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knowledge & development centre
Mainport Schiphol

Aircraft Induced Lightning

Improving the predictability for the Mainport Schiphol operation

Author(s)	Brian Verhoeven
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Author	
Name	**Function**
Brian Verhoeven	Internship student, Wageningen University

Supervisors	
Name	**Organisation**
Ferdinand Dijkstra	LVNL
Paulien Flierman	KNMI
Roy Mandersloot	KNMI
Gert-Jan Steeneveld	WUR

Approval (by Document owner)			
Name	**Function**	**Signature**	**Date**
Brian Verhoeven	Internship student		15-01-2021

Acceptance (by client)			
Name	**Function**	**Signature**	**Date**
Ferdinand Dijkstra			

Abstract

This internship assignment, commissioned by KLM, has investigated the process of Aircraft Induced Lightning (in short: AIL). AIL is a lightning phenomenon where the lightning discharge is triggered by an aircraft. This regularly occurs within showers with little to no lightning activity, and can occur very unexpectedly. As a result, continuation of flights by aircraft struck by lightning are delayed, and in some cases aircraft are forced to return to the airport. This causes a higher work load for air traffic controllers and extra costs to airlines. This internship aims to increase the predictability of AIL in the surroundings of Amsterdam Schiphol Airport, in order to decrease the amount of lightning strikes to aircraft.

In this internship report, previous research on AIL has been reviewed and summarised, containing information about AIL formation, statistics, lightning strike damages and lightning detection systems. Next to this, interviews were conducted and a questionnaire to pilots was spread. Finally, this study contains a an analysis of a dataset containing lightning strike incidents, reported by air traffic controllers. Based on the interviews and the questionnaire, it has become clear that there was the biggest opportunity in preventing more lightning strikes was in better informing pilots about AIL. Because of this, a pilot information sheet was made in order increase the knowledge about AIL for the KLM pilots, also providing some warning signs that can be acted upon if deemed necessary by the pilots. The pilot information sheet has been well received by the KLM. In the (near) future, the document will be spread to the pilots by a news article and in the long-term, it will likely be implemented into a internal training at KLM. Finally, a data analysis was performed on a dataset that contains reports by air traffic controllers of lightning strikes to aircraft, which showed that the majority of reported lightning strikes occur in meteorological conditions categorised as “Suspected AIL”, possibly more than scientific literature has currently discussed. Also, an interesting but uncertain relation was found between the amount of incidents and aircraft type, where specifically the aircraft type Embraer E190 aircraft stood out, as the aircraft’s contribution to the total amount of reported incidents was over 10% higher than the contribution to the total amount of air movements. The information in this report can contribute to an increased awareness of AIL for pilots and possibly result in less aircraft being struck by lightning.

Keywords: Aircraft Induced Lightning; aviation; thunderstorm electrification; aircraft; triggered lightning; Schiphol airport

About the author – Brian Verhoeven

I am currently in my second year of the MSc 'Earth & Environment', with a specialisation towards meteorology and air quality at Wageningen University. Before the MSc, I did the BSc 'Soil, Water, Atmosphere' at Wageningen University as well. My main field of interest is in (severe) weather and I focus on applied meteorology. Therefore, I also work as a junior meteorologist at Buienradar since December 2017, where I have gained a lot of operational knowledge next to my study.

Lightning has always been a specific interest of mine, not only as a hobby, but also as a research topic. For example, I have launched weather balloons into thunderstorms and my BSc thesis was about lightning climatology as well. The interest in lightning and it being a main topic of research for my studies makes it that this internship fitted me exactly. It is a great continuation of my work on lightning and further expands my knowledge of this rather complex and dangerous topic.

With this internship, I hope to make a positive impact in aviation, with hopes of preventing more lightning strikes to aircraft. Although lightning strikes to aircraft are not the most dangerous weather phenomena anymore, the consequences of one nowadays are still not negligible and a lightning strike will most likely not be a positive experience for the passengers too. This internship will therefore hopefully can make Dutch aviation slightly safer and more pleasant for passengers.

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List of abbreviations

AIL	–	Aircraft Induced Lightning
Cb	–	Cumulonimbus cloud
CG	–	Cloud-to-Ground
DE	–	Detection Efficiency
EHAM	–	ICAO code for Amsterdam Schiphol Airport
Et al.	–	et aliae (meaning “and others”, indicating other authors of the reference)
FL	–	Flight Level
IC	–	Intracloud
ICAO	–	International Civil Aviation Organization
KLM	–	Koninklijke Luchtvaart Maatschappij
KNMI	–	Koninklijk Nederlands Meteorologisch Instituut
LA	–	Lightning Accuracy
LVNL	–	Luchtverkeersleiding Nederland
MAS	–	Meteorological Advisor Schiphol
TAF	–	Terminal Aerodome Forecast
TCAS	–	Traffic Collision Avoidance System
VII	–	Vertically Integrated Ice

1. Introduction

1.1 Background

The Netherlands is a country located in the northwest of Europe and is located in a temperate maritime climate, as its weather is influenced by the North Sea. During summer, this means that generally speaking, the temperatures are slightly inhibited due to the North Sea being relatively cold. During winter time, the North Sea is relatively warm in comparison to the Dutch mainland and causes the temperatures to be moderate. On average, The Netherlands has 25 days with at least one lightning discharge. However, a large fluctuation can be found between years. Some years can have more than 50 days with at least one lightning discharge (KNMI, n.d.). Mostly in the summer, active thunderstorms can move over The Netherlands. However, it is also not uncommon for lightning to occur in The Netherlands, mostly near the coastal regions, during fall and winter as well. This is mainly caused by the convergence of air near the coast, which pushes air upwards and forming showers as a result, and cold (polar) upper air moving over the relatively warm North Sea, creating large enough temperature differences between the surface and upper air to form showers. On some days, these showers are strong enough to produce lightning.

Mainport Schiphol is located near Amsterdam, in the northwest of The Netherlands and is relatively close to the North Sea. The airport has transported 71.700.000passengers in 2019 from a total of nearly 500.000 air transport movements (Royal Schiphol Group, 2020). Due to the fact that the airport is relatively close to the North Sea, it is prone to lightning in winter time.

Mainport Schiphol has had experiences with aircraft being struck by lightning in the vicinity of the airport. As a result, aircraft need to be checked whether they have not been damaged by the lightning strike, which causes delays in the flight operations. In some cases, departing aircraft are forced to return to the airport. Not only does this cause delays for the flights and airlines, but also increases the work for air traffic controllers to accommodate unplanned returns.

As an example, Pan Am Flight 214 crashed on the 8th of December 1963 in the United States, near Elkton, Maryland, as a result of a lightning strike that caused an explosion. All 81 occupants (passengers and crew) were killed in the accident (Uman & Rakov, 2003). Nowadays, aircraft are designed in such a way that they do not crash as a direct result of a lightning strike. However, that does not mean that lightning strikes no longer pose a risk to aircraft. Lightning strikes still possibly result in certain damages to the aircraft, but regularly also cause disruption of flights as the aircraft must be checked for damages, with delays as a result.

For Mainport Schiphol, the Koninklijk Nederlands Meteorologisch Instituut (KNMI, Dutch National Weather Sevice) has previously researched the possibility to forecast the occurrence of Aircraft Induced Lightning (AIL) (Gough et al., 2009). They found that 40% of all lightning encounters happened in the period between the months October and April. This is outside of the "warm season", where one would expect most of the lightning strikes to occur as this is also the period in which (severe) thunderstorms form and actively produce lightning. From that research, KNMI has developed a statistical AIL forecast tool called WinterKOUW. This tool was able to predict 72% of the reported lightning strikes.

However, there still is a need for a better forecast of lightning strikes on aircraft that are a result of AIL. This is the reason why this internship has explored and developed opportunities to reach such an increased predictability.

1.2 Objectives

This study has several objectives that fall within this internship, i.e.

- Summarise current scientific knowledge of AIL and lightning detection.

- Develop a document that aims to increase a pilot's awareness and knowledge of the occurrence of AIL, allowing the pilot to act upon AIL and possibly preventing more lightning strikes to aircraft.
- Analyse lightning incident report data.
- Recommend on opportunities to further increase the predictability of AIL at various stakeholders.

1.3 Scope

The scope of this internship is, as mentioned in the background already, to increase the predictability of AIL in general. This will allow better decision making and increase the awareness surrounding AIL and could result in less aircraft being struck by lightning, especially in the period between October and April.

Therefore, this internship focusses on designing/developing an information sheet for the pilots of the KLM Royal Dutch Airlines, explaining the meteorological causes behind AIL and which warning signs (meteorological conditions and phenomena) can be used to take action and avoid certain showers that are capable of producing AIL. Next to this, the internship also attempts at gathering as much information as possible surrounding AIL. More specifically, this internship gathers experiences and information of pilots with their wishes and limits through a questionnaire.

However, a large part of this internship report also contains an extensive summary of present knowledge surrounding the topic of lightning strikes to aircraft and AIL, as has been requested by KLM at the start of the internship.

1.4 Reading guide

The internship report starts with a summary of present knowledge. This has been organised in two sections. First, section 2, summarises the present knowledge in a simplified and brief manner. It is strongly recommended to read this summary when having little to no experience or knowledge about lightning and meteorology. In section 3, a summary with the same main information is present, but containing more details and more in-depth physical knowledge. When having sufficient knowledge about lightning and meteorology, it is advised to read this summary instead of section 2 in order to gain a better and more complete understanding of the relevant processes and consequences of AIL.

In chapter 4, the research methodology is described for all researches that have been conducted during the internship. Chapter 5 then shows and discusses the results of these research projects. In chapter 6, finally, all the information within this report is briefly summarised and concluded upon. Next to this, chapter 6 includes several recommendations for future work and is of great importance for the readers who are interested in the questions that remain unanswered after this internship.

2. Summary of present knowledge (simplified)

Below, a short and more importantly simplified summary of present knowledge about AIL and lightning strikes to aircraft is given. In order to keep the information as accessible as possible, no references to literature and figures are used in this summary. A more extensive summary is found in Section 3, as well as all references to literature and figures.

2.1 Electrical charging of a cloud

In general, scientific research has concluded that within clouds that are capable of producing lightning, so called Cumulonimbus clouds (Cb), one can identify three electrically charged regions:

1. The top of the cloud, with temperatures below -20 °C, contains a positive charge
2. In the centre of the Cb, between temperatures of about -20 and -10 °C, the cloud contains a negative charge
3. At the very bottom of the cloud, between the cloud base and up to a temperature of about -10 °C, a positive charge can be found again.

A schematic overview of the above mentioned regions within a Cb, is given in Figure 1 in Section 3. These charges within the cloud, and their signs (positive or negative) are a result of collision between frozen particles within the cloud.

2.2 Aircraft-initiation of lightning (AIL)

In most of the cases where aircraft are struck by lightning, it is possible to speak of an induced lightning strike. Scientific research about AIL has generally always spoken about two different types of interactions between lightning and aircraft: triggered lightning strikes and intercepted lightning strikes. Estimates show that about 90% of the lightning strikes to aircraft are triggered (induced) rather than intercepted.

The mechanism of lightning initiation by aircraft is rather complex. When the aircraft flies through a charged region of the cloud (either positive or negative), the charge is transferred to the aircraft. This is a result of contact (collision) to charged particles. These particles can be precipitation or cloud particles, as well as volcanic ash.

When the aircraft has gained a strong enough charge, so-called “leaders” extend from the aircraft. These leaders are in generally small lightning discharges that reach out from the aircraft. One of these leaders can connect to a lightning channel that originates from the cloud, which then results in a lightning strike to the aircraft, as is shown in Figure 3.

2.3 Aircraft strike statistics

Scientific literature found that a commercial airliner is struck by lightning every ~3000 hours of flight. Generally speaking, this is equal to one lightning strike to each separate airplane yearly. However, the probability of an aircraft being struck while located on the runway in Europe is significantly lower: once every hundred years.

The main zones of an aircraft that have the highest probability of being struck by lightning, are mainly at sharp points on the aircraft, such as the nose, wingtips, engines and edges at the tail of the aircraft. In detail, the following external components of an airplane are most likely to be hit:

- Radome
- Nacelles
- Wing tips
- Horizontal stabilizer tips
- Elevators
- Vertical fin tips

- Ends of the leading edge flaps.
- Trailing edge flap track fairings
- Landing gear
- Water waste masts
- Air data sensors (pilot probes, static ports, angle of attack (AOA) vane, total air temperature probe)

The occurrence of lighting strikes to aircraft can also be related to the ambient (outside) air temperature at the time and the height of the strike. Research has shown that most lightning strikes occur around an altitude of about 8.000-12.000 feet (FL080-FL120). Relating those altitudes with the typical summer thunderstorms, most of these lightning strikes to aircraft appear to occur within the lower part of the cloud, where a positive charge is present. However, especially over Europe, a lower peak in lightning strikes can also be found. This is possibly a result of winter thunderstorms, when the cloud base and thus the region with positive charge is also located at a lower altitude.

For the ambient air temperature, a clear relationship is present as well. From a study with a total of 1360 incidents where aircraft were struck by lightning, most of the incidents occurred in temperatures below freezing level, peaking at exactly 0 °C. Again, these temperatures correspond with the lower region of a Cb cloud, where a positive charge is present.

2.4 Damages due to a lightning strike

As has already briefly been discussed in the introduction, aircraft crashes as a result of a lightning strike such as in 1963 do not happen anymore. This does not mean, however, that lightning strikes no longer pose a risk to aircraft. There still is a large list of possible damages as a result of a lightning strike to an aircraft, of which some could be considered severe.

An overview of possible damages are given in Table 1. Examples of instruments that interfered or suffered an outage as a result of the lightning strike, are the weather radar, engine RPM gauges or windshield heaters. Regularly, burn marks or sometimes even holes are found on the outside of the aircraft. In an extreme case, the TCAS (Traffic Collision Avoidance System) became out of service after a lightning strike in Finland.

3. Summary of present knowledge (scientific)

Below, a complete summary of present knowledge about AIL and lightning strikes to aircraft is given. This summary contains (schematic) figures and references to scientific literature and uses technical terms. The summary also explains certain processes more in-depth than the summary of Section 2. Finally, an extra section (3.5) is added to this summary, describing the quality of various lightning detection networks and which of those are best to detect AIL with.

