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Overview of Cloud Microphysical Measurements during the SENS4ICE Airborne Test Campaigns: Contrasting Icing Frequencies from Climatological Data to First Results from Airborne Observations

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Abstract

The European Union's Horizon 2020 programme has funded the SENS4ICE (Sensors for Certifiable Hybrid Architectures for Safer Aviation in Icing Environment) project [1], an innovative approach for the development and testing of new sensors for the detection of supercooled large droplets (SLD). SLD may impinge behind the protected surfaces of aircraft and therefore represents a threat to aviation safety. The newly developed sensors will be tested in combination with an indirect detection method on two aircraft, in two parallel flight programs: One on the Embraer Phenom 300 in the U.S. and one on the ATR-42 in Europe.

In this framework the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) is in charge of the airborne measurements and data evaluation of the microphysical properties of clouds encountered during the SENS4ICE field campaigns in February, March and April 2023. We present the instrumentation that is used in the flight experiments for the characterization of icing environments and for the validation and performance assessment of new sensors for the detection and discrimination of Appendix O and Appendix C conditions [2, 3].

Further, with partners from Centre Europeen De Recherche Et De Formation Avancee En Calcul Scientifique (CERFACS), the German Weather Service (DWD), the Italian Aerospace Research Center (CIRA) and Leading Edge Atmospherics (LEA), we present the considerations that were undertaken to find the best campaign location with highest frequency of icing occurrence on a climatological basis, taking into account the safety requirements of the aircraft. Four data sets of icing conditions based on various meteorological input data (model and observations) have been analyzed to provide an overview of the occurrence of icing. The data give a good impression on the geographical and vertical distribution of icing conditions above Europe and the Northern U.S. in general and specifically at higher altitudes (> 750 hPa or 8000ft) for the European campaign. We find enhanced icing frequencies between 1 to 5% at altitudes between 2 and 6 km even in the spring, summer and autumn months above Europe.

We show highlights from selected individual cases from the North American test campaign performed in February and March 2023. The analysis gives a first impression of the extensive data set of icing conditions made available by the SENS4ICE project for sensor evaluation and for validation of satellite observations and model forecasts.

Introduction

The aerospace industry and certifying authorities have recognized that aircraft need of a robust mechanism for the detection of Supercooled Large Droplet (SLD) icing conditions. As a consequence, the European Union's Horizon 2020 programme funded the SENS4ICE program [1] to develop hybrid ice detection methods involving onboard sensors for direct detection as well as an indirect method that assesses flight performance degradation. An overview of the project and a presentation of the deployed direct sensors and the indirect system is given in [4, 5].

The technologies being developed for the direct as well as indirect detection of SLD icing conditions need a validation, meaning highly accurate information about the microphysical cloud and icing conditions encountered during the flight. This can in principle be done with established and tested under-wing cloud probes, used for measurements of microphysical properties in research flight programs.

The flight test campaigns were carried out with two aircraft: The Phenom 300, a twin-engine jet aircraft, operated and modified by Embraer and the ATR- 42, a two-engine-turbo prop aircraft, operated and modified by Safire (see Fig. 1). The instruments used during the flight campaigns of SENS4ICE were previously used in wind tunnel tests of SLD and Appendix C conditions [6] and on other aircraft in icing conditions [7] to test and improve their working principle. For consistency and to reduce the uncertainty related to different measurement principles, the same instruments were chosen in order to compare different droplet spectra among the tunnels and to provide valuable information on the collision efficiency of bulk water content instruments. The same holds true for the comparison of the flight campaigns where similar reference instruments were deployed on both aircraft.

A first overview of available data from the North American campaign will be provided in the last section while the European campaign was ongoing at the submission of the paper.

FIGURE 1 ATR-42 operated by Safire

Climatological Considerations on the Location of Operation

In anticipation of the campaigns, different models and observational data sets were analyzed to provide the location with the highest probability of icing and SLD during the months of February and March in the U.S. and April in Europe. Using this mixture of models and observations we provide information on the climatological frequency of icing occurrence with respect to altitude, season, geographical location and severity above Europe. Next to general icing frequencies, single data sets were filtered and analyzed taking into account the safety margins of the two aircraft. The compilation of the frequency of occurrence of icing and SLD from the different model outputs and observations cannot be compared directly but rather serve as complementary data sets.

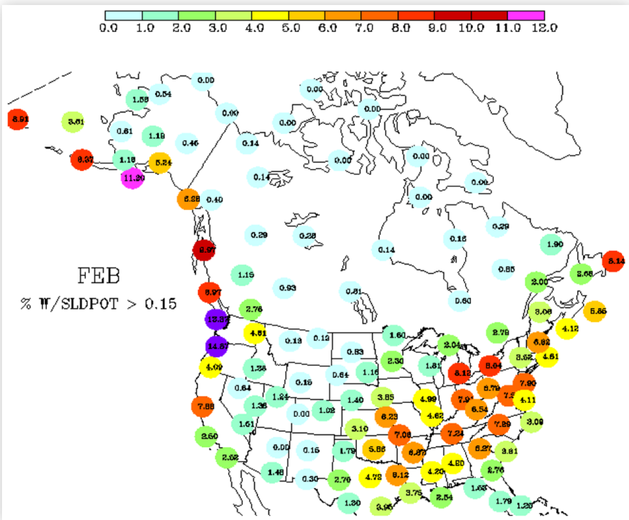
While we provide information on frequencies of severe icing in general, we also discuss the specific safety requirements of our campaigns and the constraints imposed on the selection of the campaign locations. As different data sets and icing indices are used we comment on common features and differences.

