De-icing of airplane wings:
Developing a model for wing conditions

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1. Introduction

At Schiphol Airport, KLM is responsible for the de-icing of more than 90% of all aircrafts. During wintertime de-icing is often the bottleneck that limits the number of take-offs at the airport. A detailed and accurate day-ahead forecast of icing on wings could help to plan the take-off capacity of the airport and the required de-icing capacity.

Wing icing is strongly weather related. The impact of weather on the wing however is complex and driven by many parameters and processes. The current empirical approach is not sufficient and KDC therefore asked Meteo Consult to develop a model to forecast wing icing. This will be a model based on a physical and statistical approach. Meteo Consult has lots of experiences in weather modelling. It developed for instance a model that calculates the impact of weather on the road temperature and condition. This model is used all over Europe for winter maintenance of roads and runways.

This report will describe the prototype model that has been developed to forecast wing icing. It can calculate the type of icing as well as the wing temperature on an hourly base. Icing can be a result of precipitation like snow, freezing rain, hoarfrost or freezing of water after condensation. Chapter 2 will explain the different types of icing and the relation with weather conditions. Subsequently chapter 3 will describe the working of the current version of the model and shows how the produced forecast will be presented and how it should be interpreted.

The KLM de-icing team provided Meteo Consult with all recorded de-icing events of the last two winter seasons. These data have been analysed and used to verify and tune the wing model. Chapter 4 will discuss the analysis of the de-icing data and chapter 5 describes the comparison of the model data with the de-icing events. It also shows some typical icing cases.

The current prototype model has been developed based on a general approach on how weather conditions interact with a wing surface. During the winter season 2013-2014 wing surface temperature measurements will be done. These measurements could help to improve the model significantly. Chapter 6 will contain the recommendations on how to improve the model based on these observations. Furthermore chapter 6 describes more ideas about how to improve and extend the model for instance with expected hold-over times.

2. Icing on wings

Icing of plane wings is both determined by weather and environmental conditions. The impact of weather is twofold. First precipitation, condensation, hoarfrost or freezing fog can cause water or ice to be transported to the wing surface. On the other hand weather circumstances determine the temperature of the wing surface. The wing temperature in combination with the presence of water/ice determines the type of ice on the wing. Each type is attached in a different way to a wing and requires a different de-icing approach/ time.

2.1 Wing temperature

Although the wing temperature can be strongly influenced by cold fuel that remained from a previous flight, it is in most cases forced by the weather and local environmental conditions. These circumstances determine the amount of thermal energy that is released or gained by the wing. If it gains more energy than it releases, the wing temperature will rise and otherwise, it will decrease. Since a wing cannot store much heat like for example a road, a small change of the heat fluxes will have a relatively large impact on the wing temperature. Figure 2.1 shows the different energy fluxes that influence the wing.

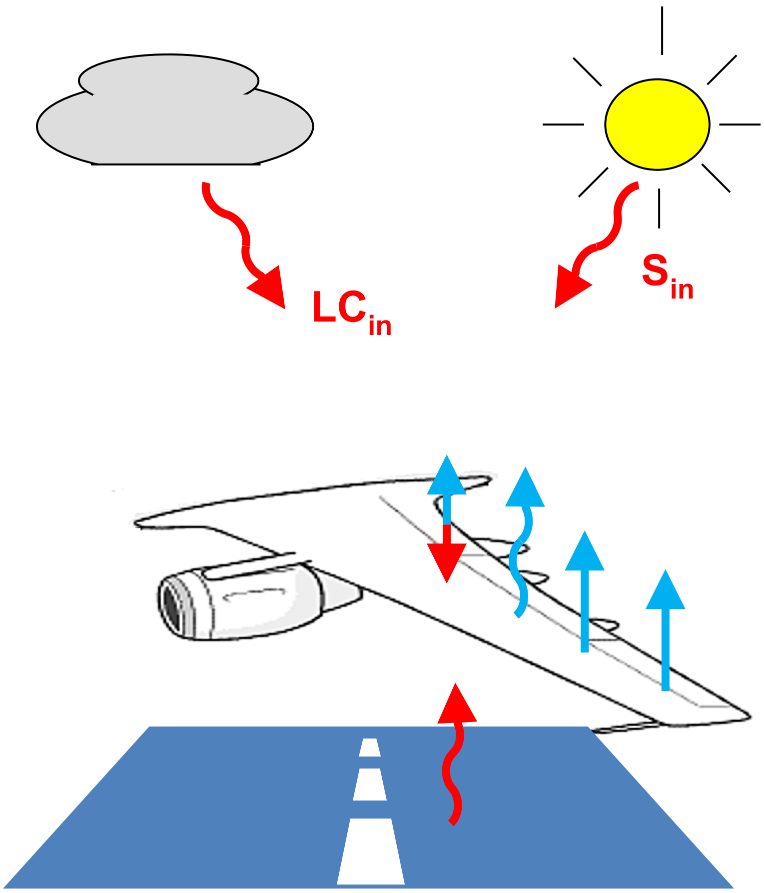

Figure 2.1: Different energy fluxes interacting with the wing surface. Long wave radiation from clouds (LCin), Short wave radiation from the sun (Sin), Albedo (α), Long wave outgoing radiation from the wing (Lout), Long wave incoming radiation from the runway (LGin). Sensible heat flux (Hin and Hout), Latent heat flux (Eout) and melting of solid precipitation (Mout).

$$Q^* = S_{in}(1-\alpha) + LC_{in} - L_{out} + LG_{in} \qquad (1)$$

$$\Delta S = Q^* + H - E_{out} - M_{out} \qquad (2)$$

- *Short wave radiation (Sin)*
  During daytime the wing will be heated by short wave radiation (Sin). This consists of a direct incoming radiation from the sun and a diffused part mainly due to clouds. A part of the incoming short wave radiation is reflected by the wing and is not influencing the energy balance. This is expressed in the albedo (1-α) term. The amount of short wave radiation depends on the day of the year, time of the day, geographical position and cloud cover. During wintertime the impact of solar heating is relatively low and during summertime relatively high.

- *Long wave radiation (LCin, Lout and LGin)*
  Each body emits long wave radiation proportional to its temperature according to the Stefan-Boltzmann law. Due to the release of long wave radiation a body will cool down. Therefore a wing will cool down by emitting long wave radiation to the sky (Lout) and it will warm up by receiving long wave radiation from clouds (LCin) and the runway (LGin). The latter will mainly warm up the underside of the wing.
  Figure 2.2 shows an example of the impact of cloud cover on the wing temperature during night time. During the evening it is clear weather, resulting in cooling down of the wing to 4 degrees below the air temperature and about 1 degree below the dew point temperature. Round midnight it gets overcast and the wing temperature starts rising due to incoming long wave radiation and becomes almost equal to the air temperature.
  As it can be seen in equation (1) these radiation terms determines the net radiation. This net radiation is divided into three energy terms (equation 2), i.e. sensible heat flux, latent heat flux and a melting flux. The remaining term ΔS determines if the wing warms up (for positive values or cools down (for negative values).

- *Sensible heat flux (Hout and Hin)*
  A wing also exchanges heat with the surrounding air. Two mechanisms are responsible for this. Firstly air can be transported to the wing by wind. A higher wind speed will result in a wing temperature that is closer to the air temperature. Depending on the fact if the transported air is warmer or colder than the wing, this mechanism can warm or cool down the wing. The second mechanism happens when the wing is warmer than the surrounding air. The wing will warm up the air close to the surface of the wing. This air will start to rise since warm air is less heavy than cold air and will be replaced by colder air that cools down the wing.

- *Latent heat flux (Eout)*
  Due to evaporation a wing can also lose heat and cool down. The magnitude of this heat flux depends on wind speed, relative humidity and the availability of water or ice. During conditions with a low humidity and high wind speed this flux could be relatively large. However the surface of a wing is solid and cannot store much water for evaporation.

- *Melting flux (Mout)*
  When solid precipitation like snow or hail falls on the wing with a temperature above 0 °C then heat of the wing will be used to melt the precipitation. This will result in cooling of the wing.

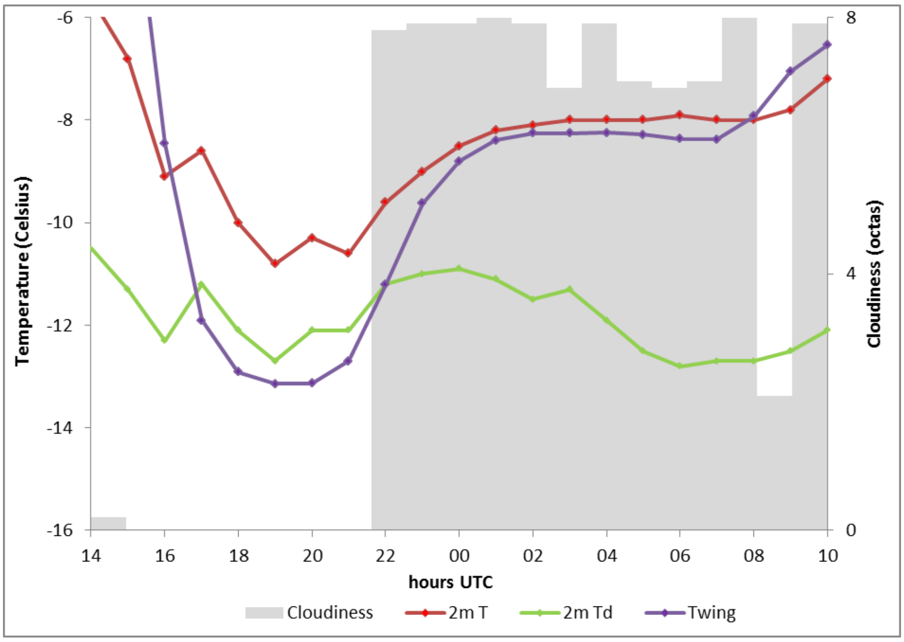

Figure 2.2: The Impact of the cloud cover on the simulated wing temperature during night time is shown here for 4 February 2012. Due to incoming long wave radiation (LC_{in}) from clouds at 22 UTC the wing temperature rises towards the air temperature.

