Assessment of Aircraft Icing using Satellite Data

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December 2022

Abstract

A sample of 115 aircraft icing events in the Western Europe and Northeastern Atlantic sector is studied, using pilot reports (PIREPs) and satellite observations and products. A detailed study of four events is performed, using also temperature, relative humidity and cloud water content (CWC) provided by the European Centre for Medium-Range Weather Forecasts model. Most of the moderate and severe icing reports ($> 70\%$) occurred between the months of October and February, and October and March, respectively. Icing events were also reported during final spring and summer months. Most of the events occurred between flight level FL100 and FL250, with a percentage of 82.7% and 78.6%, respectively, for moderate and severe icing. Moreover, the satellite products revealed that a great amount of the moderate icing events occurred in a cloud-filled environment with ice cloud-top phase, followed by mixed and water. For severe icing events, the majority of the cases were associated with ice and mixed cloud-top phases, the latter being the most frequent. Most of the icing events were associated with medium and high opaque clouds and $10.8\mu m$ brightness temperatures (BT10.8) between $-40°C$ and $-8°C$. Lastly, the four case studies analyzed were associated with small values of CWC ($< 0.18g/kg$) and high values of relative humidity ($> 74.8\%$). Moreover, in two events, aircraft icing happened below the cloud-top and two other occurred near the cloud-top (with a temperature close to the BT10.8).

Keywords: aircraft icing, PIREP, satellite products, ECMWF model, liquid water content

1. Introduction

Since the earliest days of aviation industry, weather has been recognized to have a major impact on air transport safety. Regardless of the improvements made throughout the years, according to the Aviation Weather Accidents Database (AWAD), the percentage of casualties in accidents due to the weather shows a modest increase between 1967 and 2010 [1]. Also, meteorological conditions are still one of the most significant causes of incidents and accidents in aviation [1].

Aircraft icing may occur throughout flights in the presence of supercooled liquid water clouds or mixed-phase clouds [2]. Icing is one of the meteorological phenomena that contributes for air transport accidents associated with weather conditions. Aircraft icing is of significant concern for aviation safety to the extent that, between 1998 and 2009, not less than 565 aircraft accidents were associated to ice accretion, in both commercial and non-commercial airplanes, in the United States [3]. Therefore, forecasting the icing phenomenon, areas of risk and its severity, is a major challenge to meteorologists and is of undeniable relevance [3].

Over the years, several studies were devoted to aircraft icing over North America (like in Politovich et al. [4]), however, over the western Europe only few studies addressed this topic [3]. The current study aims to characterize the aircraft icing environment in Western Europe and Northeastern Atlantic sector, using Pilot Reports (PIREPs) and satellite observations. Besides, a more detailed analysis of four events is performed, using also forecasts of temperature, relative humidity and cloud liquid water content provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) model.

2. Background

At temperatures below $-36°C$ to $-40°C$, liquid water droplets freeze spontaneously through homogeneous nucleation, depending on the diameter droplet [5]. In contrast, at sub-freezing temperatures above these values, the freezing of liquid water droplets usually requires the presence of ice nuclei [6]. However, the availability of ice nuclei in the atmosphere is small, especially at temperatures above $-10°C$. Therefore, liquid droplets at sub-freezing temperatures, known as supercooled water droplets, have been observed in several types of clouds [5]. In-flight icing is defined as the accretion of ice on the airframe during flight, caused by the presence of supercooled droplets [7]. These droplets are unstable and once hitting a cold object, they can freeze and form a thin coat of ice. This is the elementary mechanism for the icing phenomenon [7].

2.1. Icing Severity and Types of Icing

Aircraft icing can be divided into three physical types: rime, glaze and mixed ice, the latest being a combination of the first two types [4, 7, 8]. Rime ice may be formed when tiny, supercooled liquid droplets collide on the wing of the airplane and freeze instantly, before having time to spread away. Glaze ice may be formed when, upon impact on the airplane, the drops break apart and flow along the airframe, possibly to unprotected areas, before freezing into a smooth and transparent ice [7]. Hence, glaze ice has a greater impact on the performance of the aircraft when compared to rime and mixed ice [8, 9].

Aircraft icing can be classified into severity categories, which describe the impact of accreted ice on the flight of an aircraft [3]. Today, according to the Weather Meteorological Organization (WMO) the severity of aircraft icing [10] is classified as: light - accumulation rate may create a problem if flight in this environment exceeds 1 hour; moderate - rate of accumulation is such that even short encounters are potentially hazardous, anti-icing equipment must be used; severe - rate of accumulation is such that use of anti-icing equipment fails to reduce or control the hazard, so immediate diversion from the region is necessary. In Europe only moderate and severe icing events are usually reported, since this is mandatory according to the International Civil Aviation Organization (ICAO) [11]. As such, only these two categories will be analyzed here.

2.2. Atmospheric Variables that contribute to the occurrence of Icing

In general, aircraft icing occurs in extensive layers of clouds, where considerable amounts of liquid water are available and the temperature is below freezing. Moreover, the severity of aircraft icing depends on three atmospheric parameters: the liquid water content (LWC), the mean effective droplet diameter (MED) and the ambient temperature [12, 13]. Since water in the liquid state tends to exist in larger concentrations in warmer air and diminishes with decreasing temperature, icing generally occurs at temperatures between $-40°C$ and $0°C$, being more frequent between $-20°C$ and $0°C$ [7, 14]. Moreover, severe icing takes place normally between $-15°C$ and $0°C$ [12, 8].