3.1 Electrical charging of a cloud

In general, scientific research has concluded that within clouds that are capable of producing lightning, so called Cumulonimbus clouds (Cb), one can identify three electrically charged regions. This is often referred to as the tripole charge structure of a cloud (Williams, 1989). This tripole structure has been supported by many (observational) researches (Zhao et al., 2010; Soula, 2012; Qie et al., 2015).

The tripole charge structure of a Cb consists of the following three regions: The upper positive charge region, the main negative charge centre and the lower positive charge region. These regions can be related with the air temperature in which the regions are located. Below, they each of these regions are briefly discussed. These regions are also shown in Figure 1.

1. At the very top of the cloud, roughly in temperatures below -20 degrees Celsius and located in the anvil part of a Cb, positive charge is present.
2. In the centre of the Cb, in the region between -20 and -10 degrees Celsius, the main negative charge region is located.
3. At the very bottom of the cloud, near the cloud base and between 0 and -10 degrees Celsius, the lower positive charge region is present. Especially this area of positive charge is important in the process of AIL, which is discussed in Section 3.2.

This tripole charge structure is mainly explained by the process of collision between graupel and ice crystal particles within the Cb. This is extensively explained in He et al. (2018) and in Berdeklis & List (2001) and will not be further discussed in this report.

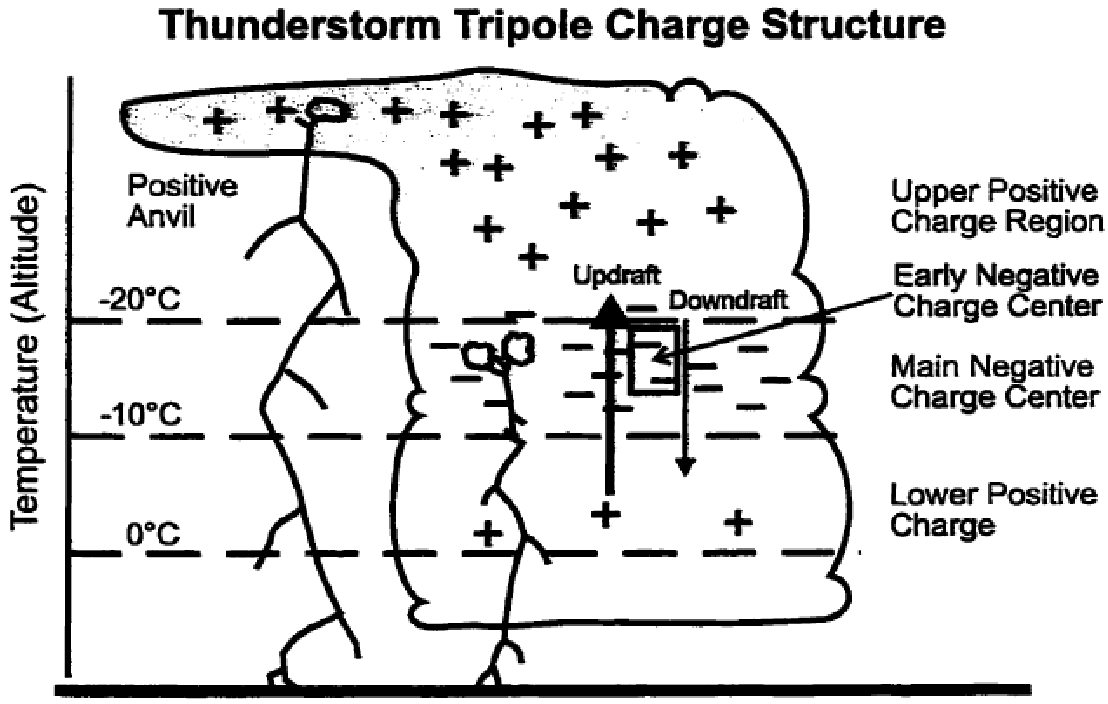


Figure 1 The tripole charge structure of a Cb cloud. The early negative charge region is the region where the negative charge first develops and is located in the region where the updraft and downdraft of the cloud transitions. Figure taken from Berdeklis & List (2001).

3.2 Aircraft-initiation of lightning

In most cases of aircraft being struck by lightning, the lightning strike is a case of AIL, as the majority of the aircraft seem to trigger the strikes, rather than intercepting a lightning discharge (Mazur et al., 1984; Reazer et al., 1987; Rakov & Uman, 2003). This is due to the fact that aircraft become electrically charged while flying.

In all researches surrounding lightning-aircraft interaction, there are two types of interactions discussed: triggered lightning strikes and intercepted lightning strikes. Several studies have shown that in 90% of cases where aircraft were struck by lightning, the lightning was triggered rather than intercepted (Rustan & Moreau, 1985; Moreau & Alliot, 1986; Reazer et al., 1987).

The process of lightning induction by an aircraft can be separated into three steps:

1. The aircraft gains a net charge.
2. The formation of bidirectional leaders
3. The connection of a leader with a lightning channel originating from the cloud

1. The aircraft gains a net charge

For aircraft, a net charge builds up on the aircraft while flying through an electrically charged region in the atmosphere (Illingworth & Marsh, 1986). The sign of the net charge of an aircraft prior to the formation of the bidirectional leaders depends on the sign of the charged region the aircraft flies through. This means that the aircraft gains a positive charge while flying through a positive atmospheric field and a negative charge while flying through a negative atmospheric field. This electrification of the aircraft is a result of contact (collision) with charged cloud particles and/or charged precipitation particles. This is also the case for aerosol particles as can be found in e.g. volcanic plumes. This transfer of charge is stronger when the aircraft flies through larger rain drops, and even more when the aircraft flies through frozen precipitation such as snow or ice particles (Vonnegut, 1965).

The sign of the charge (positive or negative) at the point extremities of an aircraft, such as the nose and engines, thus depends on the electric atmospheric field the aircraft is flying through.

However, induction of the electrical charge on the airplane fuselage causes an equal and opposite charge on the other side of the aircraft in order to balance out the charges (Vonnegut, 1965).

2. The formation of bidirectional leaders

The mechanism of lightning initiation by aircraft, can be explained with the bidirectional leader theory (Montanyà, Van der Velde & Williams, 2015). A schematic example of this is shown in Figure 2, showing four steps in total. Again, the aircraft first gains a net charge and due to induction of the charge on the airplane fuselage, an equal and opposite charge can be found on the other side of the aircraft **(step 1)**. When the aircraft flies through a large enough electric field, a positive leader emerges from the aircraft **(step 2)**. As a result, a negative charge is induced on the aircraft. This allows the whole system (the aircraft and positive leader) to remain electrically neutral **(step 3)**. However, as the negative charge increases, a negative stepped leader propagates from the aircraft as well. The direction of this negative stepped leader is in the opposite direction of the positive leader **(step 4)**.

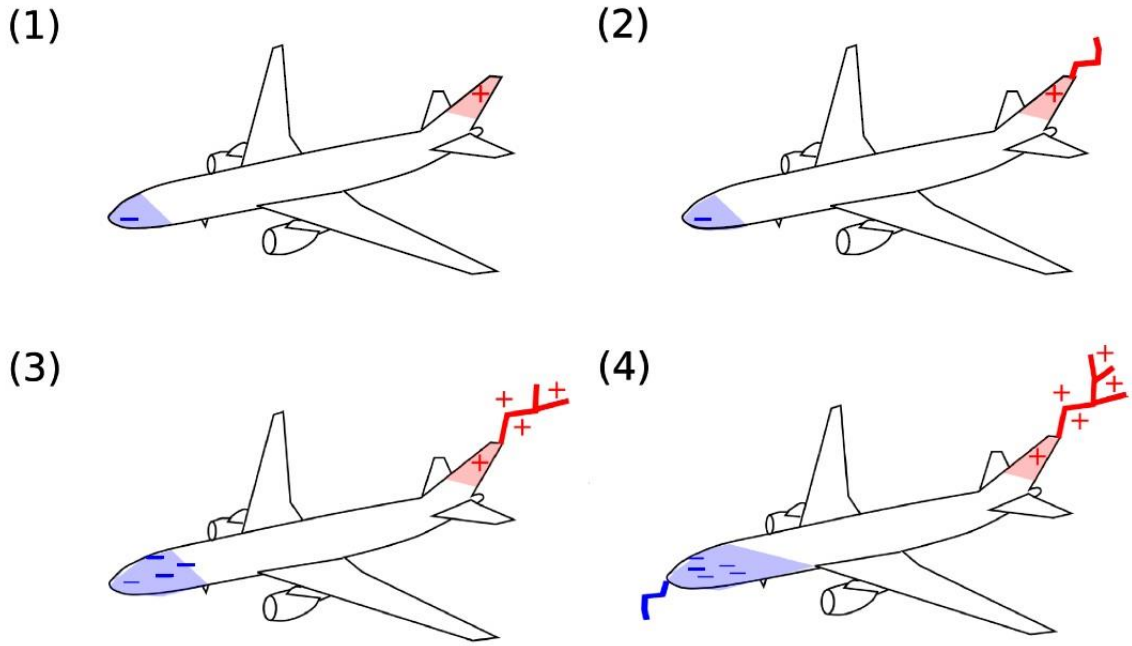


Figure 2 The formation of bidirectional leaders from an aircraft that has acquired a net charge. Figure taken and adapted from Pavan et al. (2020). See the paragraph above for a detailed discussion of the four steps.

The locations of the bi-directional leaders depend on the sign of the charge that the aircraft acquires. Most schematic overviews of the process of bi-directional leaders, such as in Figure 3, show a positive leader at the nose of the cloud. This is not always the case and can be the other way around.

3. The connection of a leader with a lightning channel originating from the cloud.

The final step of lightning initiation by an aircraft is the connection of a lightning channel that originates from the cloud with one of the leaders that have emerged from the aircraft. In most cases, this will be a negatively charged lightning channel that originates from the main negative charge centre of the cloud. As has been discussed in Qie et al. (2005), the lower positive charge region mainly acts as a conductor for a negatively charged lightning channel. This channel can then connect with the positive leader that emerges from an aircraft. However, in some cases, if a lightning channel is positively charged, the lightning channel can connect with the negative leader, as is also shown in Figure 3. With the connection complete, the lightning strikes the aircraft and the process of AIL is completed. In some cases, a lightning channel strikes the aircraft multiple times due to so-called return strokes.

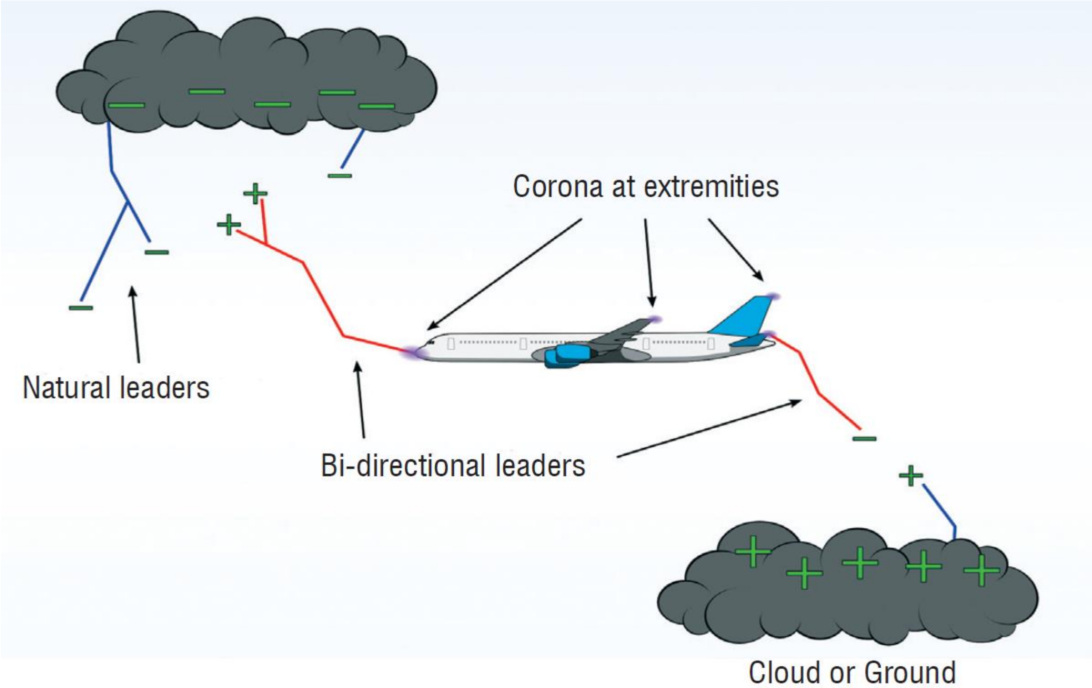


Figure 3 A schematic overview of the formation of both positive and negative leaders and their connection with charged regions within clouds. Taken from Morgan et al. (2012).

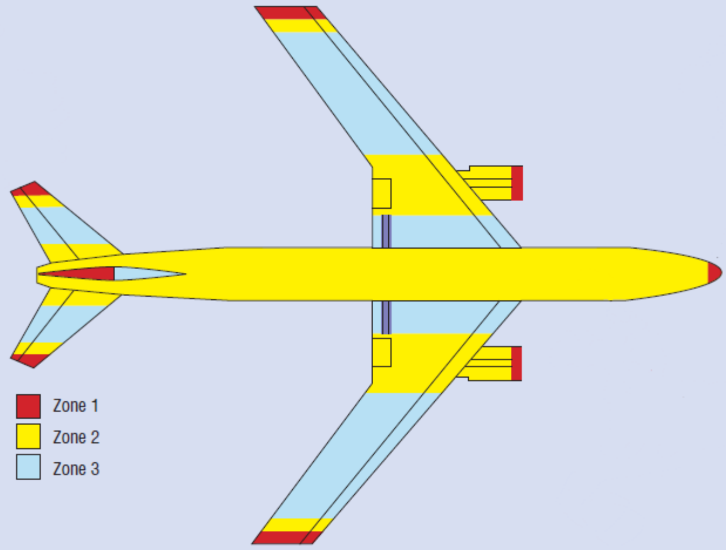
The hypothesis of the fact that most of the cases where the leaders connect with lightning channels happen in the lower positive region of a cloud, has been described in the paper of Wilkinson et al. (2013). They researched helicopter-triggered lightning over the North Sea and described that helicopters also gain a net negative charge at their rotors. However, the same statistics but for airplanes were not yet well-described in scientific literature, especially for the region surrounding the North Sea (including Schiphol Airport).