2.2 Types of icing

2.2.1 Classification based on ice structure

There are different ways to classify ice types on objects like wings. Schaub (1995), Heyun (2012) and also Minsk (1977) distinguish three ice types based on the structure of ice:

- *Glaze*
  Transparent ice with a closed structure and a typical density of 0.7 to 0.9 g/cm^3. This type is often strongly attached to the wing surface and therefore very difficult to remove. Glaze is hard to observe due to its transparency.

- *Granular rime*
  Not transparent and has a more open structure compared to glaze. The density is between 0.1 to 0.6 g/cm^3. This type is less well attached to the wing and therefore easier to remove.

- *Crystalline rime*
  The type with the most open structure and a density of 0.01 to 0.08 g/cm^3. Due to its very open structure it is loosely attached to the wing surface and relatively easy to remove.

2.2.2 Classification based on meteorological conditions

A second way to classify ice on wings is to distinguish between meteorological conditions which result in ice formation. Five main types can be distinguished.

- *Ice*
  Ice can be formed when liquid or partly liquid water is left behind on the wing after rain or wet snow. Liquid water could also be available due to dew formation when the wing temperature drops below the dew point temperature and the wing temperature is still above 0 °C. When liquid water is available and the wing temperature drops below 0 °C, water starts to freeze and a layer of well attached ice with the characteristics of glaze will be formed on the wing. This type of ice typically occurs during night time when rain or sleet is followed by clear and calm conditions.

- *Freezing rain*
  There are two types of freezing rain. The first type occurs when supercooled rain droplets fall on a wing and immediately freeze. Precipitation will get supercooled when droplets fall through an air layer with a temperature below 0 °C close to ground level. Figure 2.3 shows schematically the process of precipitation getting supercooled.
  The second type occurs when non-supercooled droplets fall on a wing surface that is below 0 °C. A wing temperature below zero during rainy conditions with air temperatures above 0 °C will be quite rare since the heat capacity of a wing is small and the wing temperature will quickly adapt to the actual weather conditions.
  Like ice, freezing rain will result in glaze ice and is very well attached to the wing and other parts of the plane and is therefore difficult to remove.

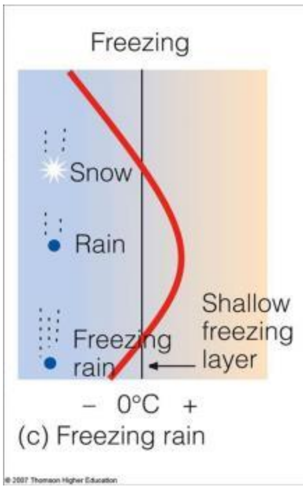

Figure 2.3: Vertical temperature profile and precipitation types at different heights. (Kuroiwa, 1965)

- *Snow*
  The way snow is attached to the wing strongly depends on the wing temperature. With temperatures just below 0 °C snow is packed and can be well attached to the wing and therefore difficult to remove. With temperatures far below 0 °C (< -5°C) snow is less packed and loosely attached to the wing. Notorious situations occur when the wing temperature is just above 0 °C when snow, wet snow or sleet falls and then drops below 0 °C. The available slush on the wing will freeze in a well attached glazy ice layer.

- *Hoarfrost*
  During nights with clear weather and little wind the wing temperature will largely drop due to radiative cooling. Because of the small heat capacity, the wing temperature can drop easily several degrees below the air temperature and dew point temperature (see Figure 2.2). When the wing temperature drops below the dew point temperature, the thin air layer just above the wing will get oversaturated and water will start to condense on the wing surface. When the wing temperature is below 0 °C, hoarfrost will form. An ice layer on the wing due to hoarfrost is relatively thin and has a crystalline structure. It is therefore not too difficult to remove.
  For air temperatures around 0 ºC or above 0 ºC the amount of hoarfrost is substantially larger than with much lower temperatures below 0 ºC under equal conditions. This is because the air can contain more moisture if temperatures are higher. Hoarfrost is not favoured for high wind speeds (Monteith, 1957 and de Bruin, 1994). In that case the small cold layer around the wing due to radiative cooling is mixed with surrounded warmer air (Norman et al, 2000).

- *Freezing fog*
  Fog in combination with air temperatures below 0 °C will result in supercooled small fog water droplets. These droplets are too small to fall and are mainly transported by wind. When they hit an object like a wing they will immediately freeze. Although the process of supercooled water droplets freezing on the wing is comparable to freezing rain, the resulting ice layer is different. Fog droplets are much smaller, so this will result in an ice layer with a more granular structure or crystalline structure. The structure will get more crystalline when the air temperature and wind speed are lower (see Figure 2.4).

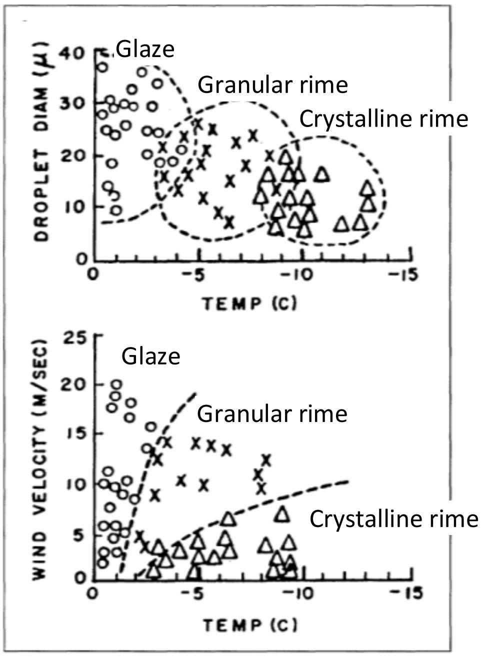

Figure 2.4: Relation between ice, droplet radius, air temperature and wind speed in m/s^2 for temperate climate zones. (Lyndon State College, 2013)

3. Wing model

3.1 Input

The wing model is schematically represented in Figure 3.1. To make a wing forecast weather forecast data and wing property data are required as input.

The Meteo Consult weather forecast is based on a Model Output Statistics (MOS) approach. A multi-model MOS approach is used, which means that different numerical weather models are used as input. Currently the Meteo Consult MOS uses data of 4 different weather models. The numerical weather model data are statistically corrected with observations of the last two years. This results in a highly detailed forecast including the impact of local phenomena that cannot be resolved by numerical models. In addition the forecaster has the possibility to manually adjust the forecast. The weather forecast is updated twice an hour based on new observations, radar and satellite information and new numerical model data.

Furthermore the wing model requires wing property information. In the current version the model does distinguish two different wings, one in the shadow and one exposed to solar radiation. If more knowledge about the impact of weather on different types of wings is available, then we could distinguish between more types.

The use of observations as input is optional however strongly recommended. It will improve the wing forecast significantly. Observations can be used to calibrate the forecast by statistical post processing.