The first parameter, LWC, which is liquid water per unit volume, is one of the most crucial variables with impact on aircraft icing. The greater the LWC, the more significant is the icing risk [8]. Curry et al. [15] showed that, in the mid-latitude regions of the North Atlantic Ocean, the average value of the cloud's LWC was approximately $0.095\,g/m^3$ ($\sim 0.069\,g/kg$) for low-level clouds and $0.043\,g/m^3$ ($\sim 0.031\,g/kg$) for mid-level clouds. Finally, the greater the MED, the higher is the impact on the airplane since the thickness of the ice increases [8]. The most dangerous icing events occurred in situations where supercooled droplets of $40 - 300\mu m$ diameter were present [9]. Note that the icing severity depends on the relationship between LWC and MED [16, 13], so that larger MED requires smaller LWC values and vice versa. LWC greater than $0.2g/m^3$ and MED greater than $30\mu m$ represent the conditions impacting most heavily on aircraft performance [12, 13].

2.3. Aircraft Characteristics that impact the occurrence of Icing

There is a vast number of aircraft characteristics that may impact differently the occurrence of icing, such as the speed of the aircraft, the aircraft size and the type of deicing and/or anti-icing equipment employed [14]. The aircraft speed may impact the ice accretion through kinetic heating [14]. The greater the speed, the larger the kinetic heating, which consequently increases the temperature, decreasing the accumulation of ice and the risk of aircraft icing. In general, smaller aircraft fly at lower altitudes where icing conditions are more frequent which, along with their diminished reserve power and de-icing capabilities, makes them more vulnerable to aircraft icing. On the other hand, for larger aircraft cruising at altitudes above icing-prone layers, icing conditions are only found during the ascent and descent maneuvers [7].

2.4. Icing Effects and Icing Detection

The icing phenomenon can affect the performance of an airplane in multiple ways. While it decreases lift and the rate of rise, it increases drag since it disturbs the smooth flow of air [8]. Consequently, the aircraft may stall at lower angles of attack and higher velocities. To counterbalance the additional drag, power is added to the engines, which increases fuel consumption [8].

Generally, pilots have a defective view of the airplane's wings so they normally use the ice accreting on wipers, windshields, and/or pitot tubes near the nose of the aircraft to evaluate the presence and quantity of ice [7].

3. Implementation

3.1. PIREPs

As expected, PIREPs are more recurrent during the day and more often find near significant airports and flight routes with hefty traffic [3]. Additionally, the reported severity of the icing event is determined by the pilot and will vary with the type of airplane, so they tend to be subjective. Furthermore, delays may occur in providing the icing report that will lead to a notable error in time and location [17], and areas of deep convection are normally avoided. Hence, the PIREPs are sporadic, non-systematic [18] and their distribution is biased. Due to these limitations, PIREPs are not suitable to perform a climatology of the aircraft icing. Nonetheless, this type of data is very useful in providing icing information and verifying icing forecasts.

This work uses a sample of 115 PIREPs provided by the Portuguese Institute for Sea and Atmosphere (IPMA). From the reports, 86 are of moderate intensity and 29 are of severe intensity. Each report contains information on severity, date, time, latitude, longitude and flight level. A flight level is the height, expressed in hundreds of feet, above the standard mean sea level pressure of 1013.25hPa at which that pressure occurs in the ICAO standard atmosphere [11]. The location of the icing reports includes the western Europe and Northeastern Atlantic sector and is shown in Figure 1. The analyzed cases were reported between January 2019 and March 2022.

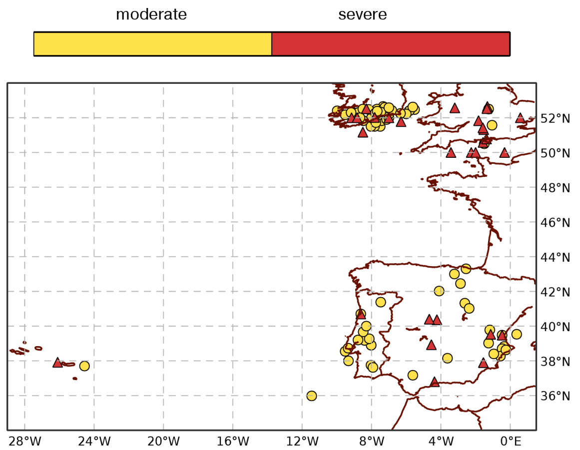


Figure 1: Location of icing pilot reports.

Regarding the PIREPs spatial distribution, it is evident that there were more icing occurrences north to the $45°N$ parallel than south (not shown). This would be expected as the region north to $45°N$ generally comprises lower temperatures associated to icing events. Concerning the selected PIREPs, the most frequent reports were of moderate icing. Most of the moderate and severe icing reports ($> 70\%$) occurred between the months of October and February, and October and March, respectively (not shown). Icing events were also reported during final spring and summer months, which is coherent with previous studies like in Sand et al. [9]. The seasonal and inter-annual atmospheric variability explains this. Regarding altitude, most of the events occurred between FL100 and FL250 (not shown), with a percentage of 82.7% and 78.6% for the moderate and severe events, respectively. In contrast, about 7% and 10% of the moderate events took place below FL100 and above FL250, while 18% and 3.5% of the severe events occurred below FL100 and above FL250.