3.3 Aircraft strike statistics

In scientific literature, it is a generally accepted statistic that a commercial airliner is struck by lightning every ~3000 hours of flight. Generally speaking, this is equal to one lightning strike to each separate airplane yearly (Larsson, 2002). However, the probability of an aircraft being struck while located on the runway in Europe is significantly lower: once every hundred years.

3.3.1 Lightning prone regions of aircraft

The main zones of an aircraft that have the highest probability of lightning flash attachment, are mainly at the sharp points: the nose, wingtips, engines and edges at the tail of the aircraft. In Figure 4, a simplified overview of those high probability zones is given.



Zone 1 - High probability of initial lightning flash attachment (entry or exit).

Zone 2 - High probability of a lightning flash being swept from a point of initial attachment.

Zone 3 - Any aircraft surface other than those covered by zones 1 and 2. In zone 3 there is a low probability of a direct attachment, however, zone 3 areas may carry substantial lightning currents by direct conduction between two attachment points.

Figure 4 Zones of an aircraft and their probability of being attached to a lightning flash. Taken and adapted from Morgan et al (2012).

In text, the following external components of an airplane are most likely to be hit:

- Radome
- Nacelles
- Wing tips
- Horizontal stabilizer tips
- Elevators
- Vertical fin tips
- Ends of the leading edge flaps.
- Trailing edge flap track fairings
- Landing gear
- Water waste masts
- Air data sensors (pilot probes, static ports, angle of attack (AOA) vane, total air temperature probe)

These regions, summarised in the bullet points above, are described in Sweers, Birch & Gokcen (2012). In that article, further information is given for both maintenance and flight crew about the lightning-strike phenomena and damage inspection as well.

3.3.2 Relation with height and ambient air temperature and

The occurrence of lighting strikes to aircraft can be related to the ambient (outside) air temperature at the time and the height of the strike. An overview of this is discussed in Uthe altitude in Uman & Rakov (2003). Figure 5 shows the amount of lightning incidents plotted against the altitude in feet.

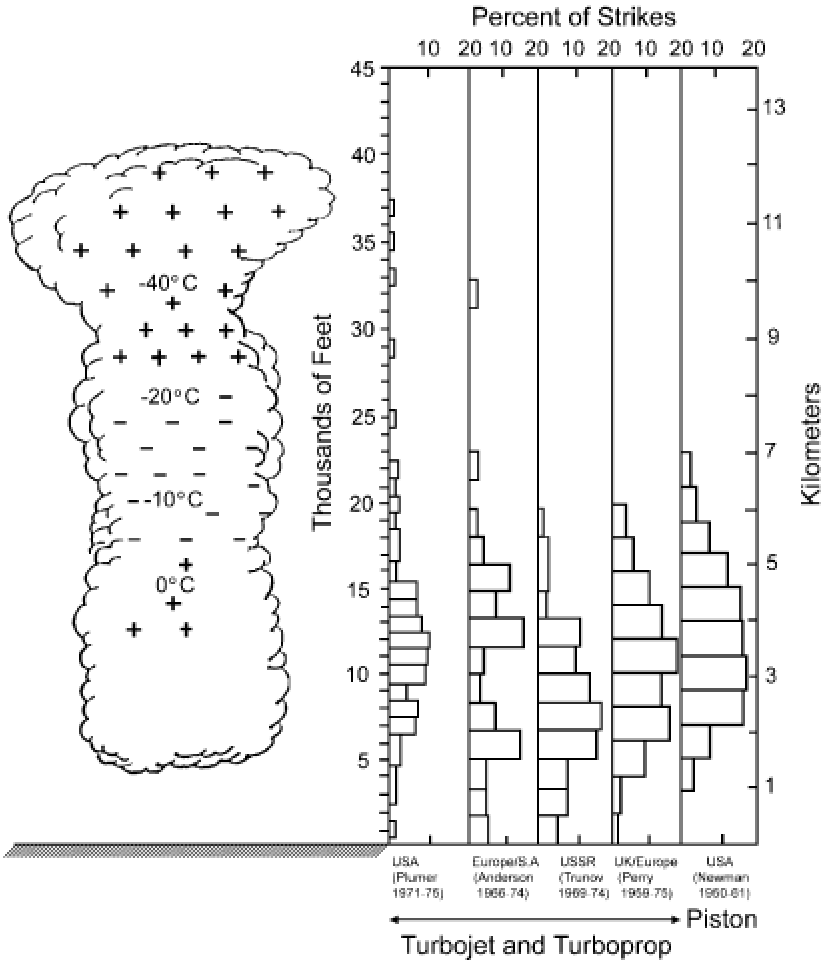


Figure 5 Total amount of aircraft lightning incidents related with the height of the aircraft in feet. On the left hand side of the figure, a schematic overview is given with the typical summer thundercloud charge distribution, taken from Uman & Rakov (2003).

From Figure 5, especially the lightning strike distribution for Europe/S.A. shows an interesting structure. In contrast to e.g. the U.S.A., Europe/S.A. shows two clear peaks where most of the lightning strikes occur, rather than only one peak for all the other regions. These peaks are near 12.000 feet (FL120) and 6.000 feet (FL060). It is possible that this is due to the difference between summer and winter lightning. In winter, the 0°C-isotherm is located lower than in the summer and thus the cloud base is lower as well. Therefore, the lower positive charge region is also lower for electrically charged clouds in winter time. For winter thunderstorms over the North Sea, estimations are that this lower positive charge region is located at about 1500m height (Wilkinson et al., 2013), corresponding to nearly 5000 feet (FL050). Taking into regard that about 40% of the lightning strikes occur between October and April (Gough et al., 2009), this could explain the second peak in lightning strikes that is located around 6.000 feet.

However, why this is not valid for the UK/Europe part or for the other countries of Figure 5, is left unclear in Uman & Rakov (2003). It is also not explained in Fisher & Plumer (1977), where the figure was based upon in the article of Uman & Rakov (2003). Therefore, it is left unclear whether or not the double peaks in the Europa/S.A. chart in Figure 5 are a result of the inclusion of winter lightning. This is, however, the hypothesis in this report.

Finally, a relation can be made between the peaks of the observed lightning strikes and the charged regions of a cloud. Figure 5 includes a schematic overview of the typical summer thundercloud charge distribution. There, the peaks in the amount of lightning incidents are all found in the lower positive charge region of the cloud. Using the knowledge of the theory in

Section 3.2. (the bi-directional leader theory), it can thus be assumed that for most lightning strikes to aircraft, the aircraft has gained a net charge from the lower positive charge region.

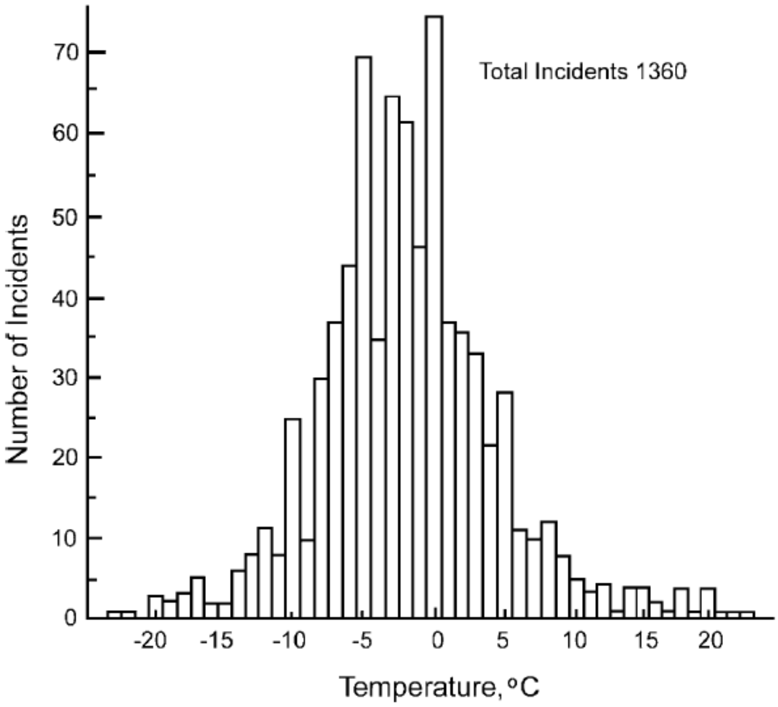


Figure 6 The relation between ambient air temperature at variable flight levels and the amount of lightning strikes to aircraft. Figure taken from Uman & Rakov (2003).

In Figure 6, a peak at exactly 0°C can be found. Most of the lightning strike incidents occur at freezing temperatures. Note that these statistics are for commercial aircraft in Japan only. However, scientific literature has frequently discussed that there are three main regions where winter lightning strikes are report: Japan, Finland and the North Sea region (including The Netherlands). This is mainly due to a combination of relatively warm sea water with cold upper air. These statistics are thus considered valid for the North Sea region as well.

Section 3.1. discussed that the lower positive charge region is located between temperatures of about -10 °C and 0 °C. Comparing that information with Figure 6, it becomes clear that the temperatures where most of the lightning strike incidents occur in, are between this range of temperatures. This again confirms that most of the lightning strikes to aircraft occur within the lower positive charge region of a Cb.

3.4 Damages due to a lightning strike

As has already briefly been discussed in the introduction, aircraft crashes as a result of a lightning strike such as PanAm flight 214 in 1963 do not happen anymore. However, that does not mean that lightning strikes no longer pose a risk to aircraft. There still is a large list of possible damages as a result of a lightning strike to an aircraft, of which some could be considered severe. Some of these damages are described in Table 1 on the next page.

Table 1 Counts of Indirect effects of lightning strikes to commercial aircraft, reported by U.S. airlines. The total amount of reported strikes is 214. The data is from the period between 1971 and 1984. Table adapted from Fisher, Plumer & Perala (1989).

	Interference	Outage
HF communication set	-	5
VHF communication set	27	3
VOR receiver	5	2
Compass (all types)	22	9
Marker beacon	-	2
Weather radar	3	2
Instrument landing system	6	-
Automatic direction finder	6	7
Radar altimeter	6	-
Fuel flow gauge	2	-
Fuel quantity gauge	-	1
Engine RPM gauges	-	4
Engine exhaust gas temperature	-	2
Static air temperature gauge	1	-
Windshield heater	-	2
Flight director computer	1	-
Navigation light	-	1
AC generator tripoff	6 instances of tripoff	-
Autopilot	1	-

The reported interferences and outages are not the only possible effects of a lightning strike to an aircraft. In other researches, more damages have been described. In Mäkelä et al. (2013), for example, a pilot questionnaire showed that the TCAS (Traffic Collision Avoidance System) became unserviceable after a lightning strike in Finland.

Other frequent damages are burn marks on parts of the airplane. Sometimes, small holes are burned into the fuselage. Below, an example is given.

Figure 7 Two images of damage to the engine of an Airbus A380. The second (right) image is a close up of the first (left) image. Images supplied by an anonymous pilot.

Figure 7 shows clear burn marks on the engine cowling of the reverse thruster. The damage on this aircraft was significant enough to cause cancellation of two flights, as the reverse thruster engine cowling was unable to extend anymore.

A few more damages and effects of a lightning strike to an aircraft are further discussed in Section 5.2., including being blinded for a period of time as a result of the bright flash that a lightning strike produces.

3.5 Lightning detection technology

There are multiple lightning detection systems available in Europe. In this Section, the most-used detection systems in scientific literature and their accuracies are discussed, as has been requested for this internship.

First off, the ATDnet detection system (Nash et al., 2006) is one that is regularly used in scientific literature (e.g. Bennet et al., 2010; Anderson & Klugmann, 2014). However, this detection system was designed to detect CG (cloud-to-ground) lightning and thus performs bad in terms of detecting IC (intracloud) lightning. In Enno et al. (2020), it has been discussed that the system is able to detect up to 90% of the CG lightning discharges, but is able to only detect an estimated 25% of the total IC lightning discharges. Since not all lightning strikes to aircraft continue and hit the earth's surface, such a bad performance on IC lightning would thus also lower the quality of detecting possible AIL cases as well.

A second lightning detection system is the Siemens BLIDS network. This detection system is part of the EUCLID network that has detection systems over the whole of Europe. The median of the location accuracy of the EUCLID network is determined at 600 meters (Jana, Zbyněk & Petr, 2019). However, within the EUCLID network, the Siemens Blids network is the only one that covers The Netherlands. Therefore, zooming into The Netherlands and their surrounding countries, has no extra value.

In the paper of Poelman, Schulz & Vergeiner (2013), a large group of lightning location systems have been assessed for their quality in Belgium. Since Belgium is relatively close to The Netherlands and also Schiphol Airport, the results of their research can thus be considered comparable for the surroundings of Schiphol Airport as well. In the paper, a total of five lightning location systems were assessed: OP, TP, EUCLID, GLD360 and ATDnet. EUCLID and ATDnet have been discussed in the previous two paragraphs as well, as those are regularly used in scientific literature. Of the five evaluated systems, EUCLID performed best, with a detection efficiency (DE) of 84% in general, and specifically detecting 98% of all first strokes. Also, the median location accuracy (LA) was the highest, with 600 meters, as is visible in Table 2.

Table 2 Overview of the stroke/flash Detection Efficiency (DE) and Median Location Accuracy (LA) of five individual lightning detection networks. Table adapted from Poelman, Schulz & Vergeiner (2013)

	Stroke DE (%)	First stroke DE (%)	Subsequent stroke DE (%)	Flash DE (%)	Median LA (km)
OP (13)	70	84	64	93	6.1
TP (12)	64	88	56	92	1.0
EUCLID (23)	84	98	79	100	0.6
GLID360 (22)	70	79	66	96	0.9
ATDnet (13)	58	75	51	88	1.0

As can be concluded from Table 2, the EUCLID network performs best for Belgium. Siemens BLIDS covers this area, just like The Netherlands. Because of this, it can be assumed that these results are valid for the Siemens BLIDS data by itself as well. Therefore, for detecting AIL lightning discharges, looking at the lightning detection system of Siemens BLIDS is thus likely the most accurate.

4. Research methodology

Next to the extensive summary of scientific knowledge surrounding the topic of AIL, this internship also includes some research of its own. This has been organised in four parts: stakeholder interviews, pilot questionnaire, pilot information sheet and data analysis. These four parts are discussed below.