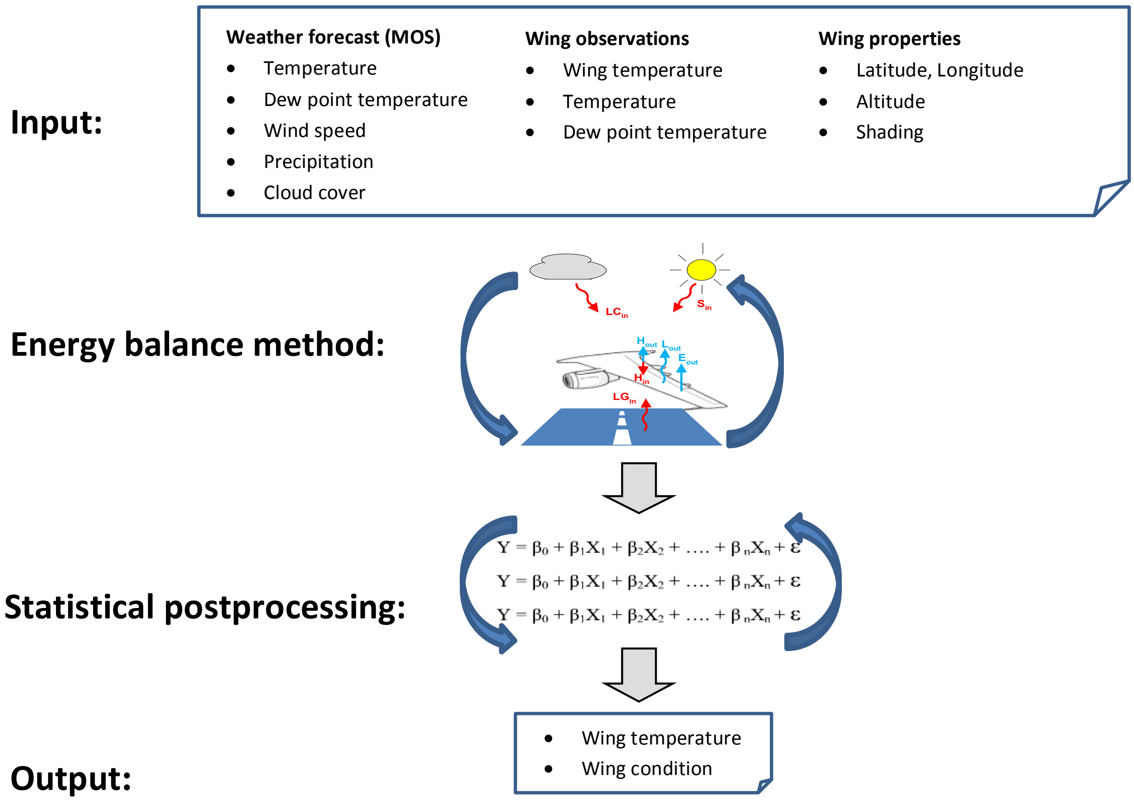

Figure 3.1: Schematic overview of the wing model

3.2 Processing

The model will calculate a wing temperature and condition by using the energy balance method as described in section 2.1. Each energy flux will be calculated separately and the sum of all fluxes should be zero. If it is not, the wing temperature will be adapted until all fluxes are balanced.

Based on the same method the model simulates the amount of water or ice that is available on the wing. After precipitation the model will start to evaporate the remaining amount of water. The rate of evaporation depends on the weather conditions.

If observations are available the wing temperature will be statistically corrected. This correction is partly based on observations of previous seasons and on observations of the previous days. This process is comparable to the MOS method used to improve the weather forecast (see section 3.1)

3.3 Model output and update scheme

Finally the output of the model is an hourly forecast of the wing temperature and wing condition up to 10 days ahead. Note that after roughly five days the forecast becomes less predictable and this long term is ment to give a trend towards winter weather or not. The forecast for the first 48 hours is updated twice an hour and the forecast up to 10 days ahead is updated four times a day. These long term updates are scheduled after major updates of the weather forecast.

Table 3.1: Model update scheme

Forecast range	Update frequency	Reason
0 – 2 d	2x an hour	New observations
0 – 10 d	7, 9, 19 and 21 UTC	Major update weather forecast

3.4 Wing condition

Based on the wing temperature, the amount of water on the wing and dew point temperature, a wing condition will be calculated by the wing model. All possible wing conditions are shown in Table 3.2. The conditions are sorted in order of significance, based on our experience on road forecasts. The preconditions are shown for critical wing conditions. A wing condition is defined as critical if de-icing is needed.

Some conditions exclude each other. For instance snow and freezing rain cannot occur at the same time. However some conditions can occur simultaneously like ice and severe hoarfrost. Since ice, as a result of freezing liquid water, has more impact on a wing than hoarfrost, the condition ice will be shown instead of hoarfrost.

Table 3.2: **All possible wing conditions as output from the model list are sorted on priority with the most severe condition on top. The conditions are described in section 2.2.2.**

Condition
Freezing rain
Snow
Sleet
Sleet and ice
Hail
Ice
Freezing fog
Severe hoarfrost
Hoarfrost
Rain
Drizzle
Fog
Wet
Condensation
Dry

3.5 Forecast presentation

Figure 3.2 shows an example forecast for the afternoon and night. As well as the wing temperature and condition all other relevant weather parameters are shown on an hourly base. To warn for dangerous conditions, different colours are used for wing temperature, condition, snow and dew point. This example shows a clear and calm night. Around 21 UTC the wing temperature drops below the dew point temperature resulting in condensation. One hour later the wing temperature drops below 0 ^{o}C resulting in hoarfrost until the end of the night.

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Datum en tijd	Weertype	Neer slag kans (%)	Neerslag (mm/uur)	Sneeuw (cm)	Temp. 1.5m (°C)	Wing Temp. (°C)	Wing Conditie	Dauw punt (°C)	Rel. Luchtv. (%)	Be wolking (8-sten)	Wind richting	Wind kracht (bft)	Max. wind stoot (km/u)
dinsdag 15 november 2011													
12:00	Geheel bewolkt	0	0.0	0	2.9	1.8	Condensatie	1.8	93	8/8	← O	3	24
13:00	Zwaar bewolkt	0	0.0	0	4.2	3.3	Droog	1.9	85	6/8	← O	3	23
14:00	Half bewolkt	0	0.0	0	4.9	4.5	Droog	1.8	80	4/8	← O	3	23
15:00	Licht bewolkt	0	0.0	0	5.6	5.1	Droog	1.9	77	3/8	← O	3	24
16:00	Licht bewolkt	0	0.0	0	5.5	4.7	Droog	1.9	78	2/8	← O	2	24
17:00	Helder	0	0.0	0	4.1	3.7	Droog	1.7	84	0/8	← O	2	24
18:00	Helder	0	0.0	0	3.0	2.7	Droog	1.5	89	0/8	← O	2	24
19:00	Nevel	0	0.0	0	2.3	1.8	Droog	1.3	93	0/8	← O	2	23
20:00	Nevel	0	0.0	0	1.7	1.1	Droog	1.0	95	1/8	← O	2	22
21:00	Nevel	0	0.0	0	1.3	0.4	Condensatie	0.6	95	1/8	← O	2	20
22:00	Nevel	0	0.0	0	0.9	-0.3	Rijp	0.2	95	0/8	← O	2	20
23:00	Nevel	0	0.0	0	0.6	-0.9	Rijp	-0.3	94	0/8	← O	2	20
woensdag 16 november 2011													
00:00	Nevel	0	0.0	0	0.3	-1.3	Rijp	-0.8	92	0/8	← O	2	20
01:00	Nevel	0	0.0	0	0.0	-1.7	Rijp	-1.2	92	1/8	← O	2	20
02:00	Nevel	0	0.0	0	-0.3	-2.1	Rijp	-1.6	91	1/8	← O	2	20
03:00	Nevel	0	0.0	0	-0.6	-2.4	Rijp	-2.0	90	1/8	← O	2	19
04:00	Helder	0	0.0	0	-0.8	-2.7	Rijp	-2.3	90	1/8	← O	2	19
05:00	Helder	0	0.0	0	-0.9	-2.9	Rijp	-2.7	88	1/8	← O	2	19
06:00	Helder	0	0.0	0	-1.1	-3.2	Rijp	-2.8	88	1/8	← O	2	19

Figure 3.2: Example presentation of the wing forecast and other relevant weather parameters

4. De-icing data KLM

From KLM we got all recorded de-icing events of winter seasons 2011-2012 and 2012-2013. Those are visualized in Figure 4.1. The winter of 2011-2012 was on average a mild winter with little snow, but had a severe cold period at the start of February (Wijnant and Sluijter, 2012). In this period most de-icing events occurred. The winter of 2012-2013 showed more frost nights and snow days than average (Sluijter, 2013). Therefore the winter of 2012-2013 required more de-icing events than the winter of 2011-2012, and the de-icing events are also more precipitation related. March 2013 was exceptionally cold, which resulted in relatively many de-icing registrations in Figure 4.1. In total the winter of 2011-2012 counted 1371 de-icing registrations on 59 days and the winter of 2012-2013 counted 3648 de-icing registrations on 84 days.