North American Test Campaign

The probability for the potential of SLD occurrence in the U.S. has been derived with surface observations and coincident humidity and temperature soundings from 1997 till 2001 using an extensively validated detection algorithm described in [8]. A positive icing potential derived for the soundings with a scale between 0 and 1 was classified with values > 0.15 for icing and > 0.4 for SLD as validated with pilot reports of icing incidents from passenger aircraft.

An overview of the SLD occurrence above the US for the month of February is shown in Fig. 2. Further information on icing frequencies above the U.S. is given in [8]. Two main target regions with highest SLD occurrence rates across the U.S. were discussed prior to the campaign: First the U.S. North West up to Alaska with the highest occurrence rate of SLD along the coast. The main reason for the high occurrence rate along the west coast is the predominantly clean marine air with reduced aerosol loads leading to fewer but larger droplets. This region however seemed inappropriate for this flight program as there are difficulties associated with terrain and thus, safety margins for operation in case of severe icing, the scales of icing in this area (often small patches), as well as a lack of alternate landing airports in several areas. Second, the Central to Northeast Regions near the Great Lakes (e.g., Illinois, Indiana, Missouri) as a known test region in terms of operations and weather conditions from previous most recent flight programs [9] was taken into consideration. The Northeast region also has areas of significant terrain and some areas of heavy air traffic. With reasonably good potential for SLD occurrence frequencies [8], icing occurring at relatively broad scales, broad expanses of flat terrain, and many areas

FIGURE 2 Frequency of SLD occurrence (in % of days) for all altitudes for the month of February across the US, inferred for an SLDPOT > 0.15 as described in [8].



of quiet airspace, the Central region was chosen for the base of operation. As a consequence, the Phenom 300 was flying in icing conditions with the main target regions near Alton, IN, in the Great Lakes region as this area has been probed extensively in past missions and showed a high occurrence rate of icing conditions, including SLD [10].

With great flexibility on the region of flight testing, the aircraft (and crew) was able to shift the time and areas towards those most favorable for encountering the best conditions for flight testing of the sensors on any given day.

As there was no fixed limitation of aircraft operation (with respect to altitude, speed or cloud type (mixed phase, convective, stratiform)) but mainly on the type of Appendix O conditions (freezing rain was avoided), the aircraft was able to operate in different cloud layers. The winter months February and March with highest icing frequencies were considered as ideal flight test conditions as will be shown in the last section.

European Test Campaign

The location of operation for the ATR-42 has been based on extensive climatological reviews of the potential of icing (including SLD) occurrence above Europe. Satellite-based observations with new retrieval methods for severe icing provided by CIRA (Zollo et al., SAE, 2023) and icing predictions of the ADWICE icing tool [11] operated by the German Weather Service (Deutscher Wetterdienst, DWD) were compared with results and discussed in the light of available literature of a SIGMA-based climatological analysis (SIGMA is short for System of Icing Geographic Identification in Meteorology for Aviation) [12], where icing frequencies were estimated using ERA-40 reanalysis, as well as a blend of surface observations and balloon-borne soundings [13]. A third analysis of the potential of icing occurrence frequencies was done with the ICEP algorithm (icing index from Meteo France's ICE Potential forecast index) here used by CERFACS on a finer-scale reanalysis (ERA-5) and 40 years of data. Others are based on new detection methods or the combination of icing forecast products with regional numerical weather prediction models. As the specific requirements for the airborne campaign may not be of general interest, the data (vertical and geographical distribution, annual variability) for icing conditions that were expected to be "severe" provided here contain a lot of information on icing frequencies aloft particularly in rather scarcely sampled regions between 2 and 6 km.

Next to general icing conditions, mainly severe icing conditions (including SLD) were investigated in the winter and spring months but also in view of the annual variability. In addition, specific safety requirements for the ATR-42 aircraft with a minimum level of operation of 8000ft above ground level for the icing cloud encounters and a required warm air layer below flight altitude for deicing were included in the investigation. Our analysis, including these specific safety requirements for the ATR-42, may be of general importance and interest for aircraft with limited available power for deicing of the relevant aircraft parts and for aircraft with inadequate protection of surfaces where icing from large drops would occur. Exit strategies are then limited to a descent into a deeper warm air layer below the flight altitude which could be included in future flight planning to reduce flight hours and fuel.

As most icing program are conducted in the winter months this campaign was planned for April, which required extensive analysis on the region, the altitude of icing and the type of icing that suits the required safety margins best. We will provide results from the different data sets from the ICON-based ADWICE icing climatology over 5 years of data, a 40 year of ERA-5 data coupled to the ICEP algorithm, supported and underlined with the monthly mean of MSG Satellite-based icing frequencies in recent years. We will contrast and discuss these specific icing conditions with the overall picture of icing in Europe in the winter months based on our data sets.

ADWICE The frequencies of the potential of icing occurrence shown in Fig. 3 were based on the ICON model with a resolution of 0.25° x 0.25° coupled to the ADWICE algorithm [11]. ADWICE reforecasts from December 2015 to March 2020 were used with a total of 16950 hours of data. As the most recent years were chosen for the icing frequency analysis, the impact of higher temperatures due to global warming may provide a view on the potential shifts for icing frequencies compared to the larger data sets of other climatologies. The model output with an hourly resolution, 4 times daily revised on 32 pressure levels is the basis of our analysis. In particular an altitude profile with a meridional cross section of the European region between 15°N and 35° E is provided in Fig. 4.