3.2. Satellite Observations

Although the icing phenomenon cannot be directly observed from satellite data, some satellite products provide information about cloud properties that may help identifying areas which favor icing conditions [15]. In this study, the satellite data was obtained through the geostationary Meteosat Second Generation (MSG) satellite from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The Meteosat satellite provides full disc imagery every fifteen minutes over Europe and Africa [19]. The satellite data and products employed in this study include brightness temperature (BT) for the channel centred at $10.8\mu m$, cloud mask, cloud-top phase and cloud type. The $10.8\mu m$ brightness temperature, a channel in the thermal infrared window, gives a good estimate of the cloud top temperature, although the exact value depends on cloud characteristics [20]. Note that warm objects radiate more energy than cold bodies. Thus, since the top of low clouds are warmer than high clouds, infrared channels can distinguish warm low clouds (higher BT) from cold high clouds (lower BT) [21]. The cloud mask product identifies cloudy and cloud free areas, flagging also the presence of snow/sea ice on the ground [22]. The cloud-top phase product allows identifying cloud tops composed of water, ice or both (mixed). The cloud type product classifies clouds into several classes: high, medium, low and very low clouds (including fog), fractional clouds and semitransparent clouds [22].

This analysis is focused in the region extending from $31°N$ to $57°N$ and $3°E$ to $32°W$, encompassing part of the paths of most flights to or from Portugal (mainland and islands), Spain, Britain and Ireland. The images captured on the same day and approximate hour of the PIREPs were considered.

3.3. Forecast Data

The forecast data is provided by the ECMWF deterministic model. Briefly, this model resolves a set of basic prognostic equations that describes the time evolution of the horizontal wind components, surface pressure, temperature and the water vapour content of the model atmosphere [23]. Besides, the model solves equations that describe physical processes within the atmosphere, such as changes in the hydrometeors (rain, snow, liquid water, cloud ice content, etc.).

The present model contains 137 vertical levels, the lowest level having a height of approximately $10m$ above the ground. In the troposphere, the vertical distance between vertical levels ranges from $20m$ close to the surface and $290m$ for altitudes above $6km$. In this work, three meteorological variables were considered, temperature (T), relative humidity (RH) and cloud water content (CWC), which consists of liquid water and ice. The model data of each variable was extracted to the nearest grid-point to the PIREP corrected location.

3.4. Methodology

As mentioned before, PIREPs are very useful in providing aircraft icing information, but they may contain errors in time and location attribution. Hence, considering that aircraft icing only occurs when clouds are present [4], the satellite cloud mask was used to confirm the PIREPs location. Thus, at the pixel(s) nearest to the icing PIREP coordinates, cloud mask should be “partly cloudy” or “cloud filled”.

After applying this verification, it was found that for 1.2% and 3.5% of the cases reported as moderate and severe icing, respectively, the satellite cloud mask was clear sky (not shown). The PIREPs position errors can explain this. Thus, the PIREPs coordinates were slightly modified, so that the cloud mask of the corrected coordinates would be either partially cloudy or cloud filled. Two different statistical analysis were then made, one using the original coordinates of the icing PIREPs and other using the modified coordinates. The lowest location error was $5km$ and the highest location error was $58km$.

4. Results

In this work, by matching up PIREPs and satellite products, i.e., satellite and meteorological fields for the same day and time of the reported aircraft icing events, the associated atmospheric conditions were studied.

4.1. Cloud Mask Analysis

Besides the differences between the original and the screened events, explained by the position errors in PIREPs, the majority of the aircraft icing events occurred in a cloud-filled environment: 96.6% and 88.4% of severe and moderate icing events, respectively, for the modified data (not shown). This result is coherent with former studies (Cober et al. [12]), revealing that even though most of the aircraft icing cases occur in a cloud-filled environment, partially cloudy conditions may also lead to aircraft icing phenomena.

4.2. Cloud-top Phase Analysis

Almost 60% of moderate icing events occurred in a cloud environment with ice cloud-top phase, followed by 30.2% and 11.6% with mixed and water, respectively. On the other hand, for severe icing events, the cases of ice and mixed cloud-top phases have a similar prevalence, approximately 38% and 41%, respectively. It should be noted that the cloud phase identified in the satellite products is most likely the phase of the upper cloud layers, while the PIREPs may have happened at lower altitude. The temperature and, hence, the cloud phase at the reported altitude may be different than the ”cloud-top” phase. The high number of cases with mixed cloud-top phase is consistent with previous studies like in Korolev et al. [6].

4.3. Cloud Type Analysis

The histogram presented in Figure 2 reveals that for moderate icing almost 40% of the events occurred under high opaque clouds, followed by 26.7% in medium clouds. For severe icing, most events were associated with medium and high opaque clouds, accounting for about 78% of total cases. Figure 2 also shows a small percentage of aircraft icing events associated with high semitransparent clouds. Even though supercooled water droplets may be present in cirrus clouds, this is not common, since the temperatures in these clouds are much lower than the typical temperatures prone to aircraft icing conditions [12, 9, 8]. Moreover, the icing events associated with high clouds may have occurred within other types of clouds that may have been formed beneath these clouds but cannot be detected by these satellite products [16, 22].