4.1 Stakeholder interviews

Surrounding the topic of AIL, there are multiple stakeholders involved. Their involvement ranges from forecasting the weather, including AIL, up to being affected by AIL directly. Each stakeholder is briefly discussed below.

First, interviews were conducted with two aviation meteorologists from KNMI. At KNMI, several aviation meteorologists work to produce forecasts for Schiphol Airport and its surroundings every day of the year. In order to get to know more about these forecasts and the inclusion of AIL in this, Roy Mandersloot of the KNMI was. Also Paulien Flierman of the KNMI was interviewed to learn more about lightning nowcasting and the difference in this between active summer lightning and winter lightning (mainly AIL). Another interview was conducted with Alwin Haklander, who is a meteorologist at KNMI as well. Alwin Haklander was interviewed to learn more about the workings of the nowcasting tool, as well as to share his opinion on the usage of the tool for AIL.

Secondly, two pilots from the KLM were also interviewed in order to learn more about their view on the topic of AIL and where they see possibilities or improvements that can reduce the amount of aircraft being struck by lightning during fall or autumn.

Finally, a Tower/Approach supervisor at Amsterdam Schiphol Airport has been interviewed as well in order to get insights on AIL and the effects operationally, as well as the views of an Air Traffic Controller on how to possibly prevent more cases of AIL.

4.2 Pilot questionnaire

Next to the information gathered via the stakeholder interviews, more information from pilots is gathered as well. The pilot questionnaire was separated in three parts:

1. General information about the pilot.
2. Experiences (if applicable) with previous lightning strikes to the aircraft.
3. Wishes and thoughts about possible (preventive) measures.

All the questions asked within the questionnaire are added in Appendix-A. The questionnaire had a total of 20 questions and gained a total of 21 responses from pilots.

The questionnaire was spread on the “European Airline Pilots” group on Facebook, containing ~20.000 members. It was also spread in an unknown Facebook group with only KLM pilots. This was done as there was no official platform made available to share a questionnaire for this internship, specifically. Because the amount of responses is ~0,1% of the total amount of pilots that could have seen the questionnaire, it is too low to be able to draw any definitive conclusions from. Nevertheless, the results are discussed as they can still give an indication.

It should be stated that there was a specific and different pilot questionnaire ready to be spread internally at KLM. However, due to unknown circumstances, it was not possible for the questionnaire to be shared internally and thus did not result in further input for the analysis.

4.3 Pilot information sheet

As a result of both the stakeholder interviews as the pilot questionnaire, which is further discussed in sections 5.1. and 5.2., it was decided upon creating a pilot information sheet for the KLM pilots, in order to better inform them about AIL.

The information sheet was made with three main goals:

- Raising awareness about the topic.
- Inform the pilots about the cause of AIL.
- Describe possible warning signs of AIL that can possibly be acted upon.

With help of these three goals, the purpose of the information sheet is to make the pilots more aware of AIL, its dangers and its characteristics. This could eventually help them to take precautionary actions in the hopes of preventing a lightning strike to their aircraft as a result of AIL.

4.4 Data analysis

As a final part of this internship, a data analysis was performed on a dataset with reports of aircraft being struck by lightning in or near The Netherlands. This dataset originates from the datawarehouse of LVNL (Luchtverkeersleiding Nederland) and contains reports from air traffic controllers. These air traffic controllers have to report each incident that occurs and/or is reported to them and add this to the database. The dataset has been specifically made and provided by LVNL for this internship.

From the database, a dataset was retrieved with a total of 83 lightning incident reports in the period between 2015 and the beginning of 2020. The structure of the dataset is shown in Table 3 below.

Table 3 Format of the provided dataset. IRIS ID is the unique identification number of the report, Unit is the unit within air traffic control where the report originated from and ATCAREA is the area in which the incident occured.

IRIS ID	Date	Time (UTC)	UNIT	ATCAREA	Incident
xxxxxx	dd-mm-yyyy	hh:mm	e.g. “TWR West” or “APP”	e.g. “EHAM CTR” or “Sector 3”	Incident description

There are a few aspects that have to be further explained about the dataset. First off all, some of the reports contain a specific ATC Area in which the incident occurred. This indicates the approximate location or region in which the lightning strike occurred, allowing further analysis to be more easy. The sectors that are mentioned in the ATCAREA column, are given in Figure 8. Next to sectors 1-5, EHAM CTR or EHAM TMA is given as well in the dataset. Those zones are shown in Figure 9. EHAM is the ICAO (International Civil Aviation Organization) code for Amsterdam Schiphol Airport and is commonly used in aviation language.

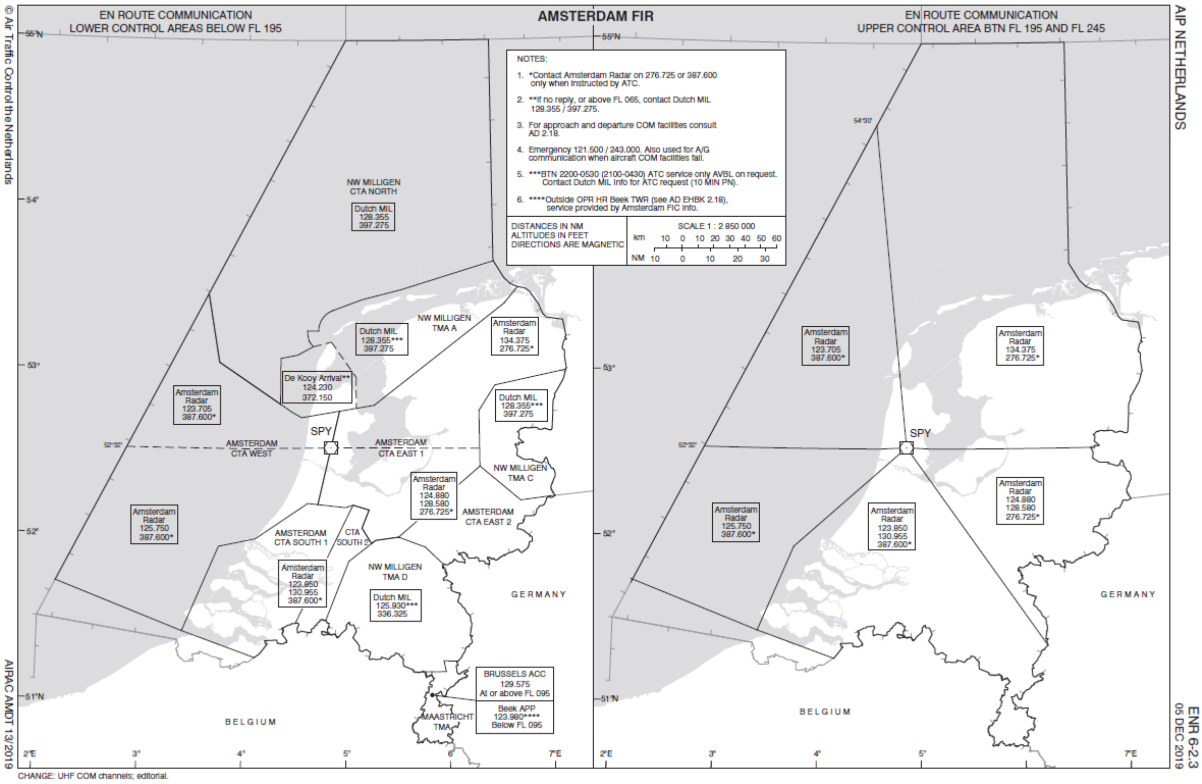


Figure 8 Overview of the sectors of Amsterdam Schiphol Airport (right hand side of the figure). Sector 1 is to the northeast, Sector 2 is to the east, Sector 3 is to the south, Sector 4 is to the southwest and Sector 5 is to the northwest. Courtesy: LVNL.

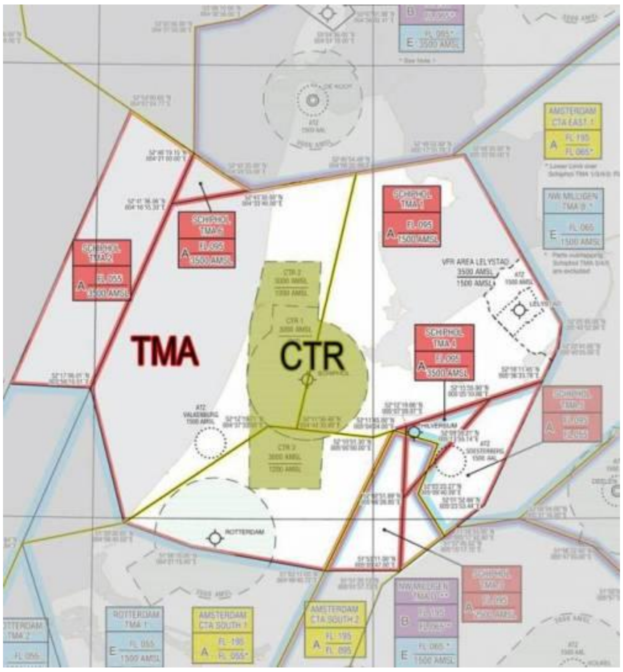


Figure 9 EHAM CTR and EHAM TMA zones, located in the northwest of The Netherlands. Image courtesy: Municipality Amsterdam.

It must be noted that the amount of information that is given in the incident description is very variable. Where one report gives a detailed description of the incident, others only state that a lightning strike occurred. Therefore, the dataset shows no consistency, making it more difficult to extract information from each report. Next to this, the reported time was not always reported in UTC, but in LT (local time).

From the dataset format as is shown in Table 3, information from the incident description is broken into sections in order to get a simple list of the following types of information:

- Aircraft Type
- Aircraft Return
- OPS
- Flight Level
- Thunderstorm Type

If the aircraft type is present in the incident description, this is added to the Aircraft Type section as well. However, for some cases, the aircraft type was not given in the incident description but still retrievable from another dataset.

Another dataset that was provided as input for this internship, is an overview of all landings and takeoff for the years 2018 and 2019. This dataset originates from the VIMMIS database, which is the data warehouse of LVNL. In the case of an unknown aircraft type where it was given that there has been a return, it was possible to find the aircraft type in the dataset with takeoffs and landings, as both the flight’s departure and arrival airport would state “EHAM”, provided that the departure or arrival time would be relatively close to the time of the incident report. Because of this, a total of 4 extra incidents were possible to be added to the Aircraft Type section, even if it is not mentioned in the incident description. Also, the aircraft types were labelled in simple way in order to get smaller groups with larger amounts. Therefore, no distinction was made between e.g. the Boeing 737 MAX and the Boeing 737-800 and both would be labelled as “B737”. This dataset was also used to determine the percentage of air movements (takeoffs and landings combined) in 2019 at EHAM for the aircraft types that are reported within the lightning strike incident dataset. This can then be used to find out whether the percentage of lightning strikes to the aircraft types are higher than the percentages of yearly air movements of the same aircraft type. If a large difference between these percentages is found, it can give an indication that the aircraft type attracts lightning more/less than other aircraft types. However, it must be noted that this includes the assumption that the time of day has no influence.

For the sections Aircraft Return, OPS and Flight Level, information was, if possible, extracted from the incident description and directly used to extract information from.

For the section Aircraft Return, the following six labels were given to the incidents:

- “Continue” – The aircraft continued its flight away from EHAM.
- “Inbound” – The aircraft was already inbound (going to land) at EHAM.
- “Return” – The aircraft returned to EHAM after departure.
- “Diversion” – The aircraft diverted to another airport instead of returning to the airport of departure.
- “Landed” – The aircraft was struck after being landed at EHAM.
- “Unknown” – It is unknown whether the aircraft continued, was already inbound, returned, diverted or had already landed.

For the section OPS, only two labels were given: “Normal” or “Unknown”, as all incident descriptions either stated that the OPS were normal (there were no direct issues with the aircraft) or no information about the OPS was given and thus labelled “Unknown”.

For the section Flight Level, in only a few occasions the approximate flight level at which the lightning strike occurred was given, if reported by the air traffic controller.

Finally, the section Thunderstorm Type was added to the data analysis. Here, each incident is attempted to find back in lightning location data, in order to label the incidents with the following three labels:

- “Undetected” – No lightning was detected.

- "Active" – There was active lightning, for this study this means that there was at least one observed lightning discharge per 5 minutes, for at least three time steps consecutively and being near each other in the same shower or thunderstorm. If multiple discharges were detected at exactly the same time, this was considered as one discharge
- "Suspected AIL" – The observed lightning discharge was not part of an active thunderstorm and corresponds to the approximate location (e.g. when the lightning discharge is found in Sector 1 and the report describes that the lightning incident occurred in Sector 1 as well.) and time of the lightning incident report.

  Additionally, multiple CG lightning discharges being located very close to each other and measured at exactly the same time was also an indication and reason to label the incident as "Suspected AIL", as experience has learned that this is regularly visible for confirmed cases of AIL. However, this is only done when there was no active thunderstorm present.

The lightning location data that was used to label the Thunderstorm Type for all incidents, was the Siemens BLIDS dataset, which is part of the EUCLID network. More details about this data and network is given section 3.5., where it also became clear that this network is the most accurate for The Netherlands and thus best to use for the classifications of the reported incidents. The data is freely accessible via Meteologix.com (the Dutch version of Kachelmannwetter.de), where the data has been visualised and is easily interpreted. An example of the data from the Kachelmanwetter website is given below, in Figure 10.

The screenshot of Figure 10 is from a confirmed case of AIL where the time of the discharge corresponded with an aircraft flying at the exact same location. It is again also typical that multiple discharges were measured very close to each other and at exactly the same time.