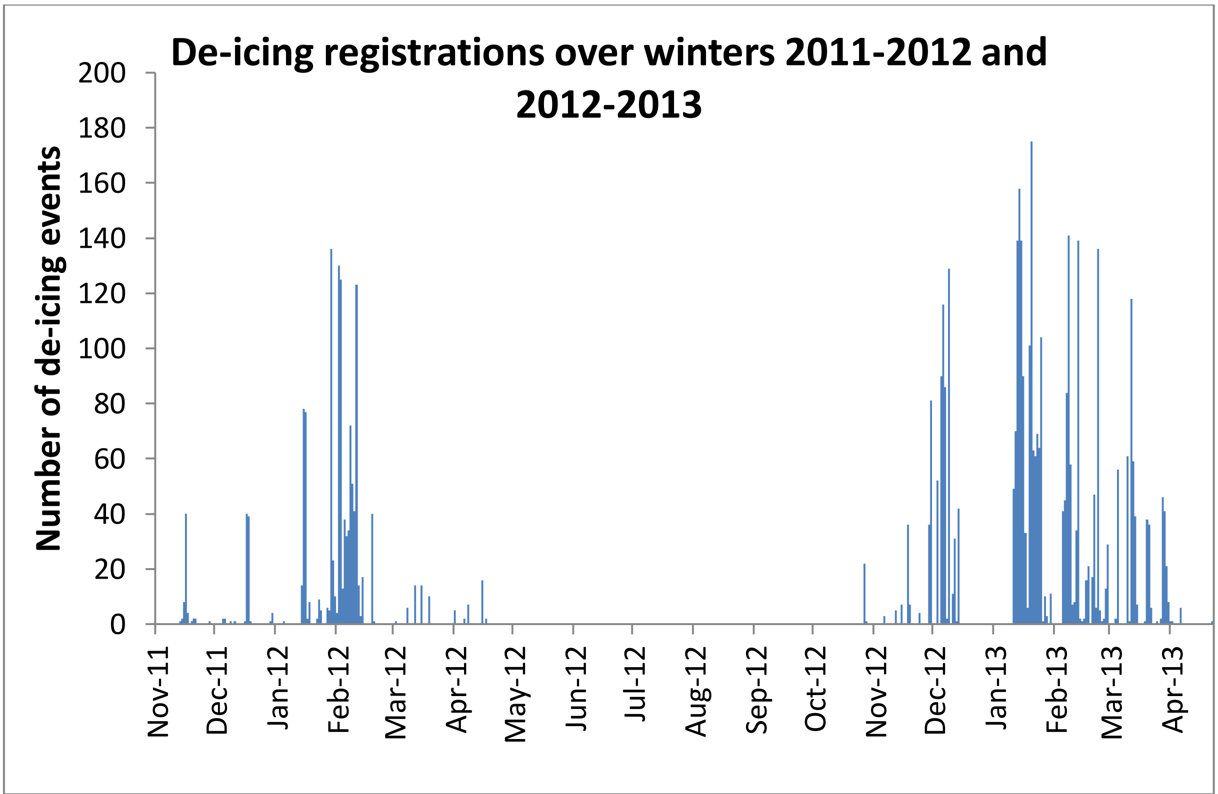

Figure 4.1: Distribution of de-icing events in the winters of 2011-2002 and 2012-2013

4.1 Description of de-icing data

Every record in the data represents one airplane that has been de-iced and each record has an exact start time and end time registration. For the analysis this start time is used. The other information corresponding to a de-icing record is stated below.

- *Categories*
  In the data there is a distinction of four categories of airplanes. Category 1 and 2 are narrow body airplanes, including the commuter types, and category 3 and 4 contain wide body airplanes.

- *Position*
  De-icing events are performed at different locations at Schiphol. However most de-icing events are performed at the central de-icing platform (Juliet platform) (location is shown in Figure 4.2). Only airplanes de-iced at the Juliet platform are considered. Meteorological observations are taken from near station Ceintuurbaan Noord (location displayed in Figure 4.2).

- *Type 1 and type 2 fluid*
  Type 1 fluid is used for de-icing and consists of glycol and water. It remains on the wing for a very short period. Type 2 fluid is thicker and has a higher viscosity and therefore it remains a longer time on the wings. Accordingly type 2 fluid is suitable for (preventive) anti-icing. Type 2 fluid is used in two different situations. First of all, type 2 fluid can be used when solid precipitation is expected in the period between de-icing and take-off. Secondly, type 2 fluid is used as prevention against hoarfrost. In this case wings are prepared with type 2 prior to a forecasted frost night.

- *OAT*
  Outside Air Temperature. This air temperature is used to determine the mixture ratio of the used de-icing fluids. The OAT is derived from the Metar and is manually set to the lower side in order to be safe. Ideally the mixture ratio should be decided determined based on the wing temperature and not on the air temperature, so that explains the current manual adaptation.

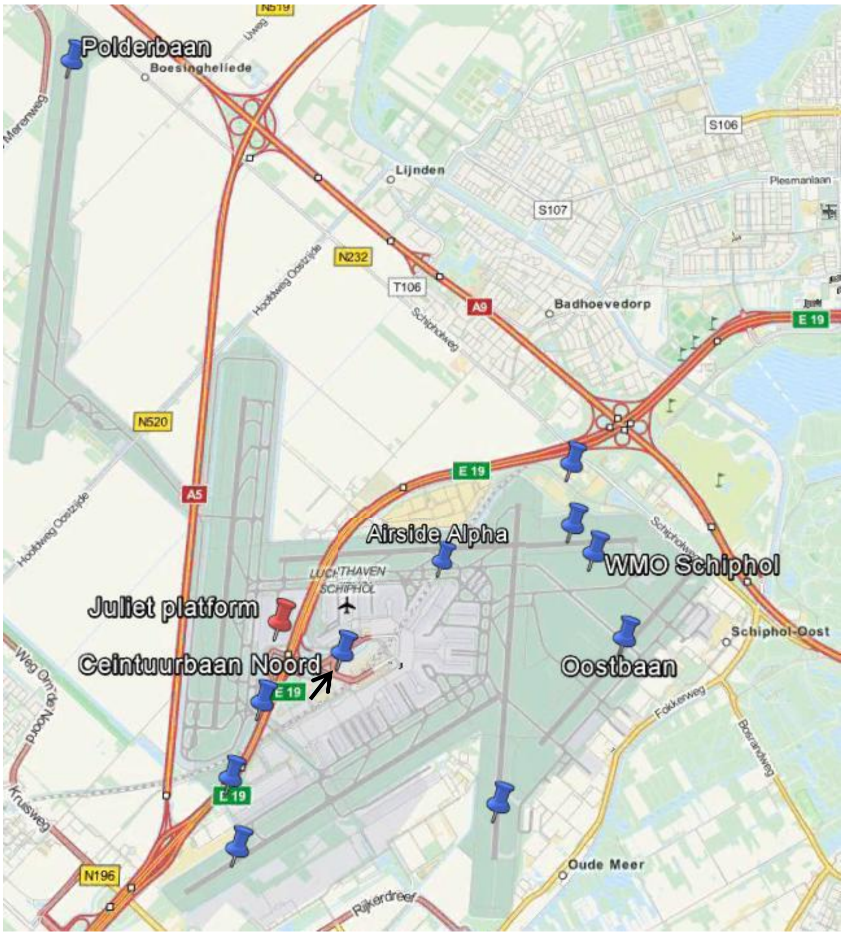

Figure 4.2: Map of Schiphol. All blue pushpins represent weather stations around Schiphol, measuring air temperature and dew point temperature. Cloudiness, wind and visibility are only measured at WMO Schiphol. For all these stations a wing temperature is simulated with the data. With a red pushpin de-icing centre Juliet platform is indicated.

4.2 Data analysis and selection

De-icing events can occur at any moment of the day. In the night relatively few airplanes depart, which is visible in the number of de-icing events during night time.

Currently, the OAT (Outside Air Temperature) is a set temperature which is based on the air temperature. In practice this temperature is set a little bit lower than the air temperature to be on the safe side, but generally OAT should be very close to the measured air temperature. In Figure 4.3 the OAT is compared to the measured air temperature at the Juliet platform. The blue dots represent all received OAT data. OAT is only reported when there is a de-icing record. However there are also test data included in the dataset. In order to determine if it is test data or real de-icing data, a comparison between OAT and measured air temperature is used to make a selection for further analysis. The red dots are the selected data used for analysis after the following criteria:

- Days with a minimum air temperature higher than 6 °C are removed from the selection. These days are too warm for ice formation. The blue dots comprising OAT above 0 °C and air temperature above 6 °C can be explained by fuel induced icing. This phenomenon can occur for some types of airplanes directly after landing. The remaining supercooled fuel in the fuel tank in the wing can freeze the wings.

- Data with a larger T2m - OAT difference than 5 °C have been removed, because that is an indication of test data. The majority of these test data was found in October 2011. It is therefore decided to remove October 2011 from analysis.