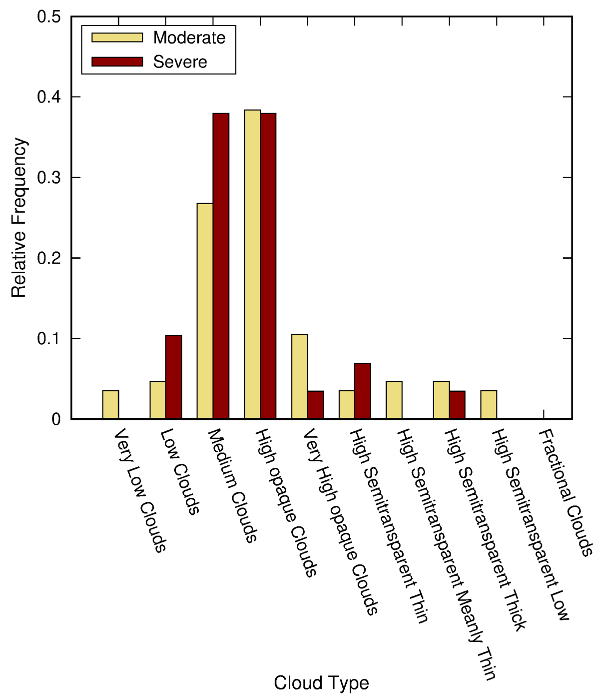


Figure 2: Relative frequency of different types of Cloud Type for the aircraft icing events.

4.4. **Brightness Temperature Analysis**

It should be emphasized that it is considered the cloud top temperature to be closely represented by the $10.8 \mu m$ (within the thermal infrared atmospheric window) brightness temperature provided by the MSG satellite. This assumption has some limitations and the following aspects should be contemplated [24]:

1. The greater the cloud top height, the scarcer will be the atmosphere between the cloud top and the satellite sensor, and, therefore, the more reliable is the approximation. Conversely, for lower altitudes the cloud top temperature may be underestimated. However, the thermal infrared channel used, $10.8 \mu m$, is less sensitive to the effect of atmospheric gases, so the approximation remains valid for medium cloud tops.

2. The problematic situations occur in the presence of semi-transparent or/and fractional clouds which are not of interest in this work; and low warm clouds, where an atmospheric correction may be necessary to apply, since a thicker atmosphere above reduces transmissivity. Nevertheless, even in these cases, the correction should be small and only above $5°C$ for very moist above-cloud atmospheres.

3. The cloud top emits radiation, following the Planck's law, with an emissivity below 1 (but very close to 1, in the $10.8 \mu m$), since it is not a black-body. Here the emissivity effect is ignored, assuming that the brightness temperature of the thermal infrared $10.8 \mu m$ channel (BT10.8) corresponds to the cloud top temperature. Nevertheless, the errors introduced are marginal, validating the use of the BT10.8 as an approximation of cloud top temperature.

The histogram depicted in Figure 3 reveals that the majority of the icing events ($\approx 70\%$) occurred with BT10.8 between $-40°C$ and $-8°C$. Moreover, nearly 19% of moderate icing and 10% of severe icing were associated with BT10.8 between -56 and $-40°C$.

Figure 3 also reveals that one moderate icing event occurred with a positive BT10.8 ($1.4°C$). This result can be associated with two scenarios. First, if an aircraft has been in below-freezing temperatures and then traverses an environment with above-freezing temperatures, the surface temperature of the aircraft may remain below freezing for some time. Another possible scenario is the presence of a temperature inversion. After resorting to its pilot report and temperature data from the ECMWF model, a temperature inversion was indeed identified in the ECMWF profile associated with a very low cloud (according to the cloud type product classification), where the ECMWF temperature was $-0.8°C$ at FL070.

Figure 3 also shows that for BT10.8 within the range between -4 and $0°C$ and -28 and $-12°C$, severe icing (accounting to 66%) is more frequent than moderate icing. The higher frequency for temperatures below $-4°C$ is consistent with previous studies showing that the liquid water content decreases as temperatures decrease, while the concentration of ice particles increases as the temperature decreases (Hu et al. [25]). Furthermore, the formation of large supercooled droplets is favored for clouds with relatively warm tops (warmer than $-15°C$), since high ice concentrations, which can deplete supercooled liquid water, are not fostered in this environment.

Lastly, comparing the statistical analysis of the original data with the histogram of the modified data, it is noticeable that, using the data with the uncorrected coordinates, there are a few icing occurrences with BT10.8 above $0°C$. After the slight correction of the PIREPs coordinates (see section 3.1) this was not verified (except for one case previously mentioned).

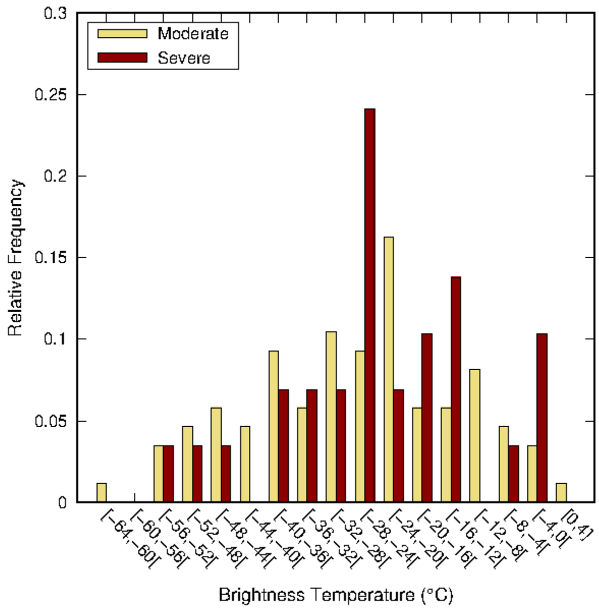


Figure 3: Relative frequency of different values of BT10.8, for the aircraft icing events, for the modified data.