Different icing scenarios (freezing, convective, stratiform and general) and intensities (severe, moderate, light) provided by ADWICE were filtered by daily maxima from hourly forecasts and a monthly mean from daily averages. The icing scenarios are described in [11] and are based on temperature and relative humidity thresholds and only a subset of the data are shown here. The predicted LWC defines the icing intensity.

FIGURE 3 Geographical distribution of icing frequencies (all conditions > 750hPa, upper panel) and severe and moderate icing conditions (all altitudes, lower panel) above Europe for the months of April based on 5 years (2015-2020) of ICON reforecasts.

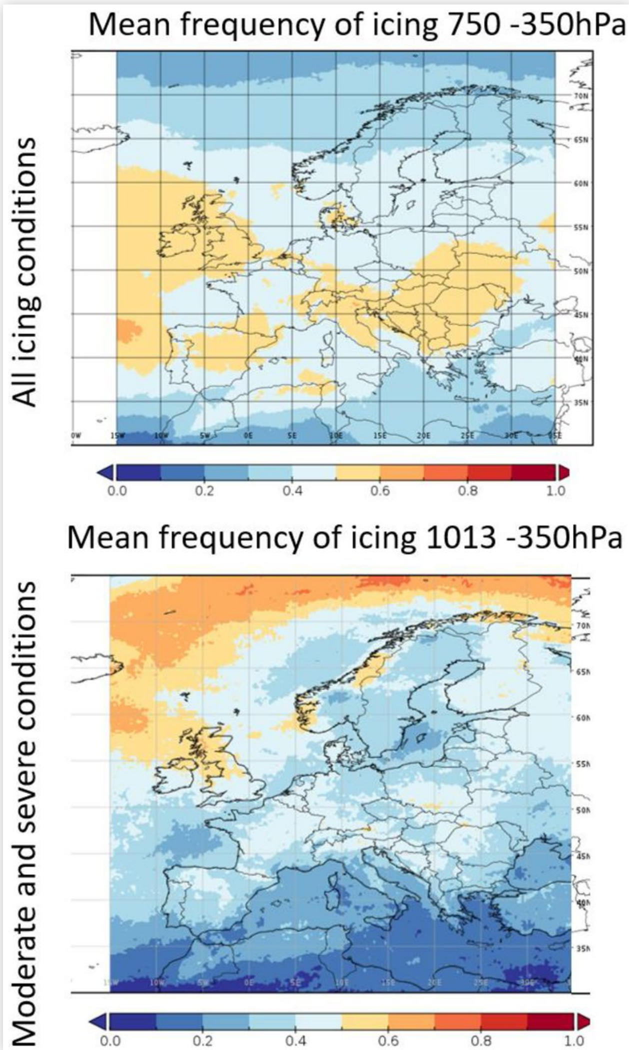
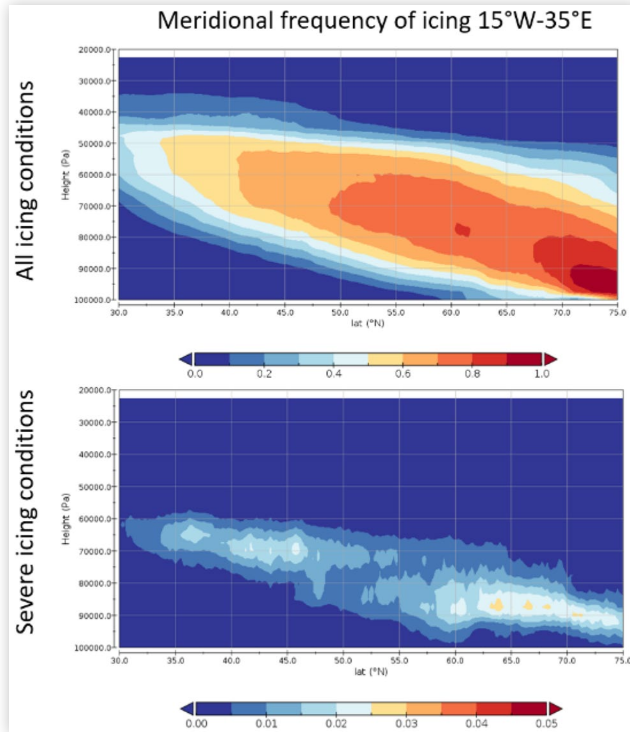


FIGURE 4 Pressure (altitude) distribution of meridional icing frequency from 15°W to 35°E for all icing conditions (upper panel) and for severe icing conditions (lower panel).



Based on these data, for the months of April, the highest icing frequencies above Europe (all altitudes, Fig. 3. lower panel) can be found in the northern countries at the coast of Norway, Ireland and Great Britain and above the Atlantic. During the winter months, enhanced icing frequencies move towards the continental regions like Germany, Netherlands, Belgium but also Russia (not shown) consistent with previous studies [13]. In the winter months (December to February, not shown), these icing frequencies shift to lower altitudes and higher latitudes. Highest icing frequencies are observed in December.

For our specific target region (Fig. 3, upper panel), above 8000ft (~750 hPa up to 350hPa) enhanced frequencies are found over the North Atlantic and West of Ireland, France and Portugal. Also, the continental Alpine region, the Balkan and Romania reveal high icing frequency aloft. If the geographical and altitude dependent icing frequency is folded with the 0°C -isotherm at 8000ft, only regions in Southern France and Northern Spain and further south match – on a climatological base -the safety criteria. These specific icing conditions at higher altitudes are mostly related to convective activity transporting supercooled liquid water into higher altitudes. Therefore, the southern European countries are more affected by these type of icing conditions.