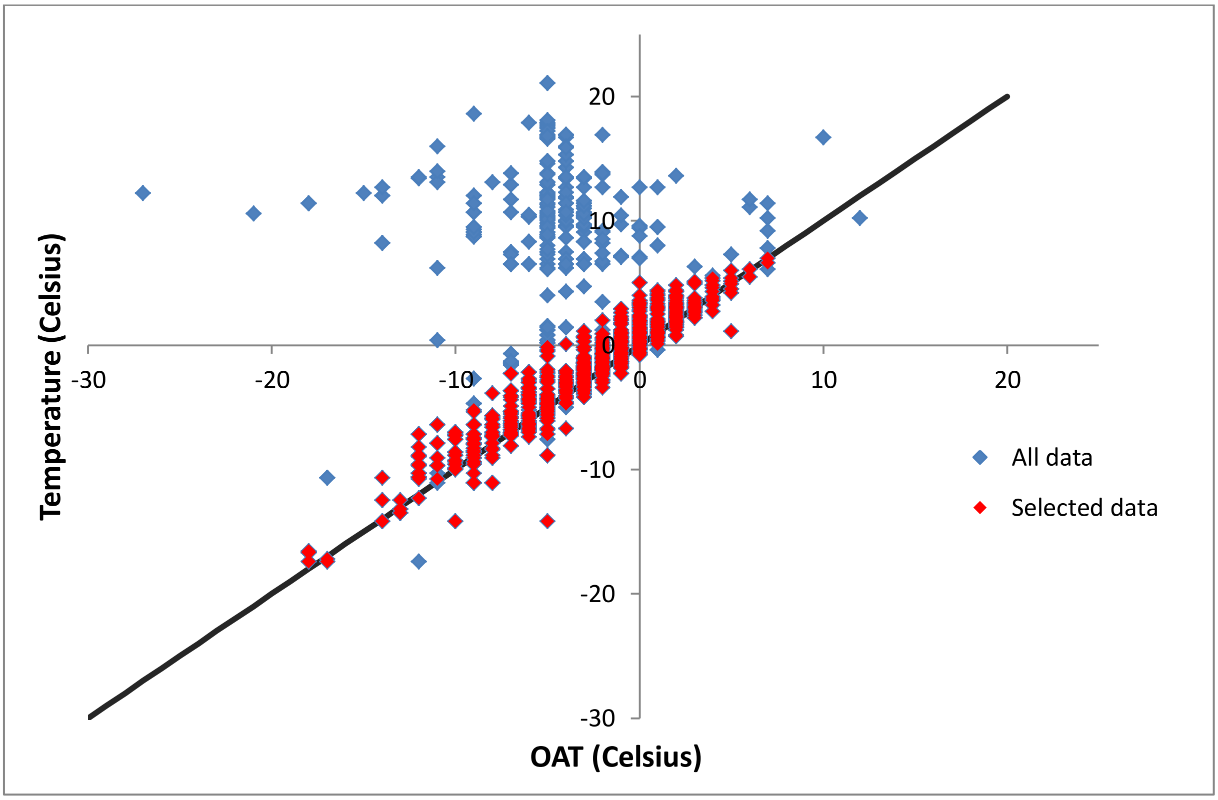

Figure 4.3: The measured air temperature at the vertical axis is visualized against the set OAT (Outside Air Temperature) on the horizontal axis used by KLM. The red dots are the selected data based on criteria of air temperature on the Juliet platform (T < 6 ºC) and a maximum difference in OAT and air temperature (T2m – OAT < 5 ºC).

For the description of the specific cases (section 5.2) the focus is on category 1 and 2 airplanes. This is because the amount of used de-icing fluid among the airplanes can be solely compared if the wing area is not varying too much. Category 1 and category 2 airplanes have a have a vast majority of 74 % in all recorded de-icing events.

5. Model validation

In this chapter the outcome of the wing model is verified against the de-icing data as provided by KLM. For the model simulations, meteorological observation data has been used as input. The advantage of using meteorological observation data is that there is no forecast error in the input parameters of the model. For testing the model physics and for tuning the model it is important to use the most reliable input data. After a general analysis of skill scores (section 5.1), some cases will be analysed in more detail (section 5.2).

5.1 Skill scores

Although the model has run with hourly observations as input, we decided not to validate the model on an hourly base. De-icing events are not necessarily occurring on the same moment as ice is accumulating on the wing. Sometimes hoarfrost occurs during midnight while planes will be de-iced during the early morning. On the other hand, periods should not be too long, because an icing at the start of the period and a de-icing at the end of the period have a larger risk not to be related with each other. We therefore decided to split the day in two parts, the first part running from 0 to 12 UTC and the second part from 12 to 0 UTC. In addition, periods with just 2 records of de-icing or less have been eliminated from analysis. In these cases where just 1 or 2 airplanes have been de-iced, it is uncertain if de-icing was really necessary. Besides this, single de-icing events could indicate that planes suffered from fuel induced ice.

When the model simulates a critical wing condition in a certain period and de-icing events occurred in this period, we considered this as a hit. In contrary, when de-icing occurred and no wing hazard was modelled, we considered this as a miss. A False Alarm occurs when the model simulated icing and no de-icing event occurred. Finally it is called a Correct Negative when neither the model simulated icing nor de-icing was performed. These Hits, Misses, False Alarms and Correct Negatives are together called contingencies and are shown in Table 5.1.

Table 5.1: All possible contingencies are schematized in a contingency table.

	Icing Forecast	No Icing Forecast
Icing Observation	HITS	MISSES
No Icing Observation	FALSE ALARMS	CORRECT NEGATIVES

The frequencies for the night / morning (0-12 UTC) and afternoon / evening (12-0 UTC) are shown in Table 5.2. For the night / morning there are 19 misses and 72 hits. In section 5.1.1 and 5.1.2 the misses and false alarms are examined in more detail. As expected the afternoon / evening shows 31 % less de-icing days which is related with the on average warmer conditions in this period of the day. However the number of misses does not decrease with the same rate and shows even a slight increase, while the amount of hits decreases almost by a factor 2. A conclusive explanation for this cannot be given. However a couple of reasons may explain the differences.

- At daytime airplanes may be parked in the shadow. In that case wing temperatures remain lower in the early afternoon and ice can be longer maintained on the wing. Currently the effect of shadow is not taken into account in the model. Also the uncertainty in albedo of the wing might introduce more misses in afternoon.
- Perhaps more fuel induced icing occurs on airplanes in the afternoon, which is related to a short stay.
- In the afternoon the air is on average drier, so probably more de-icings might have been unnecessary

Table 5.2: Contingency table of airplanes in the period 0 till 12 UTC (morning) and 12 till 0 UTC (afternoon)

Morning	
Contingency	*Frequency*
Misses	19
False Alarms	10
Correct Negatives	124
Hits	72

Afternoon	
Contingency	*Frequency*
Misses	23
False Alarms	14
Correct Negatives	134
Hits	40

A next step is to distinguish between different causes of icing. The night and morning period (0-12 UTC) is analysed and results are presented in Table 5.3. In case multiple meteorological icing conditions occur in the 12-hr period, the most severe condition is assigned as described in Table 3.2. Most de-icing events are caused by precipitation, followed by hoarfrost. Because hoarfrost has a low priority compared to other hazards, the real number of hoarfrost periods is higher than 35. Hoarfrost is overruled in 10 periods by more severe or recalcitrant hazards like freezing fog or precipitation. Individual de-icings within these periods can still be related to hoarfrost. For the skill score the Probability of Detection (POD) has been used (Panofsky and Brier, 1965). This is defined as the ratio of hits compared to the total number of de-icing events (hits plus misses).

Hoarfrost has a lot of misses compared to the other conditions and has consequently a lower POD score. However in section 5.1.3 it is explained that a lot of de-icing events are suspicious and by omitting these events the model skill is much better.

The fact that precipitation has a good score is not remarkable, because the model uses precipitation type from nearby observations to indicate a hazard. An observed solid precipitation type as sleet, hail and (wet) snow is always translated in a hazard, even with positive wing temperatures. This seems to be a correct assumption, because we see indeed many de-icing events in cases with (solid) precipitation and wing temperatures above 0 °C. The 5 misses are cases with liquid precipitation instead of solid precipitation. Those will be further analysed in section 5.1.1 .

Freezing fog and ice (freezing of liquid water) did not occur often. There are no indications of model misses due to ice or freezing fog, and therefore the POD is 100 %. However, the small number of ice and freezing fog cases don’t exclude that the model can be wrong in marginal cases.

Table 5.3: Skill score subdivided into causes by meteorological icing conditions for periods 0 -12 UTC over the winter seasons 2011-2012 and 2012-2013. In case multiple conditions play a role priority is given to the most recalcitrant ice structure, which is in succession, precipitation, freezing fog, ice and hoarfrost. POD stands for Probability Of Detection.

	Total	Hits	Misses	POD (%)
Precipitation	46	41	5	89 %
Freezing fog	6	6	0	100 %
Ice	4	4	0	100 %
Hoarfrost	35	21	14	60 %
Total	91	72	19	79 %

5.1.1 Model misses

In Table 5.4 all misses are shown with the meteorological condition and relevant weather parameters. 9 of these 19 misses occurred in weather situations where the actual need for de-icing seems unlikely. This is indicated with “no” in the column “Justified de-icing”.

5 misses are related to precipitation (marked in blue). Although the weather codes of WMO Schiphol indicate rain, in three cases snow and sleet have been registered in the surroundings. These misses can therefore not be rejected and the de-icings are justified. On two other precipitation dates, i.e. 16-12-2011 and 12-11-2012 (Table 5.4), the de-icings are not justified. In one case (16-12-2011) no de-icings took place. The airplanes were prepared with type 2 (anti-icing) as prevention for winter precipitation, which did not occur. At 12-11-2012 the air temperatures and dew point temperature were simply too high for solid precipitation.

The 14 remaining cases are related to hoarfrost or freezing of liquid water (ice). In 7 of these cases de-icing does not seem justified.

- One not-justified case is based on simulated wing temperatures clearly above 0 ^{o}C, and is classified with condensation. (2013-01-28)
- The other six cases do show wing temperatures below 0 ^{o}C, but does not seem justified because of cloudiness or a low relative humidity. Hoarfrost favours a relative humidity over 80 % (Gaceu, 2009), and this is used as criteria for justifying a miss.

Considering all de-icing data it is determined that airplanes are de-iced when air temperatures drops below 0 ^{o}C, even if the air is too dry or there is a high wind speed. An exception is the cold frost period in March 2013. In this very dry cold weather with wind speeds in the range 16-24 knots, no de-icing events are registered.

In 7 hoarfrost cases de-icings do seem justified, and are indicated as marginal in Table 5.4. These 7 cases have a small difference in dew point and wing temperature (Twing – Td < 0.8), also referred here as dew point deficit. In these cases many airplanes have been de-iced and considerably amounts of de-icing fluids are used. This gives confidence that the wings really experienced ice formation.