4.5. **Relation between Cloud Phase and Brightness Temperature**

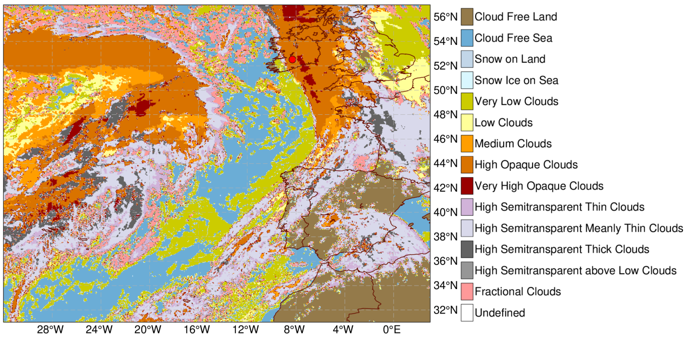
For a better comprehension of the atmospheric conditions present during the studied icing events, it was performed a statistical analysis of the BT10.8 distribution associated with cases where the cloud-top phase was classified as water and ice (not shown). For these aircraft icing events, the moderate cases show a broad distribution with BT10.8 values ranging between -34 and $2°C$. For severe icing, BT10.8 reveals a bi-modal distribution with one maximum frequency (almost 70%) between -26 and $-18°C$, and a second peak (approximately 32%) between -6 and $2°C$. For events with a cloud-top phase classified as "ice", the majority of the moderate icing occurrences ($> 70\%$) are associated with BT10.8 between -56 and $-8°C$ and, more specifically, almost 66% between -52 and $-24°C$. For severe icing, almost 64% of the cases took place in an environment characterized by BT10.8 ranging from -40 to $-24°C$. These results are consistent with other studies, which have shown that the fraction of ice particles is low for temperatures between $-10°C$ and $0°C$ (Hu et al. [25]) and that the fraction of water particles decreases for colder temperatures down to $-40°C$ (Korolev et al. [6]). Lastly, it is clear that clouds with a cloud-top composed of water are characterized by higher BT10.8 (minimum of $-34°C$) than clouds with a cloud-top phase of ice (minimum of $-64°C$).

4.6. **Specific Cases Analysis**

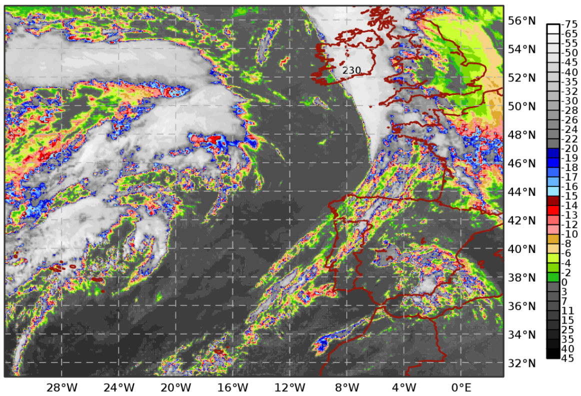
4.6.1 Severe icing Case - 1 March 2019

Figure 4 displays the geographical distribution of cloud type, BT10.8 and cloud-top phase at 1930 UTC on 1 March 2019, when a PIREP of severe icing was issued in Ireland. High opaque clouds are noticeable in the region (Figure 4 (a)), with ice near the cloud top and a BT10.8 around -47 to $-48°C$ (Figure 4 (b) and (c)). A band of very low clouds with warmer ($> 0°C$) cloud tops can be seen to the west of the former. These clouds are also characterized by the presence of water-phase at the cloud top (Figure 4 (c)).

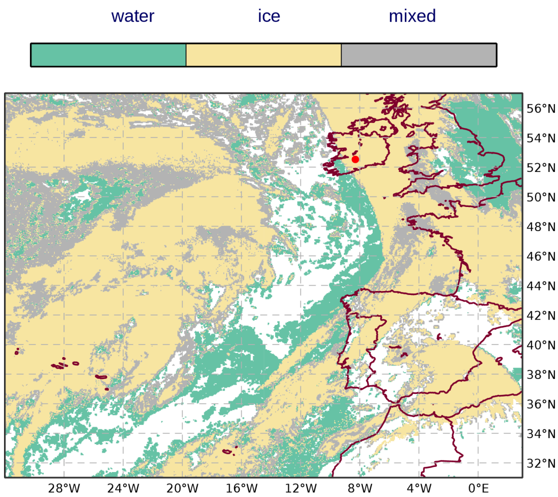
Figure 5 shows the vertical profile of temperature, RH and CWC from the ECMWF model at the nearest grid-point of the PIREP location. Bearing in mind the temperatures at which aircraft icing may happen (between $-40°C$ and $0°C$), this icing event could have occurred between FL60 and FL260 (see Figure 5 a)). The reported flight level of the icing event was FL230 which corresponds to a temperature forecast of $-32.6°C$, while the flight level corresponding to the BT10.8 observed value is approximately FL284. The vertical profiles of CWC and RH (Figure 5 b)) suggest the presence of three layers of clouds when this PIREP was issued (a threshold of $0.02 g/kg$ was used for the CWC, and a threshold of 90% was used for the RH [3]): one layer of high clouds between FL200 and FL310, and two layers of lower clouds underneath it. Thus, the highest cloud layer predicted by the ECMWF model overlaps the clouds identified in the satellite observations and the region where the PIREP was issued (FL230). Furthermore, the comparison between model and satellite data suggests that the aircraft icing event occurred in a cloud located between FL200 and FL284 and that the model overestimates the cloud top. The icing event was associated with a CWC of $0.06 g/kg$ and a RH of 92.7%, according to the ECMWF model.