Analyzing the altitude dependence in a meridional cross section from 15°W to 35°E of icing frequency, by comparison of severe icing to all types of icing (Fig. 4), severe icing is rather uncommon with only 1 to 5 % of the time and is indicated at northern latitudes (> 55°N) in lower altitudes (between 900 and 800hPa) compared to all icing conditions. Particularly in the southern part of Europe (at latitudes below 45°N) the highest frequencies of icing up to 450 hPa can be found.

ICEP The icing index from Meteo France's ICE Potential forecast index (ICEP) is computed from relative humidity (RHw) and temperature (T) on different atmospheric pressure levels. It provides a degree of severity from 0 to 10 in the temperature range from 0 to -28°C at a RHw > 80%. For a high icing index (> =8) a greater potential of severe icing is indicated by ICEP. In contrast to SIGMA, ICEP does not use satellite, radar or other observational data. It means that ICEP identify potential areas of icing risks and intensities solely based on the most favorable conditions of temperature and humidity. Those areas may include glaciated cloud conditions but ICEP only target the potential risks. Therefore, higher icing frequencies may be found when compared to other icing detection algorithms that use satellite and radar data in addition. The data set comprises more than 40 years of ERA-5 data with a resolution of 0.5° on 20 vertical levels which is the largest data set used in this comparison. Thus, interannual variability may not have a strong impact on the results here.

As mentioned above the probability for severe icing is expected if the ICEP index value is equal or above 8. Fig. 5 shows the annual variability of the altitude profile of icing frequencies above Europe (20°W to 50°E) averaged over the latitudinal range from 30°N to 60°N. Highest occurrence of severe icing, according to the ICEP index, are found at around 1 km during the months of December, January and February. For the specific safety requirements of the European flight test campaign with the ATR-42, with limited options of safe exit to higher altitudes (due to the limited power of the aircraft) a warm air layer (T> 0°C) of 8000 ft thickness was required to allow the aircraft to deice (Fig. 6). For severe icing at higher altitudes (> 2,5 km) with a warm layer below (Fig. 6, upper panel) as targeted for the European SENS4ICE campaign, the spring and autumn months (April to November) show the highest frequencies. This potential for severe icing can particularly be found at lower latitudes (around 40°N) above France and Northern Spain (here shown for the pressure level of 650 hPa).

This criterium of the warm air layer below 8000ft reduced the probability of finding icing by about a factor of 3 to 4. Nevertheless, the main regions for these specific conditions can be expected above the continents in Northern Spain and Southern France. Also, the Atlantic and Mediterranean region shows some (low) probability (~1-2 % at 650 hPa) of finding icing in April.

FIGURE 5 The upper panel shows annual variability of the altitude profile of icing frequencies for the geographical region shown in the lower panel. The lower panel shows the probability of the potential for severe icing at 650hPa in the months of April derived with the ICEP icing index based on 40 years (1979-2020) of ERA-5 data. Note the different values of the color scales

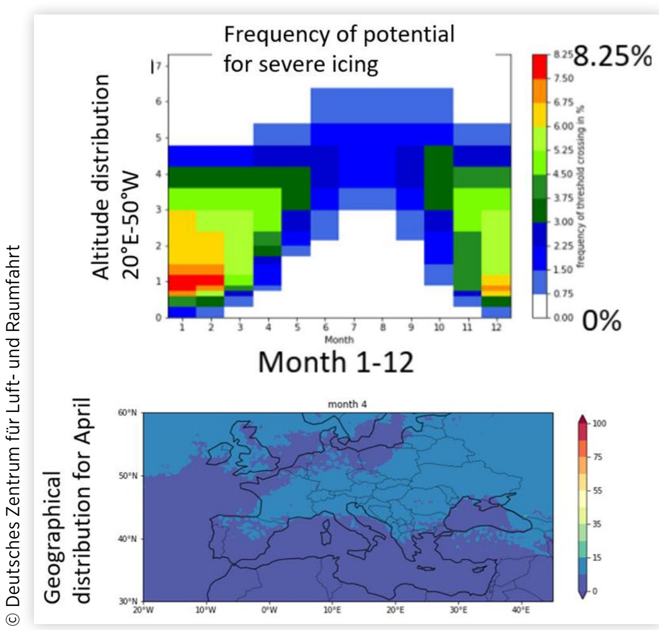
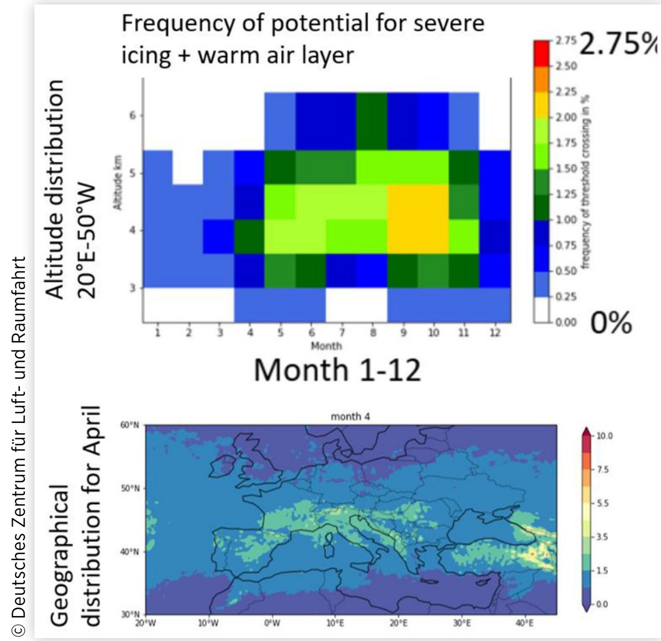


FIGURE 6 Same as Figure 5 including the criterium of a warm air layer (T>0°) below the icing region.