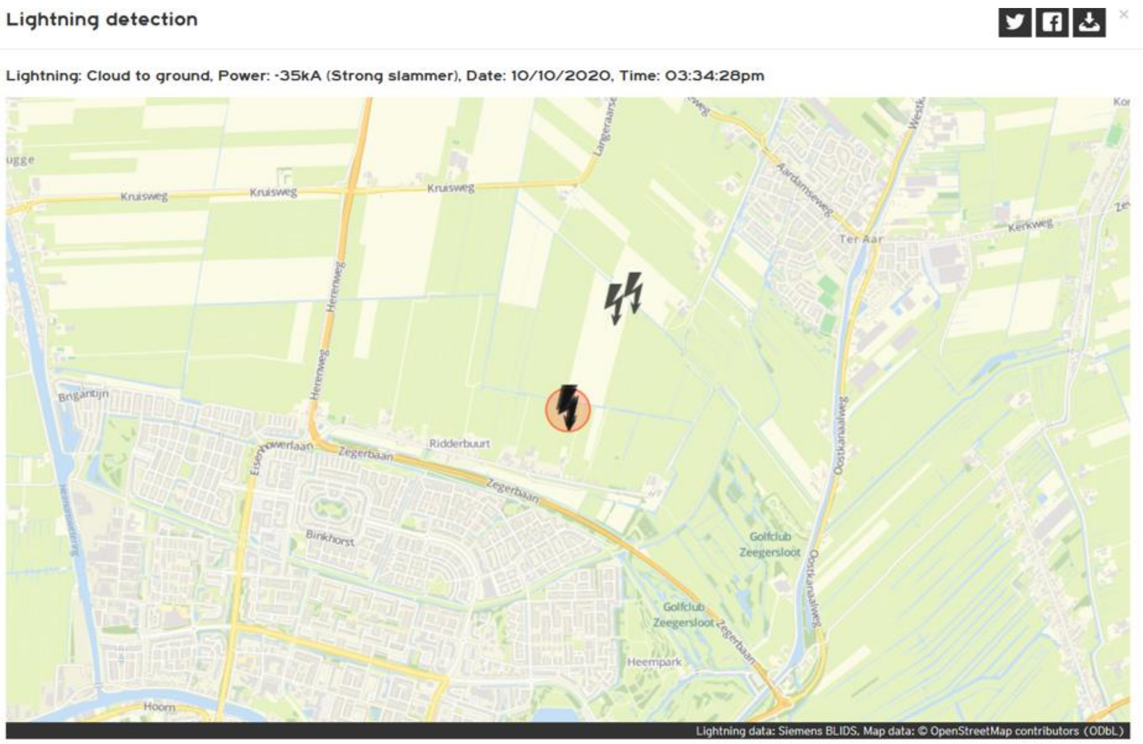


Figure 10 The visualisation of lightning strikes for a case of AIL north of Alphen aan de Rijn, 18 km south-southwest of Schiphol airport, for 10 October 2020 (15:34 CET), as has been detected by the Siemens BLIDS network. Source: Meteologix.com

5. Results & Discussion

5.1 Stakeholder interviews

5.1.1 Schiphol probability forecast

First of all, in the interviews taken with KNMI employees, useful insights were given about the supply of meteorological information to Amsterdam Schiphol airport and Rotterdam airport. Nowadays, Lelystad and Bonaire are included as well.

At all times, one mainport meteorologist is working at KNMI in order to supply this weather information to the airports. The meteorologist makes so-called TAF (Terminal Aerodome Forecast) forecasts. These forecasts are concise weather forecasts for the expected meteorological conditions at the airport during a specific period, which is often about 30 hours.

Next to making these TAF's and updating them regularly, the mainport meteorologist also makes the probability forecast for Amsterdam Schiphol airport. An example of such a probability forecast is given in Figure 11, on the next page. The forecast includes both hourly information for the next 6 hours, and then changes to time steps of 3 hours. The forecast is based upon statistical forecasts, but is adapted by the mainport meteorologist if deemed necessary.

Figure 11 shows that many variables are given and forecasted within the Schiphol probability forecast. At the top, a forecast is given for the chances of a certain height of the cloud base and/or visibility due to fog. These variables are distinguished between certain thresholds that correspond with different phases at Schiphol Airport. Such a phase determines the maximum capacity of the total number of aircraft that can land at the airport.

The second part of the Schiphol probability forecast is specifically for wind related variables, including wind direction, wind speed and wind gusts. Next to this, the uncertainty the wind direction and windspeed is added as well, in the form of the standard deviation (de Leege & Janssen, 2016).

Near the bottom, temperature, relative humidity and winter precipitation related information is given as well. Since this is relatively straightforward, this is not further discussed.

PROBABILITY FORECAST SCHIPHOL

Wednesday 23 December 10 UTC till Thursday 24 December 18 UTC

Last update: Short term: 07:12 UTC   Long term: 05:19 UTC

	10	11	12	13	14	15	18	21	00	03	06	09	12	15	18
Visibility < 5 km and/or ceiling ≤ 2000 ft (%)	100	100	100	100	95	95	90	85	80	75	50	30	25	20	10
Visibility < 5 km and/or ceiling < 1000 ft (%)	50	40	40	40	40	40	45	40	30	15	10	5	5	5	5
RVR < 1500 m and/or ceiling ≤ 300 ft (%)	15	5	5	0	0	0	5	5	0	0	0	0	0	0	0
RVR < 550 m and/or ceiling < 200 ft (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RVR < 350 m (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winddirection (deg)	190	200	210	210	210	220	240	230	230	310	350	360	340	350	350
Windspeed (kt)	5	6	6	6	7	7	8	10	11	7	11	12	12	12	12
Gusts (kt)								15	16	13	19	18	19	19	19
Standarddeviation winddirection (deg)	75	75	80	75	65	60	40	55	65	75	30	30	25	30	25
Standarddeviation windspeed (kt)	3	4	4	4	4	4	4	5	4	4	5	4	4	4	4
CB (%)	0	0	0	5	10	15	15	15	0	0	0	30	35	50	40
Thunderstorm (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AIL ISOL OCNL FRQ	no aircraft induced lightning in TMA														
Temperature (C)	10	11	12	12	11	11	11	10	9	8	7	7	8	6	6
Dewpoint (C)	10	10	10	10	10	10	10	9	7	7	5	5	5	4	4
Relative humidity (%)	100	94	88	88	94	94	94	94	87	93	87	87	81	87	87
Windchill	9							8	6	6	4	3	5	2	2
Snow (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moderate or heavy snow (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Freezing precipitation (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pressure (hPa) (modeloutput)	1007	1006	1006	1005	1004	1004	1004	1004	1005	1005	1008	1012	1014	1016	1018
	10	11	12	13	14	15	18	21	00	03	06	09	12	15	18

Remarks	Short term (till 15 UTC)	Long term
Visibility and ceiling		BZO due to vis and cld.
Wind		
Temperature		
Precipitation	Periods with rain or drizzle. In the afternoon tempo showers.	Periods with rain, during the afternoon small risk of an embd shwr. Thursday shwrs
CB in FIR	In the afternoon in SW-part isol/embd TCU/CB mov NE 15 kt, tops FL100/180.	Wednesday afternoon fm SW isol/ocnl CB, mar tops FL200, lan FL100. Thursday isol CB tops FL180.

Figure 11 The Schiphol probability forecast, issued by the KNMI. This probability forecast is issued at Wednesday the 23rd of December 2020, 07:00 UTC. The forecast is valid till Thursday the 24th of December 2020 18:00UTC. Source: KNMI / luchtvaartmeteo.nl

For AIL, the main section of the Schiphol probability forecast is of importance, located at the middle of Figure 11. Here, the probability (%) of showers is given, next to the probability of such a shower becoming a thunderstorm. Only since October 2020, the probability of AIL has been included in the probability forecast as well. This probability is not given in percentages, but in classifications: ISOL (isolated), OCNL (occasional) and FRQ (frequent). Each of these classifications have their corresponding yellow to red colours. The probability of AIL and winter precipitation probabilities are only added during winter and fall and are not visible anymore during summer months.

The meteorologist can also add remarks if this is applicable to the weather situation. These remarks are located at the very bottom of the probability forecast and can be used to e.g. further explain whether high probabilities are due to a low cloud ceiling, or due to fog, as that is not directly given in the percentages.

Finally, there also is a MAS-meteorologist (Meteorological Advisor Schiphol). This meteorologist can be called to go to Schiphol Airport and will be in the same room as the air traffic controllers. This is only done when the forecast is such that this is deemed necessary, for example in the case of severe thunderstorms. For AIL, the MAS-meteorologist will not be present at the airport.

5.1.2 Lightning nowcasting

Next to the probability forecast, the mainport meteorologist is also able to nowcast in the case of thunderstorms. At the KNMI, one important tool can give an indication whether certain showers pose a risk of producing lightning for the upcoming 10-15 minutes. This tool is called “Preflits” and has been developed in recent years (Bloemink, 2013). The tool is based upon information from e.g. Mosier et al. (2011).

Preflits uses a variable called the VII (Vertically Integrated Ice). During the interview with Paulien Flierman, the following was explained about the tool: “Preflits is a way of saying something about the process of charge separation. Interaction between liquid and frozen particles within a cloud causes this charge separation. Between different height values of the weather radar, the vertical column of ice can be determined, which gives an indication of this charge separation”. An example of the Preflits VII radar image is given below, in Figure 12.

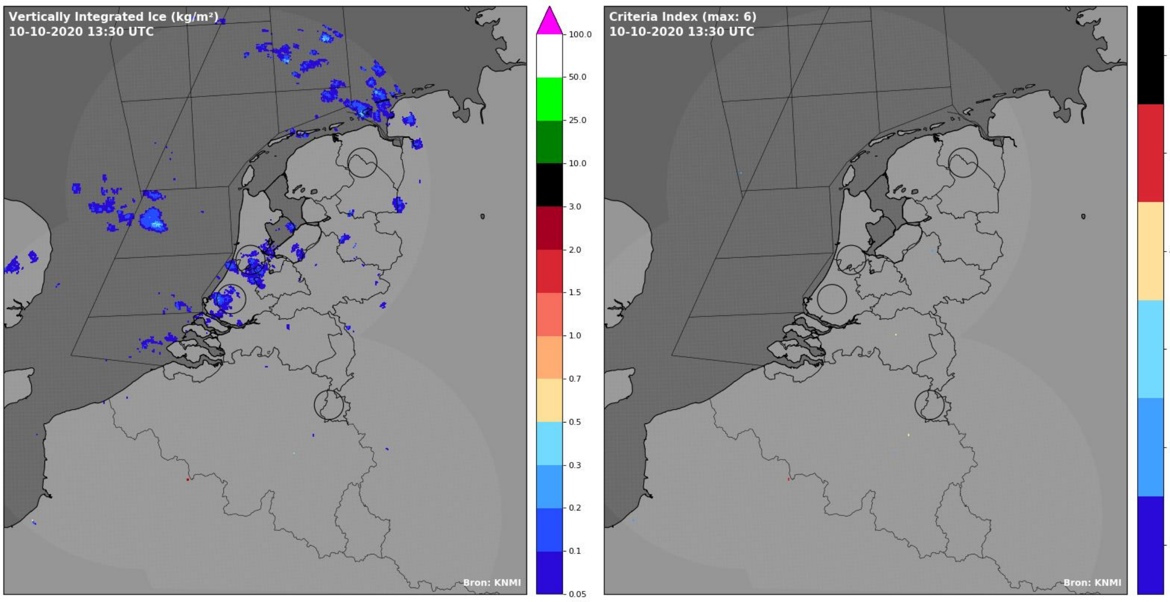


Figure 12 Example image of the VII and criteria index of the Preflits tool for the 10th of October 2020, at 13:30 UTC. Source: KNMI / Alwin Haklander.

“Preflits works best for situations where new storm cells are formed. When the cells have been present for a while already, Preflits works a little less good.” (P. Flierman, personal communication, 5th of October, 2020). Paulien Flierman also explained that next to the VII, Preflits also uses a criteria index. It is a collection of 6 of the best predictors of charge separation. When the VII shows doubtful values, this criteria index can be of help to indicate whether a shower poses a risk of producing lightning in the next couple of minutes.

What became clear, is that Preflits thus far is not good at predicting AIL. The VII only examines the vertical ice column between -10 °C and -40 °C. For AIL, most showers do not reach too high and the VII thus does not measure much ice between these two temperature values. As a result, the values of the VII are not too high and are not recognised as posing a risk of producing AIL. Paulien Flierman also explained that for AIL, the process of charge separation could be taking a relatively long time. As a result, low values of VII could possibly still be enough to cause enough charge separation within the cloud over a long period of time, resulting in a lightning strike being triggered by an aircraft that flies through the cloud.

Alwin Haklander, who also works at the KNMI, produced the Preflits tool and has also been interviewed to learn more about AIL and Preflits. He confirmed that Preflits and the VII predictor have difficulties in predicting the risk of AIL and agreed on the hypothesis that the vertical layer of ice between 0 °C and -10 °C could be of importance for AIL (A. Haklander, personal communication, 12th of October, 2020).

5.1.3 Pilot's preference

Next to speaking to the meteorologists of the KNMI, there has also been active communication with two pilots of KLM.

The pilots indicated that they feel that a pilot information sheet could be of value and impact pilots at KLM. They saw two opportunities:

1. Share the pilot information sheet within KLM via a news application, allowing the pilots to have a look at the document and become more aware of the topic.
2. Use the pilot information sheet to implement it into a type recurrent. The type recurrent is an internal training of KLM where pilots have to read important documents and train for certain scenarios.

The pilots indicated that it will be difficult to provide live-meteorological information (such as lightning detection) regarding AIL to the pilots while flying. This is mainly because it requires an internet connection and in most aircraft, this is not yet available.

5.1.4 Air traffic control preference

During the interview with the Tower/Approach supervisor at Schiphol Airport, the preferences from the perspective of an air traffic controller were clear: acting upon AIL is the responsibility of the pilot. Air traffic controllers are there to facilitate actions of the pilots. If pilots want to evade certain winter showers, they should decide on doing that and the air traffic controllers can then facilitate the changed flight paths where needed.

Again, the idea of creating a pilot information sheet for creating awareness and possibly training pilots was seen as the best option to possibly prevent more lightning strikes to aircraft as a result of AIL.

5.2 Pilot questionnaire

The pilot questionnaire gained a total of 21 responses, of which 10 indicated to fly for KLM. 12 of the responses indicated to be based at Schiphol Airport. From the pilot questionnaire, a couple of things stood out and are discussed in the next few paragraphs below.

First of all a total of 15 answers were given to the question “What was the date of the lightning strike”. Of those 15 responses, 53% (8) of the pilots indicated that the strike was between October and April. This confirms that a large part of the lightning strikes occur within these months, as has also been described in Gough et al. (2009).

Interestingly, 84% of the responses (16/19) indicated that the lightning strike occurred when flying outside of the Cb. There are two hypotheses that can possibly explain the fact that most piloted indicated this:

1. The pilots did not recognise a smaller or less strong Cb on their weather radar, believing that that was not the cause of the lightning strike and believed that a stronger Cb, located further away, was the cause of the lightning strike. It can also depend on the ability of a pilot to recognise a Cb.