(a) Cloud Type.



(b) $10.8 \mu m$ Brightness Temperature.



(c) Cloud Phase.

Figure 4: Satellite products valid at 1930 UTC on 1 March 2019. The location of the pilot report of severe icing is represented with a red solid circle in the cloud type (a) and cloud-top phase product (c), and with the FL value in the BT10.8 product (b).

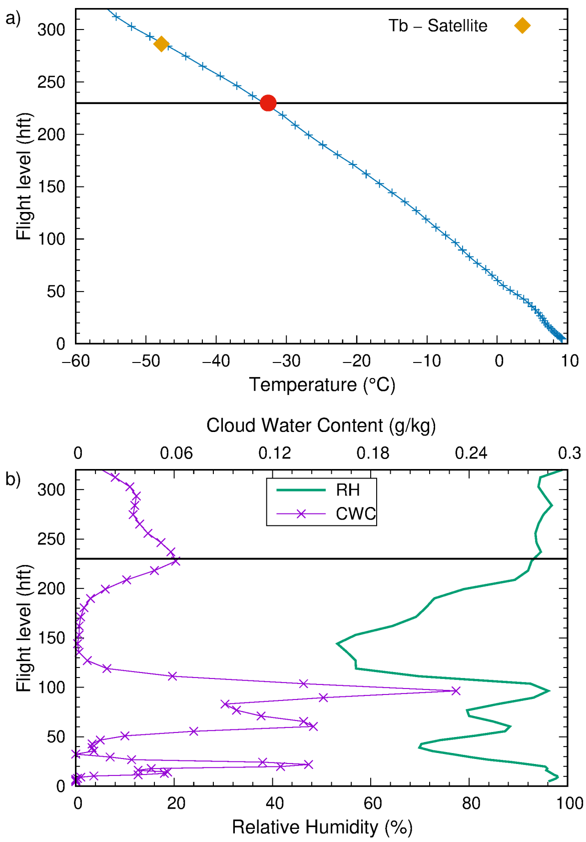
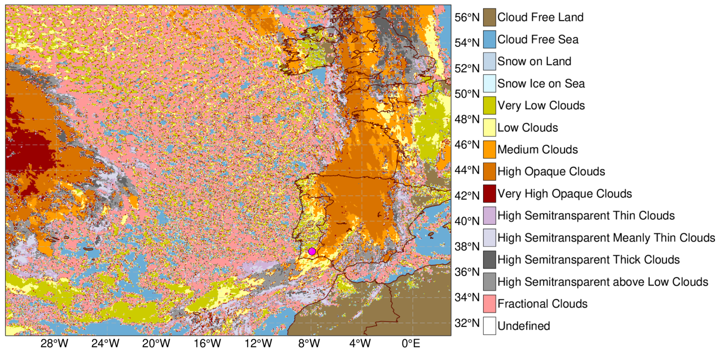


Figure 5: Vertical profile of (a) temperature (the red solid circle represents the temperature at the reported altitude of the icing PIREP) and (b) CWC and RH. The black solid line represents the FL230. The profiles are obtained from the European Centre for Medium-Range Weather Forecasts (H+7) from 1930 UTC on 1 March 2019.

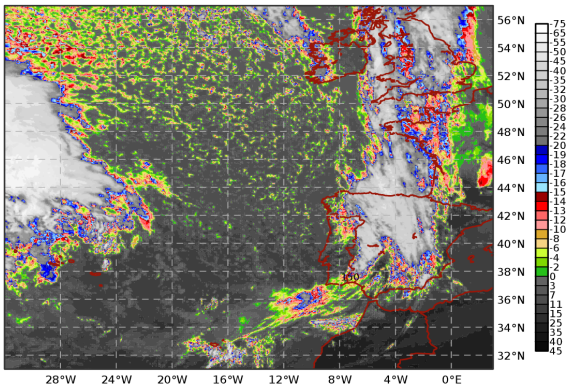
4.6.2 Moderate icing Case - 3 March 2022

Figure 6 displays the geographical distribution of cloud type, BT10.8 and cloud-top phase at 1230 UTC on 3 March 2020, when a PIREP of moderate icing was issued in mainland Portugal. The region is covered by medium clouds (Figure 6 (a)), with a BT10.8 of about $-13°C$ (Figure 6 (b)), mostly classified as being composed of ice (Figure 6 (c)). To the north of these clouds, low and very low clouds with warmer ($\geq 0°C$) cloud tops are also visible. The latter are also characterized by water and mixed-phase cloud tops (Figure 6 (c)).

