriment of LWC, as evidenced by the high FARs observed for IWC. For this reason, numerical prediction models can underestimate the presence of liquid water in mixed-phase clouds, thereby minimizing possible risks to aviation safety.

Figure 4 shows the qualitative validation results for LWC. The daily average bias shows near-zero values for members 7 and 8 (WSM6 microphysics). However, these two members showed larger deviations, indicating that they tend to overestimate or underestimate depending on event. Members 3 and 4 (Morrison microphysics) had a mean closer to 0 along with smaller deviation, whereas member 1 yielded a value furthest from 0.

For MAE and RMSE, member 3 (including the Morrison microphysics and MYJ PBL schemes) showed the best average performance, whereas member 1 (Goddard microphysics and MYJ PBL schemes) showed the poorest. Contrary to the qualitative validation described above, here, the microphysics parameterizations have greater importance than those of the PBL. By combining these results with those of the qualitative validation, the Morrison microphysics scheme produces superior results to the remaining parameterizations. PBL parameterizations are not of great importance in the quantitative validations, although they were decisive in evaluating the presence or absence of LWC. The Goddard microphysics scheme could best detect the presence of IWC, but LWC tends to be underestimated.

Few validation studies of LWC and IWC can be found in the literature, owing to the complexity and high cost of measurements in clouds. Thus, comparisons with the present study are difficult because of the use of different models, parameterizations, and sampling methods. Many studies have used ground-based observations for validation of LWC at lower levels. Huang et al. (2015) investigated LWC in PBL clouds using

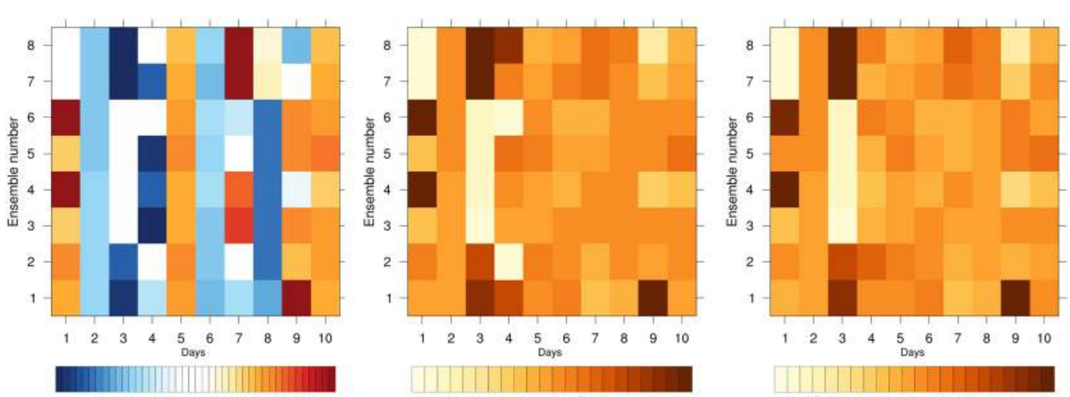

Figure 4. Average bias (left), mean absolute error (middle), and root-mean-square error (right) for liquid water content by ensemble number and day.

ground-based lidar observations. Using a limited-area model, they noted clear underestimation of LWC in PBL clouds. This was improved by introducing microphysical and PBL parameterization schemes. Naud et al. (2014) assessed several NWP models using a set of satellite observations, finding that these underestimated low-level LWC. Those authors suggested that the parametrization schemes (i.e., PBL and cloud microphysics) were most likely the source of model deficiencies. Many other studies have focused on investigating low-level LWC associated with fog events (Katata et al., 2011; Rémy & Bergot, 2009). Nygaard et al. (2011) studied episodes of in-cloud icing at ground level using WRF with a microphysics ensemble. With high horizontal resolution, the model was able to capture all icing events when the Thompson or Morrison cloud microphysics schemes were used together with the YSU PBL scheme.

On the other hand, Molthan and Colle (2012) validated WRF using aircraft measurements of hydrometeor content and size distribution in a snowfall event. They found that double-moment schemes may improve the representation of ice crystals. Nevertheless, in the present study, the availability of a database including 37 SLW events, has allowed a model validation for in-cloud icing forecast.

4. Conclusions

In the present work, we examined a set of aircraft icing events using in-cloud microphysical measurements. We used data from 10 scientific flights conducted with an aviation research platform. The flights were during winter conditions in the presence of SLW. We used the database acquired during these flights to validate a multiphysics ensemble with the WRF mesoscale model. This ensemble was constructed using four microphysics and two PBL parameterizations.

The ensemble of simulations showed large variation among results of the various members, suggesting disparate performance in predicting LWC. From the qualitative validation, the Morrison microphysics and YSU PBL schemes gave the best results for LWC, with FAR 4%, POH 96%, FOM 33%, and POD 67%. For IWC, the best combination was the Goddard microphysics and YSU PBL schemes, with POD 67% and FAR 43%.

In the quantitative validation, the Morrison microphysics scheme yielded superior results to the remaining parameterizations. PBL parameterizations were less important in that validation but were essential in ascertaining the presence of absence of LWC. The Goddard microphysics scheme best detected IWC but tended to underestimate LWC. Although these results varied, the prediction models tended to overpredict the presence of IWC to the detriment of LWC, as evidenced by high FARs for IWC, whereas LWC is underestimated. Consequently, the numerical prediction models may underestimate the presence of liquid water in mixed-phase clouds, thereby minimizing the risk to aviation safety.

Supported by in-cloud measurements, the present results can improve the prediction of icing conditions in the atmosphere. Forecast systems using ensembles such as that proposed in the present work can be used operationally in planning air routes.

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