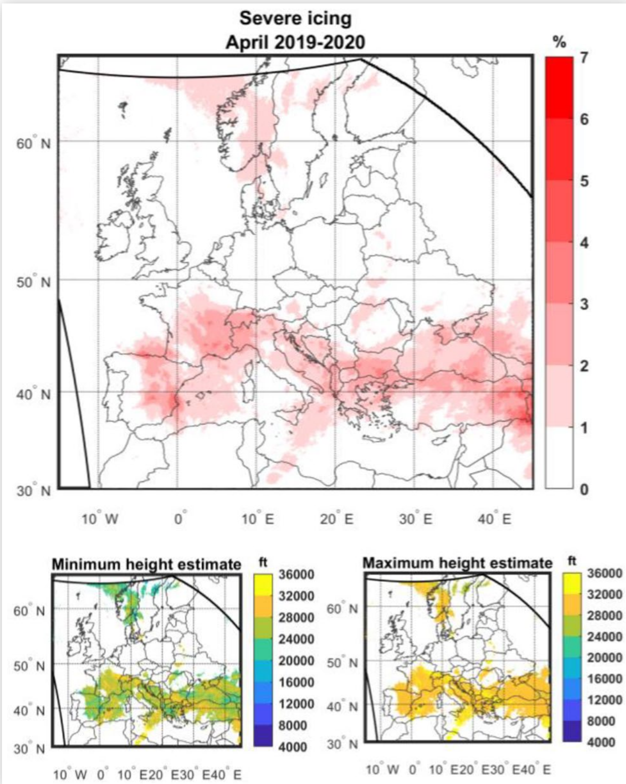
MSG Satellite-Based Icing Frequencies Within SENS4ICE, CIRA has developed a nowcasting tool for detection of icing conditions based on satellite data. High-resolution satellite products from Meteosat Second Generation (MSG) data with a spatial and temporal resolutions of about 3 km and 15 minutes during April 2019 and 2020 have been used. The original aim of this tool is to identify areas potentially affected by in-flight icing hazard. The products provide information about the severity of the icing condition (light, moderate or severe) and an estimate of the altitude at which the icing can occur. Microphysical properties of clouds derived from satellite data are merged with a set of experimental curves and envelopes that describe the dependence of cloud liquid water content, mean effective diameter of the cloud droplets and ambient air temperature. While the tool was mainly developed to provide a nowcasting system for flight guidance during the campaign, it is here used for an application of a statistical analysis of icing occurrence in the past years for the month of April. Although only two years of data go into the analysis, they are based on observations rather than pure model data, and thus provide a different perspective, particularly on the icing frequencies in recent years.

One example of a 2-year data set of icing occurrence above 8000ft in the months April is provided from the satellite based severe icing retrievals [14] as shown in the Fig. 7. The red colors indicate enhanced probability of finding icing at higher altitudes (minimum height estimate at 12000 ft).

Discussion

A quantitative comparison of the three data sets for the European sector is not possible as icing frequencies have been derived from input variables of different years and different

FIGURE 7 Overview of minimum and maximum altitudes (lower two panels) and frequency (upper panel) of severe icing conditions above Europe based on an average of two years (2019 and 2020) of MSG satellite data in months of April provided by CIRA (see also Zollo et al., SAE, 2023).



sizes of the data sets underlying the analysis. We focus here particularly on the month of April, relating it to annual icing frequency and specifically to the occurrence of icing at higher altitudes (above 8000ft). As most icing occurs at lower levels (< 2000m) in the winter months (~6-8%) (based on ICEP climatologies), the icing frequency expected for the European campaign conditions is rather somewhat lower with about 2-5 % of the time, however it is not negligible. However, in a general context it needs to noted that liquid supercooled droplet icing is not only hazardous at lower altitudes but also at higher altitudes during the spring to autumn seasons, with the highest frequencies for that period in the southern European countries between 2 and 6 km. The conditions that lead to these liquid water content at higher altitudes are mainly convectively driven.

The data provide a large view on the statistical, climatological occurrence of icing (including SLDs) at higher altitudes.

Based on these constraints for the month of April, the location of Toulouse, the main base of the Saphire-ATR-42, was chosen as it offers the opportunity to probe severe icing formed over the ocean as well as continental icing in clouds that allow the aircraft to safely deice. Mainly convectively driven supercooled droplets (Appendix C but also O) are expected at altitudes above 8000ft AGL which may have the potential to form non-classical SLD. Icing conditions in stratiform clouds may also be targeted if they meet the above-mentioned safety requirements.

Selection of Reference Instruments for the Detection and Characterization of Icing Environments

The challenge of detecting and classifying atmospheric SLD conditions in flight often lies in the measurement of few large droplets in the presence of many small droplets, the determination of the phase of the droplets particularly in the size range between 50 to 150 µm and the measurement of the cloud water content of this large droplet spectrum, which can sometimes contain mixed phase.