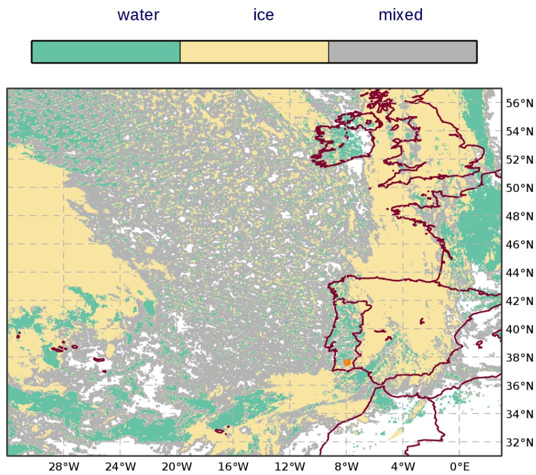
Figure 7 shows the vertical profile of temperature, RH and CWC from the ECMWF model at the nearest grid-point with respect to the PIREP location. This figure shows that temperature ranges from $-20°C$ to $0°C$ between FL085 and FL200, where the environment is very favorable to aircraft icing. The reported flight level was FL150, which corresponds to a predicted temperature of $-11°C$. The corresponding flight level of the BT10.8 is approximately FL158. Thus, this icing event occurred near the cloud top. The vertical profile of CWC shows the presence of two cloud layers (using a threshold of $0.01g/kg$): one thin cloud near FL200 and



(a) Cloud Type.



(b) $10.8\mu m$ Brightness Temperature.



(c) Cloud Phase.

Figure 6: Satellite products valid at 1230 UTC on 3 March 2020. The location of the pilot report of moderate icing is represented with a magenta solid circle in the cloud type (a), an orange solid circle cloud phase product (c), and with the FL value in the BT10.8 product (b).

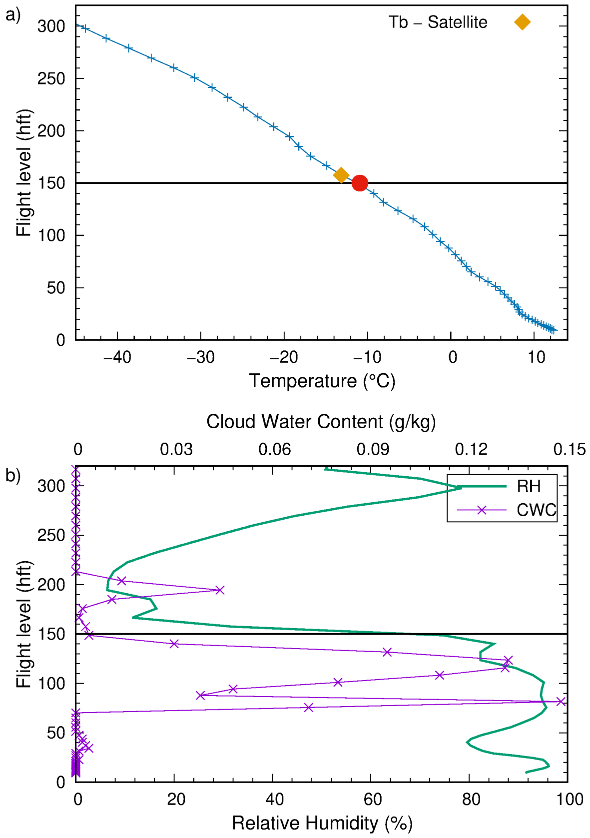


Figure 7: Vertical profile of (a) temperature (the red solid circle represents the temperature at the reported altitude) and (b) CWC and RH. The black solid line represents the FL150. The profiles are obtained from the European Centre for Medium-Range Weather Forecasts (H+12) from 1230 UTC on 3 March 2022.

other lower cloud layer between FL70 and FL140. The RH profile suggests the presence of one cloud layer between FL10 and FL140, using a threshold of 80% (lower than in previous cases). At the level of the icing PIREP (FL150), the model predicted a CWC of $0.004g/kg$ and a RH of 74.8%. Thus, the model underestimated the cloud top height, by nearly $20hft$. It is also interesting to note that for this event of moderate icing the values of CWC and relative humidity were lower than those obtained in the previous cases (of severe icing), which is coherent with previous studies (Curry et al. [15] and Cober et al. [12]).

5. Conclusions

The current study aims to characterize the environment favorable for aircraft icing in the Western Europe and Northeastern Atlantic sector, using PIREPs, satellite data and forecasts from the ECMWF deterministic model. The studied sample comprises 115 icing events, 86 reports of moderate icing and 29 of severe icing, in the region extending from 31° to $57°N$ and $3°E$ to $32°W$. Satellite products including brightness temperature for the channel centred at $10.8\mu m$, cloud mask, cloud type and cloud-top phase were employed.