2. The aircraft was struck due to a positive lightning discharge from the anvil of the Cb, while flying outside of the core of the Cb. This is also a process that has been described in Wilkinson et al. (2013) as a possible cause for some of the lightning strikes to the investigated helicopters in the paper.

These hypotheses cannot be confirmed or denied without further investigation, which is not possible within this internship. Therefore, it remains unclear why most pilots indicated that their aircraft was struck while flying outside of the Cb and cannot be concluded on.

A large variety of answers were received on the question whether the pilots observed anything noteworthy near the time of the lightning strike. Whereas some only responded with “yes” and did not elaborate on what exactly they observed, Saint Elmo’s Fire is a reoccurring answer and can be considered as a possible warning sign for a lightning strike. Saint Elmo’s fire is a type of corona discharge and is an indication that the aircraft has gained a net charge due to it flying through an electrically charged field of a cloud. These corona discharges regularly occur on the windshield of an aircraft. An example of Saint Elmo’s fire is visible in Figure 13.

Figure 13 Saint Elmo's fire on the windshield of a KC-10 aircraft. Image courtesy: Wikipedia / Senior Airman Brian Kelly.

Saint Elmo’s fire, or corona discharges on the aircraft, has been discussed as an indication of the aircraft becoming electrically charged in scientific literature as well (e.g. Laroche et al., 2012; Uman & Rakov, 2013; Morgan et al., 2012).

Other observed phenomena near the time of the strike were a bright light surrounding the flight deck for a few seconds, extreme turbulence & hail and snow. In one answer, the pilot indicated that he/she saw “about a 5 meters long ‘lightning’ coming out of the nose forward”. It is most likely that the pilot saw one of the streamers that has been described in section 3.2. (one of the bi-directional leaders).

In terms of damages, black (burn) marks or blackened parts were occasionally reported by the pilots that have responded to the questionnaire. Other reported damages were an approximate 4x4 cm hole in the nose landing gear door and a damaged radome/nose cone. One answer indicated that both pilots were completely blinded by the lightning strike and that “according to cabin crew, the cockpit door was lit as if heaven/hell was on the other side”. Being blinded by a lightning strike is an issue that has been reported in literature as well (Uman & Rakov, 2003; Mäkelä et al., 2013), and of course is quite logical if the lightning strikes the nose of the aircraft.

Interestingly, out of a total of 20 answers to the questions whether the pilots were informed about the possibility of AIL or about previous strikes, 17 (85%) answered that they did not. This indicated that there is much to gain in terms of making the pilots better aware of the possibility of AIL. Yet, the pilots gave relatively good marks for the weather forecast on the day of the strike. Out of the 19 responses, only five gave the forecast the mark “5” or lower. The other 14 responses awarded the forecast with marks “7” or higher.

The wishes of the pilots regarding the supply of more information in the cockpit are quite diverse. Out of the 20 responses to the question whether the pilots think it would help to have live lightning location data in the cockpit., 12 stated that they do think that it would help. However, 7 others did not think it would help and argued that they doubt whether it would help as it could be distracting or that they think the regular weather radar is sufficient.

The same is valid for the question whether the pilots think it could be helpful to have an AIL warning on a weather radar. Whereas some think it could be helpful, provided that it does not cause too much clutter or that it does not needlessly compromise the already few options when navigating around weather. Moreover, some aircraft do not have onboard Wi-Fi that is needed in order to supply such type of information.

Again, the opinions of the pilots are different when asking whether they think better training about the process of AIL is required. About half of the pilots did not think this was needed as training, but some of these answers did include that some refreshment of the knowledge or more local information about weather could not harm in their opinion. On the other side, about half of the pilots also indicated that they think better training about AIL is required, mainly also because some of them were completely surprised by the lightning strike. One answer stated that “the interaction of aircraft with stormy clouds is not fully and deeply instructed”.

5.3 Pilot information sheet

From the information that was gained from the stakeholder interviews and pilot questionnaires, it became clear that there was substantial opportunity in supplying better and more clear information about AIL to pilots. It is also clear that the information sheet had to contain location-specific information as the cause of lightning differs between places around the world. Since the document is specifically made for KLM, the region around Schiphol is the focus of this information sheet. The full pilot information sheet is added in Appendix-B.

The complete document was made as short as possible, without causing a lack of information. It contains a balance of being as brief as possible while giving all the necessary information for pilots to better understand the process of AIL and what can possibly done to avoid being struck. However, it mainly also causes more awareness of AIL. This way, pilots would be less surprised when struck, allowing them to understand what happened more quickly and act upon the lightning strike the way that necessary.

Of course, not all information that is given in the summary in this internship report is also added to the information sheet. The main process of why an aircraft triggers lightning is discussed only very briefly and some of the processes are not explained. As a final note, the document explained the process of shower formation during fall and winter months over the Netherlands and the North Sea. This was done to add location-specific information that could help pilots to recognise the synoptic weather situations where a risk of AIL is present.

The process of implementing the pilot information sheet into a type recurrent is for the long-term. The first option would be to implement the document for the second type recurrent training in 2021. However, due to the legal requirements to this training, it cannot be stated for sure if and when exactly the document can be implemented. Nevertheless, the pilot information sheet was appreciated within the KLM and will be published as a news article in January 2021.

5.4 Data analysis

From the 83 analysed lightning strike incidents that were reported by air traffic controllers, it was unknown which aircraft type was struck for 48 of the cases. On the other side, for 35 cases, this was known. The results of the analysis regarding aircraft type is shown in Figure 14. In the figure, the contribution (percentage) of the aircraft to the total amount of lightning strike incidents where the aircraft type is known is shown (blue bars), as well as their percentages of total air movements in 2019 (orange bars). Next to the aircraft type, the x-axis also contained the total amount of incidents belonging to the aircraft type between brackets.

12 out of 35 lightning strike incidents occurred for a B737 aircraft. This equals 34,3% of the reported incidents. Although the B737 is the most-reported aircraft type of all 35 lightning strike incidents, the total percentage is barely higher than the percentage of B737 air movements in 2019 at Amsterdam Schiphol airport, which is 30,7% (162.191 B737 air movements out of a total of 528.027 air movements).

For the E190, which is on the second spot in terms of most lightning strike incidents, the same cannot be said as for the B737. With a 9 out of 35 incidents being from the E190, it contributes to 25,7% of the lightning strike incidents where the aircraft type is known. However, only 14,1% off all air movements at EHAM is from the E190. The difference between these percentages is 11,6% and could be an indication that the E190 attracts more lightning than other aircraft. According to Embraer, the manufacturer of the E190, the aircraft is predominantly metallic, which could explain the difference as metal is known to attract lightning more easily. However, there are more variables, such as the ascent/descent speed and level-off altitude, that could result in more strikes to the E190 than other aircrafts. This is something that should be further researched and is discussed in section 6.2.

For all other aircraft types (such as the A320), only 1 to 3 lightning strike incidents have been reported within the dataset. Therefore, little can be said about their relation with the total amount of lightning strike incidents.

Finally, the F70's percentage of air movements is 0%. This is due to the fact that the percentage of air movements is determined for 2019, when the F70 was already no longer part of the KLM fleet since 2017.

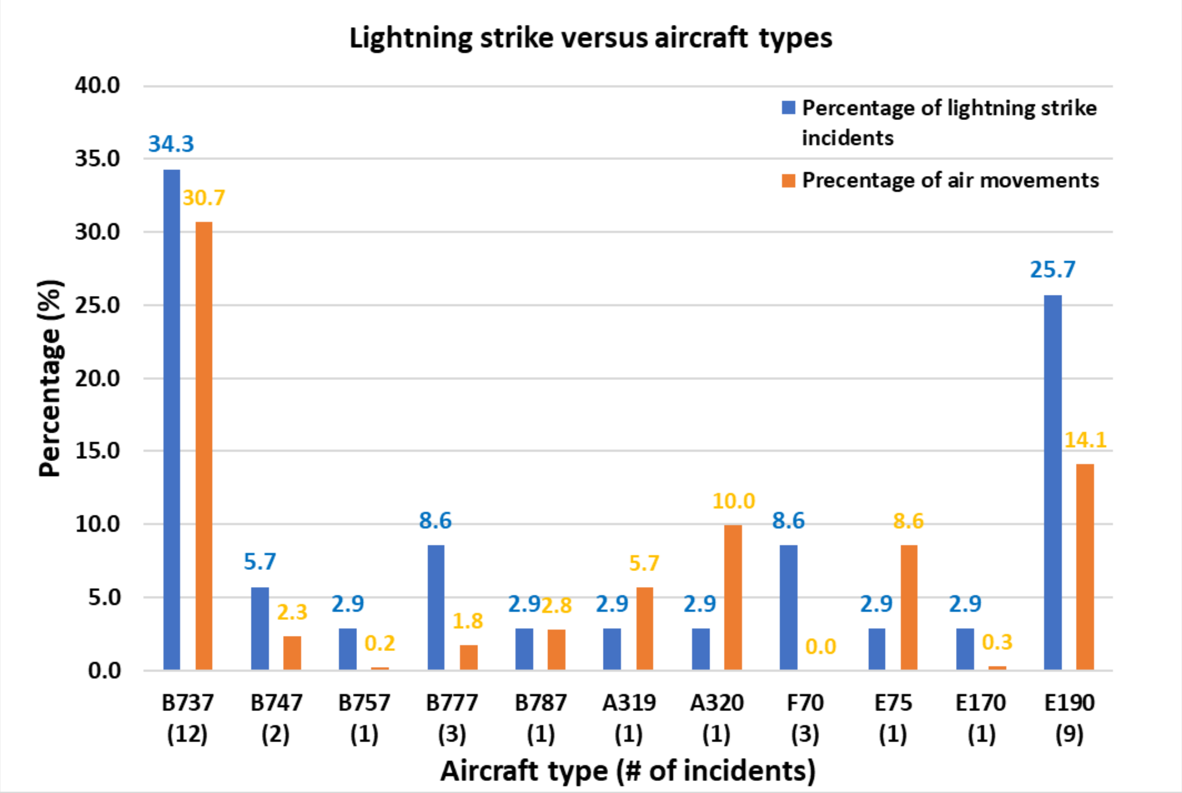


Figure 14 The percentage of lightning strike incidents and percentage of total air movements in 2019 versus aircraft type.

Out of the 83 reported incidents, a total of 28 returned to the departure airport and only 14 continued their flight. Next to this, 3 flights diverted to another airport. A total of 14 flights were already inbound when being struck by lightning and 1 aircraft was already landed on the airport when it was struck by lightning. For 13 of the 83 incidents, it remained unknown whether the aircraft returned, continued, was already inbound or on the ground. This shows that lightning strikes to aircraft does cause returns, resulting in extra costs for the airline, significant delays and a higher workload for air traffic controllers. However, it should also be noted that these 83 cases are most likely not the only cases of lightning strikes to aircraft between 2015 and 2020. Since not all incidents are reported to and/or by the air traffic controller, it is well possible that there are more lightning strike incidents than are currently known within the examined period. Therefore, it is not possible to state anything about the ratio between returns and aircraft that continue their flights.

For most of the reported incidents, it was not stated whether the OPS were normal. Only for 23 of the incidents the OPS were reported normal, but it does not show and mean that there are no damages as a result of the lightning strike.

Only 7 out of the 83 incidents contained information about the flight level at which the aircraft was flying when being struck by lightning, ranging between FL050 and FL130. Due to the low amount of reported flight levels, no conclusions can be drawn from these values.

Finally, a strong relationship was found between the incidents and their thunderstorm type. Out of all 83 reported incidents, a total of 46 were labelled with “Suspected AIL” and thus occurred in inactive thunderstorms. Only 18 cases were during active thunderstorms and occurred especially in summer months as well. For another 19 cases, no lightning was detected by the Siemens BLIDS network and it was thus not possible for the case to be classified with “Active” or “Suspected AIL”. What stands out, is that especially in the year 2015 and the beginning of 2016, most of the cases remained undetected, whereas after that period almost no cases were left undetected. This gives the impression that something changed within the Siemens BLIDS network that caused this. Siemens BLIDS has indeed confirmed that in 2016, there was a change in technology that allowed the lightning detection network to detect more lightning strikes than it did before, which can explain why so many incidents in 2015 and 2016 were undetected.

From the numbers in the previous graph, at least 55% of all reported incidents were labelled with “Suspected AIL”. This means that it is very likely that those incidents occurred within thunderstorms that did not actively produce lightning themselves. This does not yet include the 23% of cases where no lightning was detected. Since it is most likely that at least some lightning strikes were detected in active thunderstorms in 2015 and the beginning of 2016, the majority, if not all, of the undetected cases would have otherwise also be labelled with “Suspected AIL”. This being said, the percentage of suspected AIL cases would then become a total of 78%. The vast majority of this 78% also occurred within the period between October and April: 60 out of 65 (92%). This is much larger than the 40% that has been reported in Gough et al. (2009) and could indicate that more lightning strikes to aircraft are a result of AIL than has been previously thought.

6. Conclusions and recommendations

6.1 Summary and conclusions

This internship has been investigating the process called Aircraft Induced Lightning (AIL) for the region around The Netherlands and the North Sea. It has summarised scientific knowledge around this topic, bringing a large group of scientific researches together into one large summary that discusses the electrical charging of clouds, their interaction with aircraft, statistics regarding aircraft and lightning, damage as a result of lightning striking aircraft and lightning detection systems.

Next to this, this internship has conducted several (small) researches of its own as well. Interviews were conducted with several stakeholders that are related to the topic of AIL. From the meteorological point of view, several people from the KNMI were interviewed. These interviews were used to get a clear overview of the meteorological information service that the KNMI provides to pilots and Schiphol Airport. This is mainly done in the form of the Schiphol probability forecast, where AIL is one of the (new) variables included. Next to the probability forecast, the KNMI also has a specific weather radar tool called “Preflits” that assists them in nowcasting showers that pose a risk of producing lightning. However, for the case of AIL it has proven difficult to predict with help of this nowcasting tool and further development is needed.

From the pilots’ and air traffic controllers’ perspective, the best chance to improve the predictability of AIL and mainly prevent more lightning strikes to aircraft is to better inform pilots about the process of AIL, the warning signs of AIL and how to act accordingly.