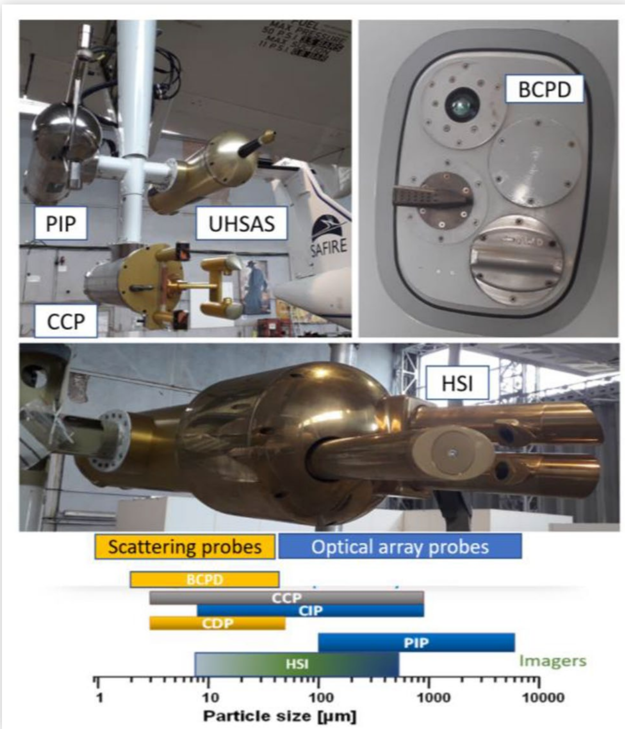
For the Phenom 300, two instruments were chosen as the reference instrumentation for the campaign: a cloud combination probe (CCP) owned and operated by Embraer and an ice crystal detector (ICD) [15] operated by SEA. The CCP was previously used in SENS4ICE during the wind tunnel measurement and therefore the instrument's data evaluation is done as described in [6]. The combination of droplet spectra between 2 and 960 µm and liquid water content measurement provided a good base to differentiate between small and large droplet icing.

A set of instruments was selected by DLR for Safire's ATR-42 aircraft to cover the large size range of droplets encountered in both Appendix C and Appendix O conditions as well as their phase (Fig. 8, DLR instruments marked in green). The aim of the instrumentation is to provide highly-resolved particle size distributions (PSDs) from 2 to 6400 µm and derived parameters such as the median volume diameter (MVD), the liquid water content (LWC) and the cumulative mass distribution (CMD).

The optical sensors are deployed together with bulk liquid and total water content (TWC) instruments such as the Nevzorov Probe (ATR-42) [6, 16] and the Ice Crystal Detector (ICD) (Phenom 300) [15], also well known for the use of droplets and glaciated cloud conditions. Next to classical

FIGURE 8 Safire ATR-42 aircraft with sensor location of the DLR reference sensors. Green squares show the location of DLR instrument while more sensors for redundancy are operated by Safire.

FIGURE 9 Picture of the DLR and Safire instruments used for microphysical characterization of the icing environments installed on Safire's ATR-42 and their respective size range and detection method.



scattering spectrometers (CDP) and optical array probes (CIP (Cloud Imaging Probe) and PIP (Precipitation Imaging Probe) from Droplet Measurement Technologies (DMT)) [17], Artium's High Speed Imager (HSI) [18] using a 2D-CMOS array for particle images, and a multi-beam illumination will provide additional high resolution information for particles below 100 µm, where uncertainties remain due to the depth of field criterium.

The CIP and the PIP both consist of 64 photodiode arrays illuminated by a laser beam moving at the speed of the aircraft. When a particle passes through the laser beam, it projects a shadow on the diode array and each pixel is triggered if the light intensity falls below a threshold value (here grey scale of 50%). The images are constructed by appending consecutive slices. The monoscale cloud probe PIP has only one light intensity level and a reduced size resolution (100 µm for PIP as compared to 15 µm for the CIP) covering a larger size range.

Image analysis is performed with a Python-based code developed at DLR and described in [6, 19]. Particles were filtered by shape (phase) to select the type of icing conditions (mixed phase and supercooled droplet icing). The procedure to discriminate between Appendix O and C icing is following the strategy described in [10].

Further, DMT's Backscatter Cloud probe with Polarization Detection (BCPD) [20, 21], tested in wind tunnel and flight experiments during SENS4ICE, will be deployed in order to provide information on the phase (asphericity) of the particles in the lower size range.

The TWC measurement installed on Safire's ATR-42 features a new sensor head of the Nevzorov Probe, with an additional 12 mm cone (diameter of the cone) next to the 8 mm cone [6]. The combination of the two lightweight, low-drag sensors (BCPD and Nevzorov, here called cloud multi detection device (CM2D)) allow for a combined characterization of the total and liquid water content distribution where the size and phase information of the BCPD is used to correct the collision efficiency of the Nevzorov [21].

In addition, instruments operated by Safire like a Licor water vapor instrument, Goodrich icing detector, Robust Probe, a CDP, and UHSAS are installed for redundancy and additional meteorological information.

While the North American campaign was exclusively supported by Leading Edge Atmospherics in terms of forecast and flight planning, the flight planning of the European campaign is supported by teams from Météo France, the German Weather Service, and Leading Edge Atmospherics. Next to the prediction of icing conditions of different severity, models with information on the microphysical properties of the clouds will be employed for the specific prediction of supercooled droplets (Jaron et al., SAE, 2023). Satellite based retrievals of the presence of SLD (CIRA) [14] and information of the cloud phase (DLR) derived from Meteosat Second Generation (Mayer et al., 2023) will be provided on a nowcasting time scale. The teams support the planning of each flight several days in advance and also provide inflight-guidance. An overview of the meteorological forecast tools and the conditions found during the campaign is provided by [22].