- One case has modelled hoarfrost in the evening without hoarfrost is modelled in the consecutive night (2012-02-05). Thus hoarfrost is missed in the analysis, since the window is from 0-11 UTC. Because temperatures stay below 0 ºC in the night, one might still expect frozen wings at night.
- Four other justified hoarfrost cases do simulate hoarfrost at other stations at Schiphol, like the Oostbaan, Polderbaan or Airside Alpha. (the locations are displayed in Figure 4.2)

In conclusion, 7 misses due to hoarfrost are classified as marginally. This means that these cases have justified de-icings as noted in Table 5.6. These 7 cases come back in the Justified misses column in Table 5.6. Measurements are indispensable for tuning the model to decline the number of marginal cases, especially if the air temperatures are below 0 ºC.

Table 5.4: Overview of all dates where the model does not forecast a hazard while there are de-icing events. Dew point deficit is defined as (Twing – Td). A small difference means that the wing temperature is just not low enough to form hoarfrost and is indicated with marginal hoarfrost. In the column 'Justified de-icing it is indicated if the miss is plausible or not. If this is indicated with no, de-icings were probably unnecessary. The Wing Cond. column shows the simulated wing condition by the model. Dry means that the whole time interval of de-icings no other wing condition was simulated. The column with 'Ne' represents the cloudiness in octas for the night (0 UTC until end de-icings). The indicated air - , wing - and dew point temperature corresponds with the moment of the smallest dew point deficit for the hoarfrost related misses. For the misses related to precipitation the air – dew - and wing temperatures are shown at the moment the wing temperature is the lowest. RH in the description column stands for Relative humidity.

Date	Meteorological condition	Justified de-icing	Time interval of de-icings	Nr. cases Juliet	T2m (°C)	Td (°C)	Twing (°C)	Wing Cond.	Ne	Type 2	Description
2011-12-16	Precipitation	No	4-5	5	3.2	2.4	2.9	Rain	8	yes	In this case only anti-icing is conducted (only Type 2). At daytime precipitation is solely rain by T2m > 4. Snow did not occur and the high temperatures indicate that anti-icing was not needed. This is not a real miss.
2012-02-01	Too dry for hoarfrost	No	6-8	8	-6.0	-9.6	-7.8	Dry	0	no	Cold air combined with low RH, even if Td > Twing little hoarfrost is deposited, high wind speed, >12 kts.
2012-02-02	Too dry for hoarfrost	No	1-8	4	-6.0	-10.3	-7.7	Dry	0	no	Cold air combined with low RH, even if Td > Twing little hoarfrost is deposited. High wind speed, > 12 kts.
2012-02-05	Marginal hoarfrost	Yes	1-12	9	-8.5	-10.9	-8.8	Dry	2-8	no	Before 0 UTC hoarfrost is modelled and is associated with clear spells. So it is logic that airplanes were de-iced, since it continued freezing during the night. Night itself is cloudy and windy, ~10 kts.
2012-02-06	Marginal hoarfrost	Yes	5-10	33	-9.6	-12.8	-12.1	Dry	0-8	no	RH is not high, but a low wind speed and clear spells may permit hoarfrost between 6-9 UTC. Dew point deficit is relatively small, 0.7 °C. Hoarfrost simulated at Airside Alpha.
2012-02-07	Marginal hoarfrost	Yes	5-10	23	-11.4	-14.3	-14.1	Dry	0	no	RH is not high, but a low wind speed and clear spells may permit hoarfrost formation. Dew point deficit is small, down to 0.2 °C. Hoarfrost simulated at Oostbaan.
2012-02-08	Too dry for hoarfrost	No	6-10	5	-3.3	-6.5	-3.6	Dry	8	no	Although there are clear spells before 0 UTC there is continuously too much wind for hoarfrost. In addition, the rest of the night show also clouds which hampers hoarfrost formation any further. Min. dew point deficit is 1 °C at 0 UTC.
2012-02-11	Marginal hoarfrost	Yes	6-11	19	-10.0	-13.6	-13.1	Dry	0	no	RH is not high, but low wind speeds and clear weather may permit hoarfrost formation. Dew point deficit is small, down to 0.5 °C. Hoarfrost simulated at Polderbaan.
2012-02-19	Precipitation	Yes	5-10	4	2.9	-0.1	1.1	Rain	0-8	no	Rain with Twing temperatures down to 1.1 °C. In the surrounding, wet snow and sleet is detected
2012-11-12	Precipitation	No	6	3	4.9	4.4	3.7	Rain / Condens.	0	yes/ no	Strange de-icing event, T2m and Twing far above 0 °C.
2012-12-13	Precipitation	Yes	5-10	29	-2.1	-4.2	-2.9	Dry	5-8	no	Cloud cover is 5 octas between 2-5 UTC. Dew point deficit is at least 1.3, so no indication hoarfrost. Snow observed 0 UTC in Amsterdam, not detected above Schiphol with radar (model does not detect too).

2013-01-28	Condensation	No	6-9	10	2.3	1.6	0.8	Condens.	2-8	no	Clear weather and condensation. Small difference T2m and Twing, related with much wind, 12 kts. Twing above 0 °C.
2013-02-07	Precipitation	Yes	5-12	12	2.6	0.2	0.9	Rain	5-7	yes	Clear spells at 23 UTC brings Twing towards 0.9 °C. Thereafter rain in the model. Planes use hardly any type 1, except one plane. Snow cover at 8 UTC in N-H and Utrecht (not Schiphol). Observations of hail and wet snow in surrounding.
2013-02-11	Too dry for hoarfrost	No	3-12	6	-3.0	-7.7	-4.6	Dry	0-8	no	Low RH and much wind, also during clear spells (15 kts). So, hoarfrost is unlikely.
2013-02-12	Too dry for hoarfrost	No	6-7	6	-2.3	-5.7	-4.4	Dry	0-8	no	Normal RH (78%) together with quite high wind speed (10 kts) makes this hoarfrost just not likely to occur. Min. dew point deficit is 1.3 °C.
2013-02-20	Marginal hoarfrost	Yes	6-9	21	-1.3	-4.1	-3.6	Dry	0-7	no	Quite high RH (82%) but with quite high wind speed (10 kts). Hoarfrost cannot be excluded. Td did just not reach Twing in clear spells. Dew point deficit is only 0.5 °C.
2013-02-21	Marginal hoarfrost	Yes	6-9	16	-1.9	-4.8	-4.3	Dry	0-8	no	The wind is just in the range that hoarfrost is likely (8 kts). RH is quite high. Td did just not reach Twing in clear spells. Min. dew point deficit 0.5 °C
2013-02-22	Marginal hoarfrost	Yes	5-10	42	-2.9	-5.4	-5.1	Dry	0-7	no	The wind is just in the range that hoarfrost is likely (8 kts). RH is quite high. Td did just not reach Twing in clear spells. Dew point deficit 0.3 °C, small/moderate wind, 9 kts. Hoarfrost simulated at Polderbaan
2013-02-23	Too dry for hoarfrost	No	6-7	6	-2.8	-7.2	-5.3	Dry	0	no	Clear dew point deficit > 1.9 °C, wind > 9 kts.

5.1.2 False alarms

The false alarms should indicate in which weather situations the model is too sensitive in giving a hazard. Six out of ten false alarms were preceded by preventive anti-icing (Table 5.5). These cases can therefore not be regarded as false alarms. They were a correct warning if we suppose that the model is correct. There are two possible explanations for the four remaining false alarms:

- Hoarfrost was simulated in two nights at 1 UTC, when few airplanes depart. So, probably there were no departures when hoarfrost was simulated. Thereafter wing temperatures rose above 0 °C, so that the hoarfrost is melted before the first airplanes depart.
- The long wave incoming radiation from the ground is not taken into account. It is noticed that most false alarms occur in the spring. This also accounts for the afternoon. The shorter nights together with the larger incoming global radiation heat up the soil, which is released at night. This might not just warm the bottom side of the wing but also the top side. This is because of the wing material is a good conductor.

Table 5.5: Table of false alarms. The last column indicates if there were preventive anti-icing treatments at Schiphol. The column with 'Ne' represents the cloudiness in octas.

Date	Meteorol. condition	Time of icing in model	T2m (°C)	Td (°C)	Twing	Ne (octas)	Wind Speed (Kts)	Description	Prev. ice.
2012-02-25	Hoarfrost	1	2.7	2.6	-0.4	0	4	After hoarfrost, variable clouds and Twing up to 3°C on 6 UTC.	no
2012-03-20	Hoarfrost	0-1	2.4	1.4	-0.2/ -.1	0	8	Cloudless, thereafter Twing just slightly above 0 °C.	yes
2012-03-27	Hoarfrost	4-5	3.7	2.3	-0.7	0	4	Cloudless, little wind 3 kts.	no
2012-04-14	Hoarfrost	0-1	3.6	2.7	-0.3/ 0	1	3	After this time interval clouds and slight positive Twing.	yes
2012-12-21	Precipitation	1	2.6	2	2.4	8	12	0.4 cm of snow did not stick to the wing with Twing > 2.5 °C.	no
2013-02-19	Hoarfrost	0-2	-0.3	-0.8	-0.6/ -1.7	6	4	Lot of clouds, not typical for a hoarfrost night. After hoarfrost indication, weather is completely overcast. Together with wing temperatures of 2 °C it is logic that no de-icing occurs	yes
2013-04-07	Hoarfrost	0	0.4	-0.8	-1.4	3	5	After hoarfrost completely overcast, Twing slightly above 0 °C	yes
2013-04-20	Hoarfrost	2-5	1.5	0.5	-1	1	6	Cloudless or slight cloudy	no
2013-04-21	Hoarfrost	3-4	2.5	0.7	-0.7	0	5	Cloudless	yes
2013-04-28	Hoarfrost	3-4	1,9	0,6	-0,9	2	4	Cloudless or slight cloudy	yes

5.1.3 Reanalysis of skill scores

As described in the previous paragraphs, a large part of the hoarfrost misses are probably not real misses. In these cases the wing model could help in making a better decision for de-icing, than just based on air temperature. Also for precipitation this accounts for two cases. Here the new skill scores are presented in Table 5.6 based on the justified misses, related with a justified de-icing. For hoarfrost the POD based on a half day period is 75 %, which is a large improvement compared to the uncorrected value of 60 %. Considering all hazards the amount of misses diminishes to 12 %. In the afternoon we find similar results.