From a pilot questionnaire, it was indicated that opinions about where improvements are possible are divided. Nevertheless, about half of the responding pilots stated that they believe that better training regarding AIL can be of added value. However, this had to be location-specific. However, the questionnaire cannot be considered representative of all pilots as the total amount of replies is low in comparison with the total amount of pilots that could have responded to it. The results of the questionnaire therefore only serves as an indication.

Because of the interviews and questionnaires, a pilot information sheet has been developed for KLM. In this information sheet, the process of AIL formation and the possible warning signs are explained so that pilots can use this to recognise these warning signs and act accordingly if deemed necessary. The pilot information sheet was appreciated within the KLM and as a results, will be spread internally via a news article, which will be published in the near future. It will also likely be included in an internal training, a type recurrent, in the future. The current goal is to do so for the second type recurrent training in 2021.

Finally, a data analysis was performed on a dataset containing 83 lightning strike incident reports by air traffic controllers of LVNL. From the dataset, which is relatively small, the E190 aircraft seems to be attracting more lightning, as it contributes over 10% more to the lightning strike incidents than it does to the total amount of air movements in 2019. Due to the low amount of incidents in comparison to the total amount of air movements, it is uncertain whether and why this is and should be further investigated.

The data analysis also showed that the majority of the studied incidents can be labelled as “Suspected AIL” and that there are most likely even more, as also a part of the incidents remained undetected in a lightning location network. The total percentage of the incidents labelled with “Suspected AIL” is much larger than has been previously mentioned in research for Schiphol airport, indicating that most likely more lightning strikes occur as a result of AIL than has been previously thought. This increases the relevance of the topic and research around AIL even more important.

6.2 Recommendations

From the summary and research that is part of this internship, some questions have been answered, but some questions have also remained unanswered, require further investigation and also new questions have arisen. Because of this, there are a few recommendations for further work and research are described next.

6.2.1 Future information sheets

Although a large group of the pilot questionnaire respondents fly for KLM, KLM is of course not the only aviation company that flies across the world and also uses Amsterdam Schiphol Airport. Also pilots from other companies stated that they feel like better training can be useful if it is about AIL. If KLM pilots are able to decrease their amount of lightning strikes, this of course decreases the work load for air traffic controllers as well, as it would result in less returns. However, there still are plenty of other airlines that make use of Amsterdam Schiphol Airport and can encounter AIL. In order to further decrease the work load for air traffic controllers, it its therefore recommended to also spread (perhaps different) information sheets to other companies as well. This could also lower the nuisance at the airport as a result of lightning strikes, delays and unplanned returns

6.2.2 Creation of a AIL nowcasting tool

As has been described in section 5.1.1., KNMI already has an existing nowcasting tool for showers that are capable of producing lightning in the future. This radar is based upon the variable called Vertically Integrated Ice (VII) as it is an indication of charge separation within clouds. However, the tool has also proven to be inefficient in predicting AIL.

The current hypothesis is that this partly is due to the exclusion of the vertical layer of ice between freezing point and -10 degrees Celsius. Since showers that produce no active lightning by themselves but are capable of producing AIL are relatively shallow and have cloud tops with relatively high temperatures, including this small important layer of ice can make the difference.

Consequently, it is recommended that further work is done in creating a tool that is able to predict AIL without a too high false alarm ratio. Although this tool is most likely not of value for pilots yet since not all aircraft are equipped with airborne Wi-Fi, it can still be of assistance for KNMI mainport meteorologists in forecasting and nowcasting AIL.

6.2.3 Further extensive data analyses.

Even though some data analysis has already been done in this internship, there is a lot more left open that needs to be done. For example, the relation between lightning strikes to aircraft and the ambient air temperature/height has only been discussed from other scientific articles. However, none of those articles have investigated these relationships for The Netherlands and/or North Sea specifically. In order to gain better and location-based knowledge about AIL in these regions, it is therefore strongly recommended to acquire this type of data for further work. This allows a more clear understanding of the conditions in which AIL occurs around Amsterdam Schiphol Airport, also allowing pilots to better understand the process of AIL and taking action accordingly when this is deemed necessary by them.

Another data analysis that is recommended to perform in the future is one that relates the strikes with the aircraft types. Although the small dataset that was used for this internship already has done such an analysis, the total amount of strikes are relatively low and perhaps not certain enough to gain clear conclusions out of it. A dataset with hundreds of strike reports and known aircraft types can help in also gaining a better understanding of this relationship. It can also possibly confirm or deny the current idea that at least the E190 aircraft attracts more lightning. This knowledge can eventually also help to have pilots become more aware of how prone their aircraft are in attracting lightning, allowing certain aircraft to navigate around certain showers more quickly than others, decreasing the amount of unnecessary circumnavigations and decreasing extra costs as well.

It is also recommended to create a new overview of (recent) damages as a result of lightning strikes. The damages that have been discussed in Table 1 (Section 3) originate from a paper in 1989. During the literature research, no scientific papers were found that show more recent overviews of damages to aircraft as a result of lightning strikes. Therefore, creating such a new overview will most likely have added value and give a better insight in the dangers of lightning strikes to aircraft.

6.2.4 The effect of climate change on AIL

A final recommendation is to research the effect of climate change on the occurrence of AIL in the future, using multiple climate scenarios. This can be done with e.g. WRF/Harmonie/HIRLAM model simulations that make use of climate projections by manually adapting the sea surface temperature, as the North Sea is warming due to climate change.

However, one should also take into account the possible warming that occurs higher up in the atmosphere. If climate projections show that the upper air is also warming, this must be included in such a research. As the temperature difference between the surface and upper air is of great importance for the formation of showers that pose a risk of producing AIL, adding the effect of a change in temperature of the upper air is necessary.

By examining the effect of climate change on AIL, one can make a forecast that states whether it is likely that more or less AIL will occur in the future climate.

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Appendix A – Pilot Questionnaire

Hi all,

My name is Brian Verhoeven and I am a Dutch 2nd year MSc student at Wageningen University. I specialise in meteorology and am currently performing research about AIL (Aircraft Induced Lightning) for my internship. I aim to increase the predictability or preparedness of AIL in order to prevent aircraft being struck by lightning and possibly being damaged or having to return to the airport.

What is AIL?
Aircraft Induced Lightning is the process of lightning being triggered to strike the aircraft as it is passing through the (loaded) electric field of a thunderstorm. Most AIL cases are in the winter, which is slightly counterintuitive. However, during summer thunderstorms, most big Cb's are evaded and aircraft are thus not struck.

During the winter, however, showers that often form above warm sea water with cold (polar) upper air above it, can also produce AIL. These are the most tricky situations as the Cb's are relatively small and do not (actively) produce lightning themselves. However, when aircraft fly through or near these polar showers, they possibly are enough of a trigger to cause a lightning discharge, striking (and leaving) the aircraft. This is what my internship focusses on. In order to increase the predictability/preparedness of AIL, I also need to know more about previous experiences and wishes from pilots.

Below, I have a few questions regarding your experiences with lightning striking your aircraft. In the case that you have experienced a strike during the winter months, please answer the questions for that case! In the case that you only have been struck during the summer months, please answer the questions for your most recent case.

Please note that all questions are optional. You can leave any questions that you would not like to answer blank.

Thank you for helping me with this internship and I wish you all the best during these difficult times.

Should you have any questions and whish to reach out to me, my e-mail is: brian.verhoeven@wur.nl

Q1: What airline do you fly for?

Q2: What airport are you based at?

Q3: What aircraft type do you fly?

Q4: What was the date of the lightning strike?
(Day, month, year)

Q5: What was the approximate time of the strike?
(Time)

Q6: What was the approximate location of the lightning strike (e.g. North Sea or North of Schiphol)?

Q7: Have you ever experienced a lightning strike to your aircraft prior to the one you discuss here?

- Yes
- No
- Other…

Q8: Near which airport did you experience AIL? (Please use the airport code)

Q9: Were you inside or outside the Cb?

- Inside
- Outside

Q10: If you were outside of the Cb, what was the approximate distance to the Cb?

Q11: Did you observe anything special near the time of the strike (e.g. St. Elmo's fire)?

Q12: Did you experience any issues or damages as a result of the lightning strike?

Q13: Were you informed about the possibility of AIL or about previous strikes?

Q14: How good was the weather forecast (METAR/TAF/SIGWX charts) of that day?

	1	2	3	4	5	6	7	8	9	10	
Completely off											Exactly on point

Q15: Do you think that it would help to have live lightning (location) data in the cockpit? Please elaborate your answer.

Q16: Do you think that it would help to have a weather radar with warnings for possible AIL in the cockpit? Please elaborate your answer.

Q17: Do you think that better training about the process of AIL is required? Please elaborate your answer.

Q18: Do you have any additional comments regarding AIL and being better informed about it?.

Q19: There is a chance that I would like to speak some of you personally with further questions. Would you be willing to do that? If so: please leave your e-mail below.

Q20: If you have any further comments, please leave them here.

Appendix B – Pilot Information Sheet

Introduction

Back in 1963, Pan Am Flight 214 crashed on the 8th of December as a result of a lightning strike that caused an explosion. All 81 occupants (passengers and crew) were killed in the accident. Nowadays, aircraft are designed in such a way that they do not crash as a direct result of a lightning strike. However, that does not mean that there is no danger to aircraft being struck by lightning.

Lightning strikes can still cause significant damages. Recent pilot reports have shown damages such as a 4x4 cm hole in the nose landing gear door and burn marks on several places. In another case near Finland, the TCAS (Traffic Collision Avoidance System) became unserviceable after the lightning strike. Every lightning strike demands a maintenance inspection which could lead to a severe network disruption. Especially the composite structure of the 787 can show little damage on the outside, but extended delamination within. This stresses that, even though lightning cannot cause an explosion anymore, it still poses a risk to the aircraft and airline operations. The more lighting strikes can be prevented, the better!

Summer versus winter lightning

There is a significant difference between lightning during the summer and lightning during the winter. Knowing the difference and the causes of lightning is key to be able to take action whenever needed. Below, the process of lightning formation is discussed, along with the difference in the process between summer and winter thunderstorms.

Summer thunderstorms

Thunderstorms during the summer are often the easiest to recognise. CB (Cumulonimbus) clouds are shown on the aircraft weather radar as strong cells with red or sometimes even purple colours (if applicable). You might be able to see the cauliflower and anvil top towering above you to altitudes above FL400. This would normally serve as more than enough reason to evade these cells and the chances of being struck are quite slim, as the core of the CB is evaded.

Any shower or thunderstorm has one main requirement in order to form: the rising air must be and remain warmer than its surroundings in order to keep on rising for kilometres. Therefore, a large difference in air temperature between the lower atmosphere and upper air is required. In the summer, this often originates from heating of the earth's surface by the sun. This is also the reason why most summer thunderstorms form in the (late) afternoon or evening, as that is the moment when the surface temperature peaks.

Winter thunderstorms

During winter, showers cannot grow as high and sometimes have cloud tops at FL200 or less. Due to these lower cloud tops, winter showers are less strong than summer thunderstorms and are often not able to produce lightning themselves. Yet, the cloud can still (slowly) become electrically charged and pose a risk of producing Aircraft Induced Lighting (AIL). This is also the reason why most AIL cases are observed during fall and winter: the showers are not recognised as posing a risk for AIL and not evaded, resulting in a lightning strike.

The difference in air temperature that is described earlier, cannot originate from heating by the sun, as it is too weak in the winter. However, Dutch winters are known to be governed by low pressure areas, where frontal zones pass over the country. Behind a cold front, cold (polar) upper air is transported over The Netherlands. As a result, the temperature difference between the surface and upper air is still strong enough to allow formation of showers, of which some have a risk of producing Aircraft Induced Lightning (AIL). An example of such a weather situation is shown in the KNMI weather map, visible in Figure B1. These weather maps can be found on their website.

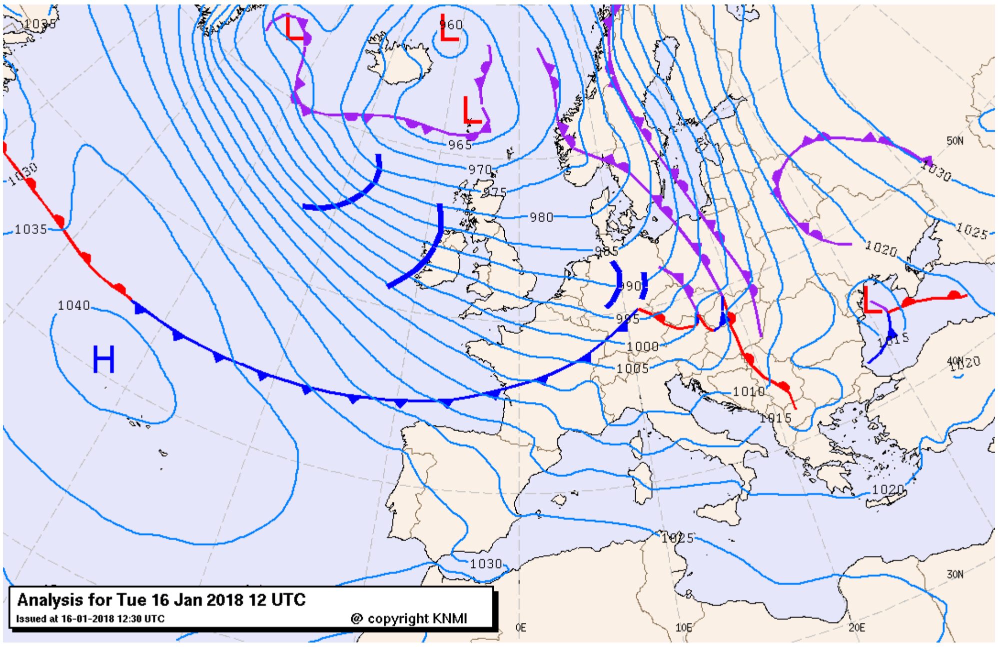

Figure B1 The weather map for the 16th of January, 2018 (12UTC). The Netherlands is behind a cold front and the wind direction is westerly. Source: KNMI.

Situations like these are recognizable as days where showers arrive from the west, northwest or north. On the weather radar, many showers are visible. Figure B2 is an example of how such a weather radar would look like. Most cells are relatively weak, but some cells are visibly stronger. Especially these stronger cells are capable of producing AIL. Showers in fall or winter also have the tendency to strengthen just west of the coast, which is very typical for The Netherlands. This is mainly a result of both high seawater temperatures and the effect of stronger friction by the earth's surface, which forces air to move vertically (upward), strengthening the showers.