With a limited payload for aerosol (UHSAS), and water vapor (Licor) measurements the data provides the opportunity to investigate the impact of aerosol and humidity on aerosol-cloud interaction, cloud droplet formation and evolution. The flight strategies are chosen such that continental as well as oceanic air mass are probed to contrast the dependence of CCN on cloud droplet number. A special focus is given on cloud tops as the aircraft approaches the newly formed droplets in growing convection as well as stratiform cloud decks from dry layers above the cloud [24].

The data from the reference instrumentation of the two SENS4ICE field campaigns provide a sufficient and valuable base to compare and validate the performance of the new icing detectors developed during SENS4ICE that were installed on

FIGURE 10 Picture of the DLR and Safire instruments installed on Safire's ATR-42 with ice accretion on the unheated parts while flying through supercooled liquid clouds.

TABLE 1 List of the main reference instruments for the European and North American flight test campaign.

Instrument	Measured parameter	Range	Reference
Cloud Combination Probe (CCP)	Cloud droplet number and size	2 – 960 µm	[6]
Precipitation Imaging Probe (PIP)	Cloud droplet and ice crystal number and size	100-6400 µm	[23]
High Speed Imager (HSI)	Droplet and Ice particle size and complexity	2-2000 µm	[18]
Nevzorov Probe	LWC and TWC	0.03 –3 g m^{-3}	[6, 16]
Backscatter Cloud Probe with Polarization Detection	Droplet and ice crystal size and asphericity (phase)	2- 42 µm	[21]
Cloud Combination Probe (CCP) operated by EMB	Cloud droplet number and size	2 – 960 µm	[6]
Ice Crystal Detector operated by SEA	LWC and TWC	0.02 –5 g m^{-3}	[15]

The last two instruments on the list (grey shading) were installed on the EMB- Phenom 300, while all others were installed on the Safire ATR-42.

the two aircraft for first flight testing. They further allow to extensively validate new satellite products in North America and in Europe as well as model data on both continents.

In the next section, we provide a first overview of the data acquired during the SENS4ICE North American campaign. While the campaign preparation and first flight test for the European campaign were carried out during the submission of the manuscript, we focus on highlights of the North American flight campaign emphasizing that the analysis of the data is in a very early phase.

Microphysical Properties of the Clouds Sampled during the North America SENS4ICE Campaigns

In this section, we present a first impression of the cloud conditions during the North American flight test campaign. Instrumentation for measurement of icing cloud characteristics was provided by Scientific Engineering Associates (SEA) and by EMB and was mounted on one pylon on the side of the aircraft forward fuselage. In total 14 flights (including transfer to the U.S. from Brasil) with about 9 local flights and more than 200 minutes (LWC > 0.02 g m^{-3} measured by the ICD) in clouds were achieved. To give the location and temperature range of all cloud conditions, we combine the LWC content measurement of the ICD with the droplet number concentration measurement by the CDP. This mainly covers Appendix C conditions and the lower mass mode of Appendix O. Fig. 11 provides the geographical overview of LWC at the specific location sampled by the ICD installed on the EMB Phenom 300. Altogether seven flights were taken into this overview chart. The LWC measurement is used here as indication to provide information on droplet icing conditions (Appendix C and O) in general.

As indicated in Fig. 11, several encounters of icing conditions aloft including SLD have been reported. LWC ranged up to 0.8 g m^{-3}. The flight program targeted SLD mainly in the early morning, and some were targeted twice during consecutive flights when the cloud was advected. The aircraft generally approached the clouds from the top. An overview of the (static) temperature range where supercooled droplets were found is provided in Fig. 12. We want to emphasize, that the LWC shown here represents only a subset of the total liquid water content as the hotwire sensor has a lower detection efficiency for larger droplets, mainly due to splashing [6].

Temperatures between 5 and -14° C were probed with high droplet number concentration up to about 760 cm^{-3} in the size range between 2 and 50 µm (CDP size range). Higher number concentrations were reported in the temperature range between 0 and -6°C, associated with high LWC (> 0.44 g m^{-3}), thus most likely related to Appendix C icing conditions.

A profile of LWC measured during the flight on 23 February 2023 is shown in Fig. 13. The static temperature profile is plotted in grey. Two main profiles can be identified with a temperature inversion at 800 m and approximately at 1.5 km. Such inversions are commonly found at the top of icing clouds. LWC was mainly found below 2000 m with a short intersect at 4000 m. In both clouds larger droplets with diameters > 40 µm together with many small droplets were observed as indicated by the droplet images on the left side of the graph taken from the CIP. Both layers (separated by about 200 km) had MVDs below 40 µm and Dmax > 100 µm, thus they fall into the category of freezing drizzle.

FIGURE 11 Overview on the geographical distribution of sampled LWC from the ICD instrument aboard the Phenom 300 during the SENS4ICE North American campaign. The color code denotes the LWC in g m^{-3}, grey dots show cloud-free air.

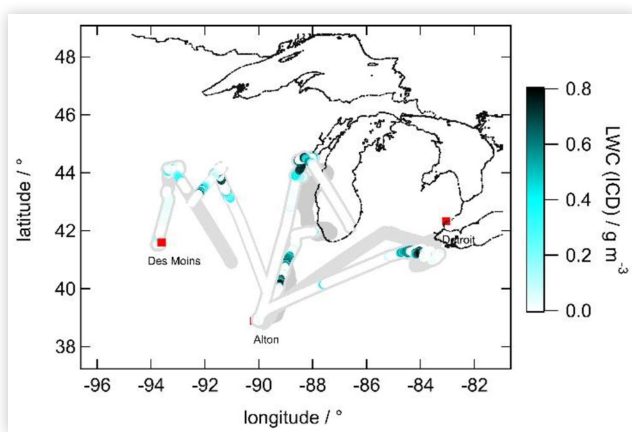


FIGURE 12 Temperature profile of LWC (10Hz time resolution) measured by the ICD during the North American SENS4ICE flight test campaign.