Table 5.6: Reanalysed skill score for 0-12 UTC period. In the Justified Misses column the unlikely misses are filtered out. In case multiple meteorological conditions play a role the priority is given to the most stubborn ice structure, which is in succession precipitation, freezing fog, ice and hoarfrost.

	Total	Hits	Misses	Justified Misses	POD (%)
Precipitation	44	41	5	3	93 %
Freezing fog	6	6	0	0	100 %
Ice	4	4	0	0	100 %
Hoarfrost	28	21	14	7	75 %
Total	82	72	19	10	88 %

5.2 Cases

After showing the general model skills in the previous section, some interesting cases are highlighted in this section. These cases comprise one night or a couple of consecutive nights. Simulated hoarfrost as calculated by the model is compared to the de-icing registrations. Time series are shown of relevant weather parameters and the wing temperature which together declare the occurrence of hazards. This variety of cases must show the anticipation of de-icing events and the model behaviour.

Four cases will be discussed, i.e. two hoarfrost cases, one snow case and one freezing fog case. The first hoarfrost case represents a cold freezing night (also frost at 2m). The second hoarfrost case is characterized with ground frost. In this situation the simulated wing temperature drops below 0°C, while the air temperature remains well above 0°C. The snow case covers three days with an alternation of rain, sleet and snow. The freezing fog case is characterized by fog with wing temperatures slightly below 0 ^{o}C. These four cases were only preceded with a few preventive anti-icings, which will not have a large influence in declining the number of de-icings.

5.2.1 Hoarfrost case 13 January 2013

This night is characterised by wing temperatures simulated just below Td. Observed ice is solely coming from hoarfrost, so no precipitation or fog occurs. It is the start of a frost period initiated by easterly winds due to high pressure above Scandinavia (Figure 5.1). The relative humidity is not high, nevertheless the clear conditions enables the condition for hoarfrost.

Figure 5.2A and C shows that de-icing events are concentrated in the evening around 21 UTC and during the entire morning. The model takes up the hoarfrost in the evening by simulating wing temperatures below Td at 18-19 UTC. After these hours the wind increases from 8 to 10 knots (Figure 5.2B), which is just enough to prevent hoarfrost (Twing < Td). In addition, the sky is partly covered with clouds resulting in less radiative cooling.

Later in the night again hoarfrost is simulated for a longer period of time, which is confirmed by the de-icing events in the morning of January 13th. The wing temperature is modelled during this period slightly below the dew point temperature. After the simulated wing temperature has risen above 0 ^{o}C, only one de-icing event occurred. Here, the model does a good job. In general, de-icing events occurring after Twing is simulated above 0 ^{o}C, might be explained that airplanes are parked in the shadow or the albedo of the wing is higher than expected.

The low relative humidity and the small difference between Td and Twing suggest that the hoarfrost was not heavy. The quantity of used de-icing fluid is just on average for a situation without precipitation. The relative large difference between T2m and Td shows that wing temperatures are required for forecasting hoarfrost.

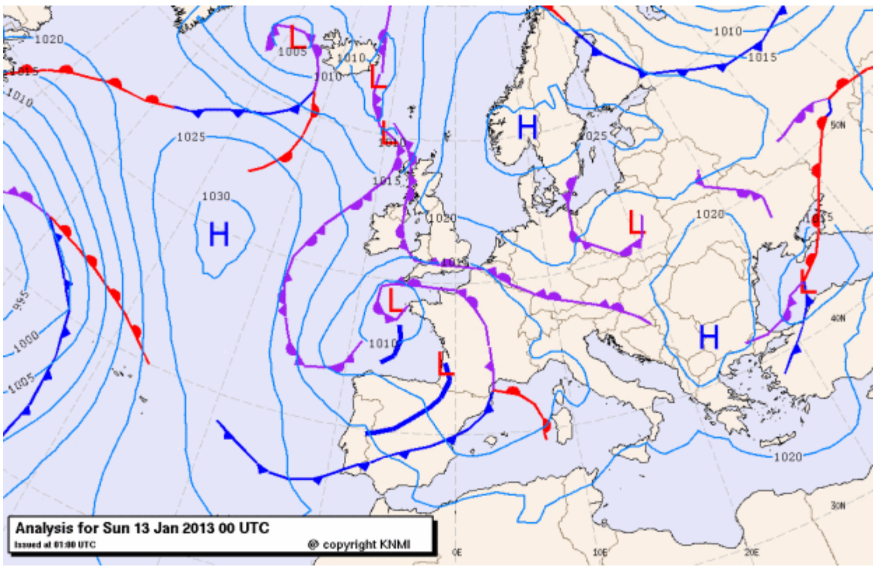

Figure 5.1: Synoptic weather map of Europe January 13th 2013, 0 UTC

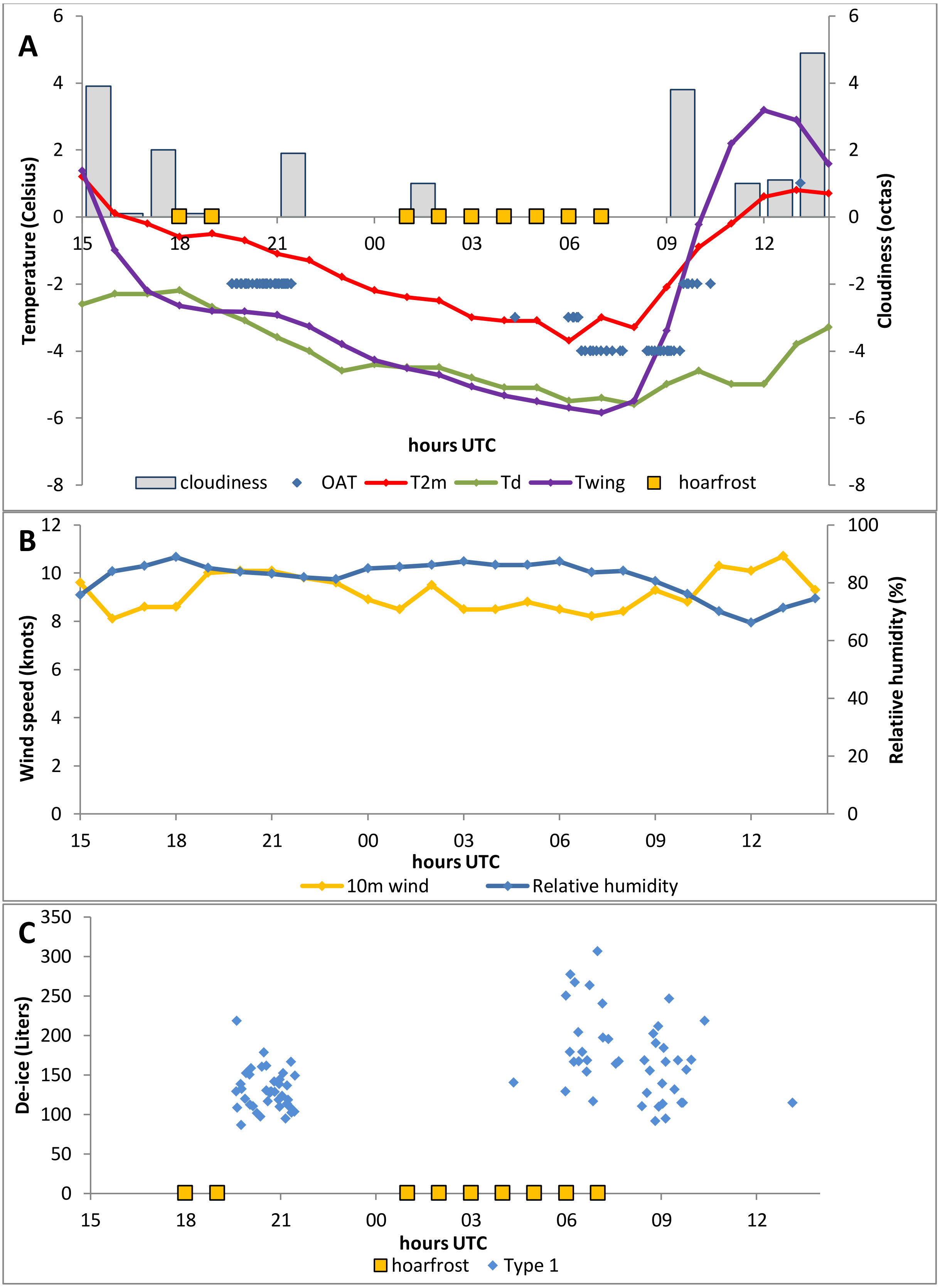

Figure 5.2: (A) This panel shows temperature and cloud cover observations and simulated wing temperature. Also hoarfrost is indicated dependent of the observed (dew point) temperatures. (B) Relative humidity and wind speed are displayed. (C) The dots indicate de-icing records of 1 airplane. Only narrow airplanes (category 1 and 2) are considered. For this particular case no airplanes of category 1 departed.