Figure B2 Radar image for 16th of January 2018. Some cells, also nearby Schiphol Airport, are stronger with dark blue or red colours.

The effect of aircraft

Various researches have shown that aircraft become negatively charged during a flight. Thus, in order to cause a lightning discharge, this negative charges must be connected to a positively charged electric field.

In order to be able to explain the mechanism behind AIL, it is key to look at where the positive charges of a cloud are located. This is shown in the figure below.

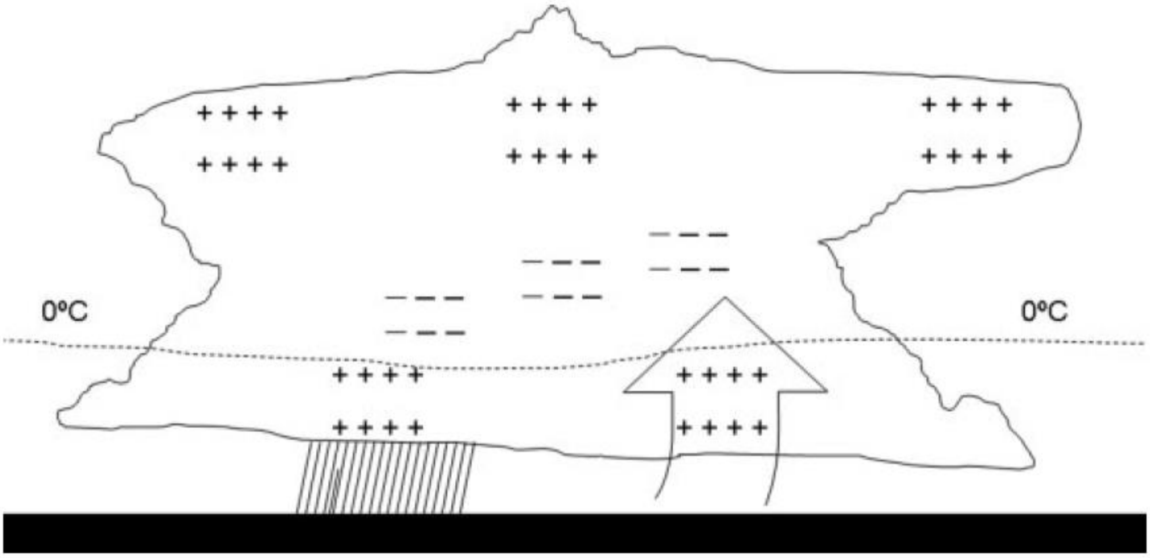

Figure B3 Sketch of the charged regions in a CB. Source: Wilkinson et al. (2013), Investigation and prediction of helicopter-triggered lightning over the North Sea.

As one can see from Figure B3, there are two areas that are positively charged within the cloud. The first and primary region is near the very bottom of the cloud. Especially in the case of winter showers, these cloud bases are located relatively close to the ground. Flying just below or through these cloud bases, could trigger AIL, as the negative charge that the aircraft creates, can interact with the positive charge of the cloud.

However, the cloud base is not the only part of the cloud that could result in AIL. Figure B3 also shows, the top of the cloud is also positively charged. This is the anvil of the CB and especially during winter time, such a cloud top can be located as low as FL150-FL200. When flying through or nearby such a cloud top, AIL can also be triggered.

Important warning signs for AIL

Although AIL remains difficult to predict, there are indications that could warn the pilot for AIL.
First of all, the pilot can see the forecast for AIL in the Probability Forecast Schiphol, issued by the KNMI. There, a colour indicates whether there is a chance of AIL in three degrees: ISOL (isolated), OCNL (occasional) and FRQ (frequent). This forecast purely aims to raise awareness.

This awareness allows the pilot to more actively search for warning signs for AIL. Below, a list of such possible warning signs is given. These warning signs are based upon reports and scientific literature.

1. **Outside air temperature at flight level is near freezing level.**
2. Cells that show moderate echoes (yellow colours or darker on the aircraft radar)
3. Frozen (snow, hail or other ice crystals) or mixed precipitation occurs.
4. CB within 5NM of the aircraft.

5. St. Elmo's Fire

In order to assess the possibility for AIL, it is most important to realise that the outside air temperature around freezing level (mainly ranging between +5°C and -7°C) is in most cases critical for AIL to occur, especially with negative temperatures. Thus, when flying with an outside temperature near this level, the pilot should be extra aware of warning signs for AIL and evade e.g. the cloud bases of these moderate showers when deemed possible and necessary.

Final note & example

As a final note, it is important to realise that not all cases of AIL are straightforward. Such a situation can be embedded CB's within a large field of precipitation. An example of this, is given below.

On Tuesday, the 3rd of November 2020, an inbound flight from Mexico City to Amsterdam Schiphol Airport most likely got struck by a single lightning strike. There was no other lightning event at that time and location. However, the aircraft did not fly through an isolated CB, but rather through a strong embedded CB within a large area of precipitation. This shows that it is key to remain aware of AIL, even when isolated CB's are not clearly visible. It is worth noting that the aircraft in question was flying at roughly FL045, where the temperature was very close to 0 degrees Celsius.

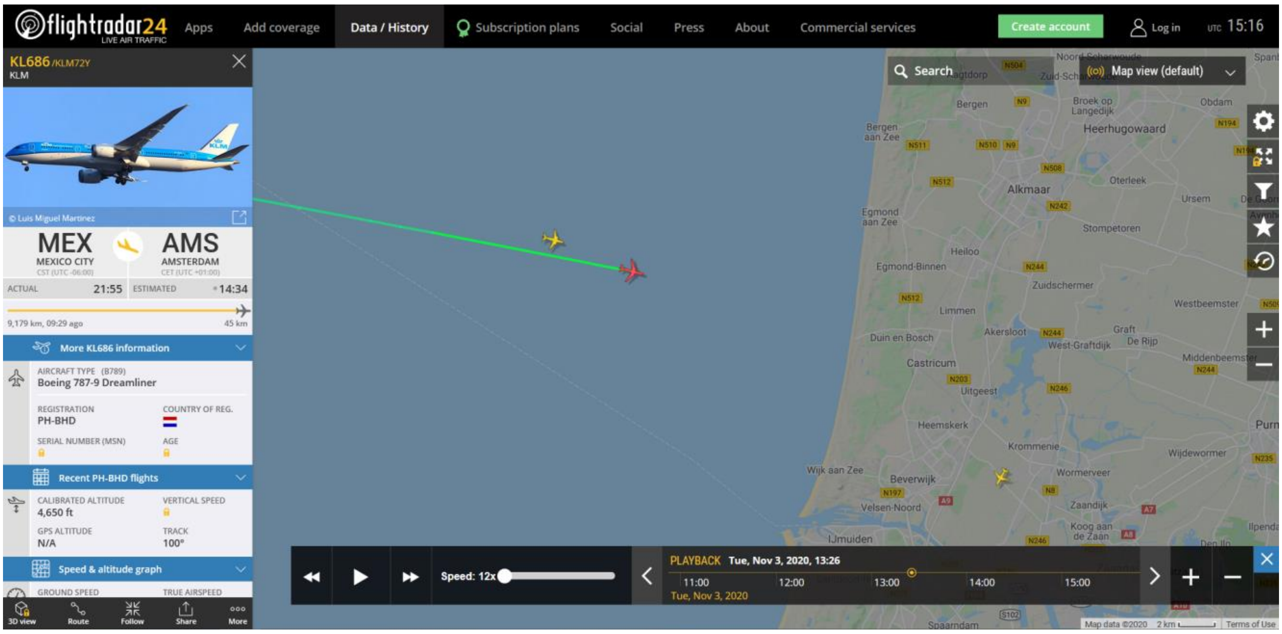

Figure B4 Screenshot of the flight (path) for the AIL case off the coast of Egmond aan Zee (The Netherlands) on the 3rd of November at 13:26, taken close to the moment of the lightning strike. Source: Flightradar24.

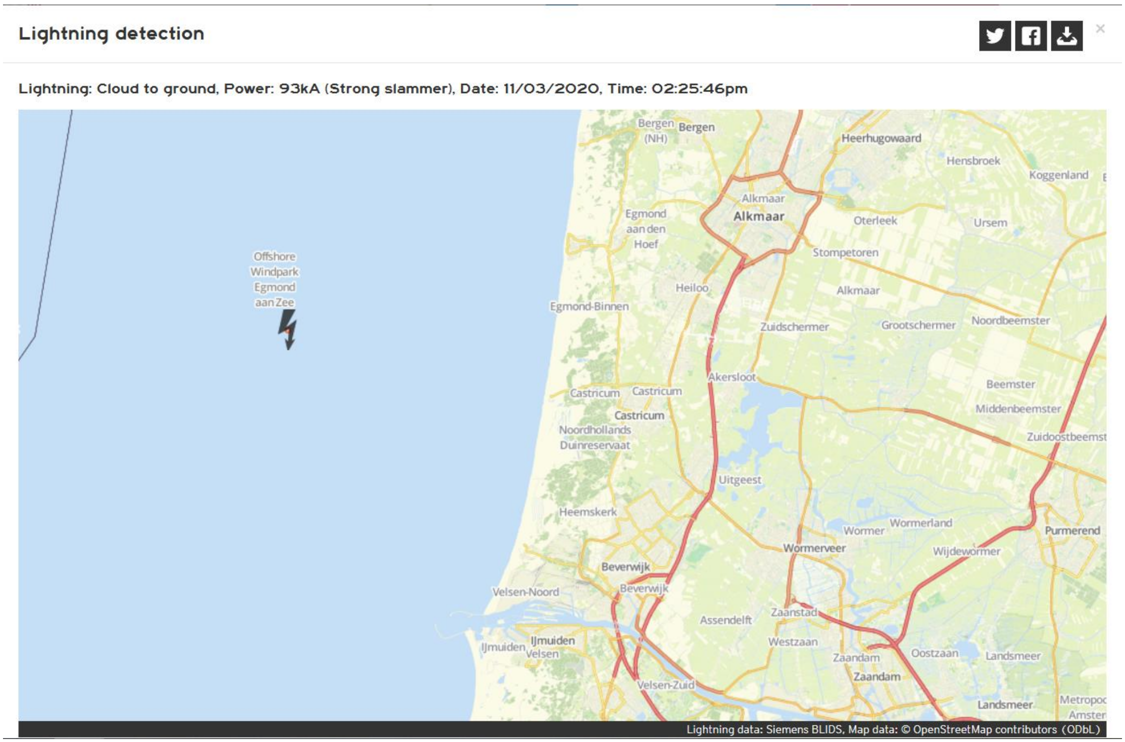

Figure B5 Screenshot of the observed (single) lightning strike. Source: Meteologix.

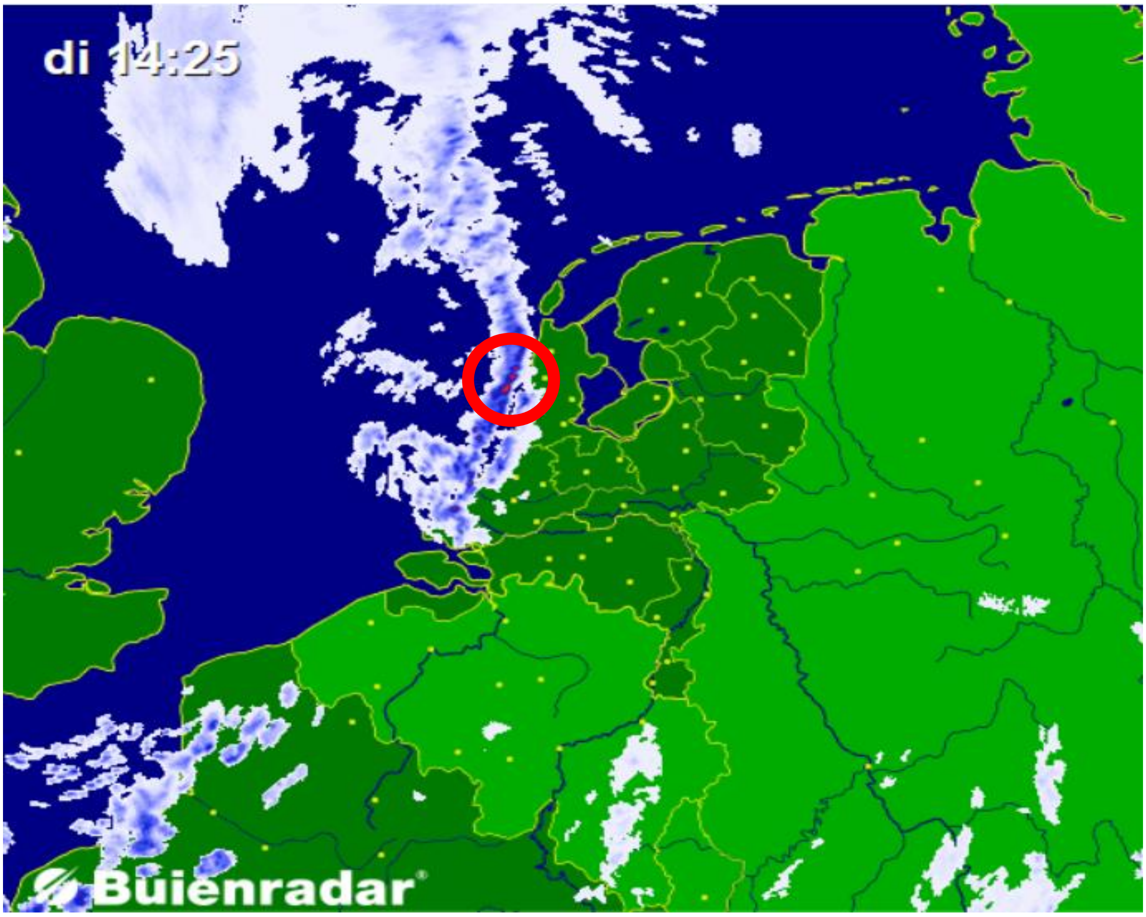

Figure B6 Screenshot of the radar, close to the moment of the AIL case. Note the red colours, indicating the presence of the embedded CB's (withing the red circle). Source: Buienradar.