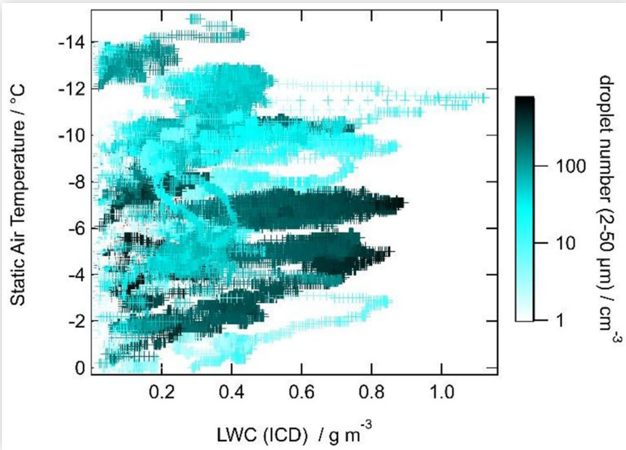
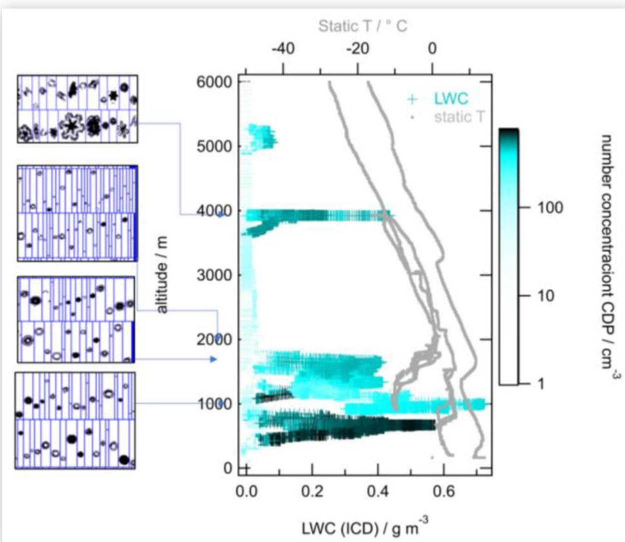


FIGURE 13 Altitude profile of the LWC from flight on 23 February 2023 with SLD encounters. Large droplets with many small droplets have been reported in the two inversion layers at 800 and 1500 m.



In the lower layer, several hundreds of small droplets were also measured indicated by the number concentrations of the CDP (color coding). At 4000m and temperatures of -15°C a mixed phase layer with larger ice crystals and large droplets was encountered. The lower layers in particular exceed the LWC range of the Appendix O envelope, which is reduced to values within the envelope if averaged over 30 s. Thus, relevant icing conditions as described Appendix O have been encountered on that day.

Summary and Outlook

During the SENS4ICE project new sensors including an indirect ice detection system were tested on two aircraft. The new detectors were tested in relevant icing conditions in February and March 2023 in the U.S. and in April 2023 in Europe. In order to provide high resolution and high accuracy data of the cloud conditions encountered during the SENS4ICE campaigns established so-called reference sensors were installed on each aircraft providing information on the particle size and number and the total cloud water content. The EMB Phenom 300 flying in the U.S. was equipped with a CCP (EMB) and an ICD (SEA) while DLR instrumentation installed on Safire's ATR-42 consisted of a large spectrum of cloud probes and measurement techniques covering a broad size range for the detection of supercooled large droplets and other icing conditions.

The data evaluation is performed by DLR including high resolution and detailed information on the microphysical cloud conditions along the flight path as well as a general overview on the microphysical properties encountered during the campaigns. We here present only a short impression on the expected data products and strategy of data evaluation.

In particular, we plan to discuss and compare the data to the extensive analysis of icing occurrence rates above Europe and the U.S. from four different data sets in the region of operation which have been presented in this paper.

The data obtained by the reference instrumentation not only help to judge the performance of new sensors but also provide valuable input for the validation of numerical weather prediction models and icing forecast tools as well as nowcasting products based on remote satellite instrument detection or ground-based radar observations.

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Definitions/Abbreviations

SLD - Supercooled Large Droplets

SENS4ICE - Sensors for Certifiable Hybrid Architectures for Safer Aviation in Icing Environment

DLR - Deutsches Zentrum für Luft- und Raumfahrt

CIRA - Centro Italiano Ricerche Aerospaziali

DWD - Deutscher Wetterdienst

CERFACS - Centre Europeen de Recherche et de Formation Avanceee en Calcul Scientifique

CCP - Cloud Combination Probe

UHSAS - Ultra-High Sensitivity Aerosol Spectrometer

EMB - Embraer

PIP - Precipitation Imaging Probe

HIS - High Speed Imager

BCPD - Backscatter Cloud Probe with Polarization Detection

MVD - Median Volume Diameter

LWC - Liquid Water Content

TWC - Total Water Content

CMD - Cumulative Mass Distribution

PSD - Particle size distribution

SEA - Science Engineering Associates Inc.

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