Most of the aircraft icing events occurred north to the $45°N$ (72 cases) and during the end of autumn and wintertime (≈ 70%). Besides, 43 cases happened south of $45°N$, mainly in the vicinity of airdromes, with a higher prevalence in December and October. The prevalence of aircraft icing during autumn and winter months is coherent with the higher frequency of frontal systems and relatively cold temperatures during these months. Nevertheless, icing events were also reported during the spring and summer months, in agreement with Sand et al. [9], who also found summer icing encounters. Regarding altitude, most events occurred between FL100 and FL250, with a relative frequency of 82.7% and 78.6%, respectively, for moderate and severe icing events. It should be noted that north of $45°N$ there were more icing events between FL100 and FL150 (20.6%) than above FL250 (2.9%), while south of $45°N$ there were more icing events above FL250 (16.7%) than between FL100 and FL150 (11.9%), which is coherent with higher temperatures at equatorward latitudes.

The preliminary analysis of the cloud mask product showed that nearly 1.2% and 3.5% of the events reported as moderate and severe icing, respectively, were associated with a cloud mask of clear sky. The PIREPs errors in time and location attribution can explain this. Therefore, the PIREPs coordinates were slightly modified, so that the cloud mask of the corrected coordinates would be either partially cloudy or cloud filled. The lowest location error was $5km$ and the highest location error was $58km$.

The analysis of the cloud mask product revealed that the vast majority (96.6%) of severe icing events occurred in a cloud-filled environment, whereas the remaining happened in partially cloudy conditions. The percentage of cloud-filled cases is slightly lower (88.4%) for moderate icing. Moreover, most of the icing events occurred in medium and high opaque clouds, with BT10.8 between $-40°C$ and $-8°C$ (≈ 70%). On the other hand, nearly 19% of moderate icing and 10% of severe icing were associated with BT10.8 between −56 and $-40°C$, which is not propitious for icing formation. Furthermore, a small percentage of aircraft icing events was associated with high semitransparent clouds. This may reflect the presence of thin cirrus layers overlying medium clouds, where icing may have formed. Finally, nearly 12% of the severe icing events were associated with low clouds and BT10.8 ranging from −4 to $0°C$. Concerning the cloud-top phase product, 60% of the moderate icing events corresponded to a cloud phase of ice, followed by 30.2% and 11.6% with mixed and water. For severe icing, the cases of ice and mixed cloud-top phases had a similar prevalence, approximately 38% and 41%, respectively. As expected, the clouds with tops composed of liquid water droplets were related to higher BT10.8 (minimum of $-34°C$) than clouds tops composed of ice particles (minimum of $-64°C$).

To better illustrate the favorable environment for icing formation in different situations, four case studies were presented: three cases of severe icing and one of moderate icing. For these cases, the forecast profiles of the ECMWF model were examined. The combination of BT10.8 and model data suggest that the first case was associated with a high-level cloud (FL200-FL284) and although the model was able to predict a cloud layer (with RH $\approx$ 93% and CWC $\approx$ $0.06g/kg$) intersecting the PIREP level, apparently it overestimates the cloud-top altitude. In the second case, the model predicts a thick nearly saturated subfreezing layer above FL080 and results suggest that the icing event happened within a thick cloud at nearly $-13°C$ underneath the cloud top (at nearly $-26°C$). The third severe icing event was associated with low clouds with a BT10.8 of $-4°C$ and the presence of liquid water droplets at the top. The last case was a moderate icing event that took place near the top of a cloud with a subfreezing layer from approximately FL080 to FL160, where the BT10.8 was $\approx -13°C$. In this case, the cloud-top phase was ice. In general, the ECMWF model was capable to predict the cloud layers associated to the aircraft icing events, although with errors on the order of $20hft$ (and $100hft$ in one case). In addition, the maximum predicted CWC and RH values were $0.18g/kg$ and 100%, respectively, in a case of severe icing. Also, the four case studies analyzed were associated with high values of RH: $>$ 74.8%.

As discussed early, PIREPs may contain errors in time and location. Moreover, in Europe only moderate and severe icing events are mandatory to report [11] and consequently PIREPS do not provide information about the absence of icing. Therefore, PIREPs are inappropriate to compute standard measures of over forecasting, such as the false-alarm (number of events that were forecast but were not observed) ratio [26]. For these reasons, it is important to use other sources of information to validate or calibrate icing algorithms. The satellite products used in this study can only observe the highest level of clouds and therefore cannot detect icing conditions beneath the cloud top. Nevertheless, these satellite products can provide useful information on the non-icing events, because they can identify the cloud-free areas and areas where subfreezing clouds are absent. In addition, matching satellite data with icing PIREPs can be used to correct the location errors of PIREPs. Then, these validated PIREPs together with information of non-icing events provided by satellite products become very useful for the validation and calibration of icing algorithms, such as that currently used operationally at the Portuguese MWO [3]. This will be the subject of future work. Lastly, other satellite products could also be considered, such as cloud optical thickness and effective droplet radius, so the icing potential could be derived from satellite data.

Acknowledgements

The author would like to thank the supervisors Professor Pedro Serrão from Instituto Superior Técnico and Dr. Margarida Belo from the Aeronautical Meteorology Division at IPMA, who were always available to give the necessary guidance, advice and support. A special thank you to Dr. Margarida Belo for all the help, unthinkable availability and for collecting all the indispensable data. The author is also thankful to Dr. Ricardo Conceição Tavares, Head of the Aeronautical Meteorology Division at IPMA, for his hospitality in allowing the use of IPMA's facilities and resources. Finally, the author also thanks Dr. Isabel Trigo, for the constructive discussions and for collecting the data of the satellite products.

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