5.2.2 Hoarfrost case 15 March 2012

This case is characterised by calm weather due to high pressure in the surrounding of the Netherlands (Figure 5.3). The case has been selected by a large difference in both T2m and Td with the wing temperature. Prior to the case a high pressure system moved slowly from the UK to the centre of Europe. In this time period stratocumulus clouds from the North Sea covered the Netherlands. In the evening of March 14th the wind veered from northerly to easterly directions and clouds slowly dissolve (21-22 UTC).

Figure 5.4A shows that due to the clear and calm conditions of that night, the wing temperature dropped to -3 °C. This is 5 degrees below the air temperature and 4 degrees below the dew point temperature. The dew point – and air temperature stayed almost the entire night above 0 °C. Together with the much lower wing temperature this means that potentially a lot of hoarfrost can be formed. (recall that warmer air contains more moisture) During 9 hours the wing temperature is below the dew point temperature and moisture is deposited. First in the form of dew, which becomes ice the next hour when the wing temperatures drops below 0 °C. Thereafter, the ice on the wing grows by hoarfrost.

In Figure 5.4C it is shown that 13 airplanes are de-iced in the morning (wide bodied airplanes excluded). The fact that de-icings doesn't occur before 6 UTC might be related to less airplane departures in the night compared to the morning. The number of airplanes and the amount of used de-icing fluid is not that much and would suggest that it is an average frost night. The calm wind speed (Figure 5.4B) and large difference in Twing and Td suggest severe hoarfrost, which is also indicated by the model. Nevertheless, with support of the modelled wing temperature below 0 °C a hazard of hoarfrost is given, while this would not be the case if air temperatures were used instead.

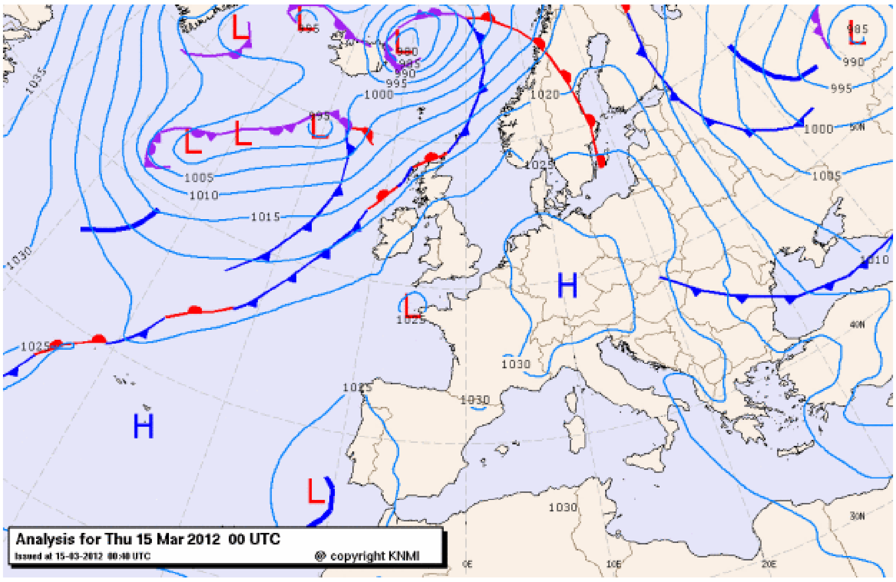

Figure 5.3: Synoptic weather map of Europe March 15th 2012, 0 UTC

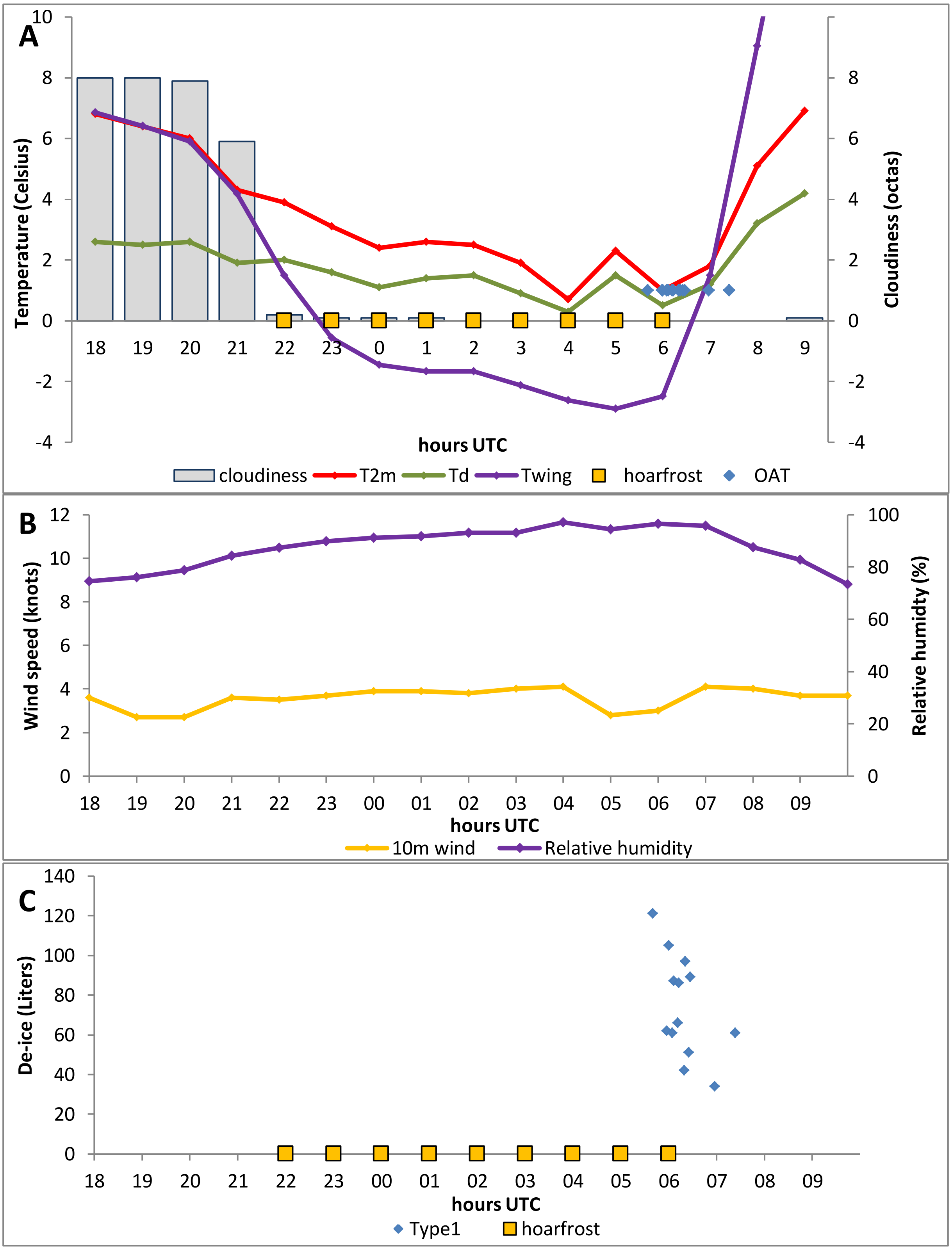

Figure 5.4: (A) This panel shows air temperature and cloud cover observations and simulated wing temperature. Also hoarfrost is indicated dependent of the observed (dew point) temperatures. (B) Relative humidity and wind speed are displayed. (C) The dots indicate de-icing records of one airplane. Only narrow airplanes (category 1 and 2) are considered. In the other categories only one wide body airplane (category 4) was de-iced.

As an example the spatial variation of wing – and air temperatures are shown in Figure 5.5 for March 14th 23 UTC. Over the Schiphol area there are significant local temperature differences which may affect the occurrence of hoarfrost on different places. Interesting is to compare station Airside Alpha with Juliet platform. Recall that Juliet platform is coupled to station Ceintuurbaan Noord, where it gets the input parameters. Station Airside Alpha is located on the border of the gates and is the most representative station for airplanes parked between the gates. Airside Alpha shows a simulated wing temperature above 0 °C (0.6 °C), while Juliet platform shows wing temperatures below 0 °C (-0.6 °C). The air temperature differences between these stations are similar with 4.0 °C for Airside Alpha and 3.1 °C for Juliet platform.

The differences in simulated wing temperature between Juliet platform and Airside Alpha shown in Figure 5.5 are exemplary for the average differences during clear and calm conditions. On average the simulated wing- and air temperatures are 1.1 °C and 1.2 °C warmer in simulated hoarfrost cases for the Juliet platform. However, the exact air temperatures between the gates are unknown, since we have no measurements there.

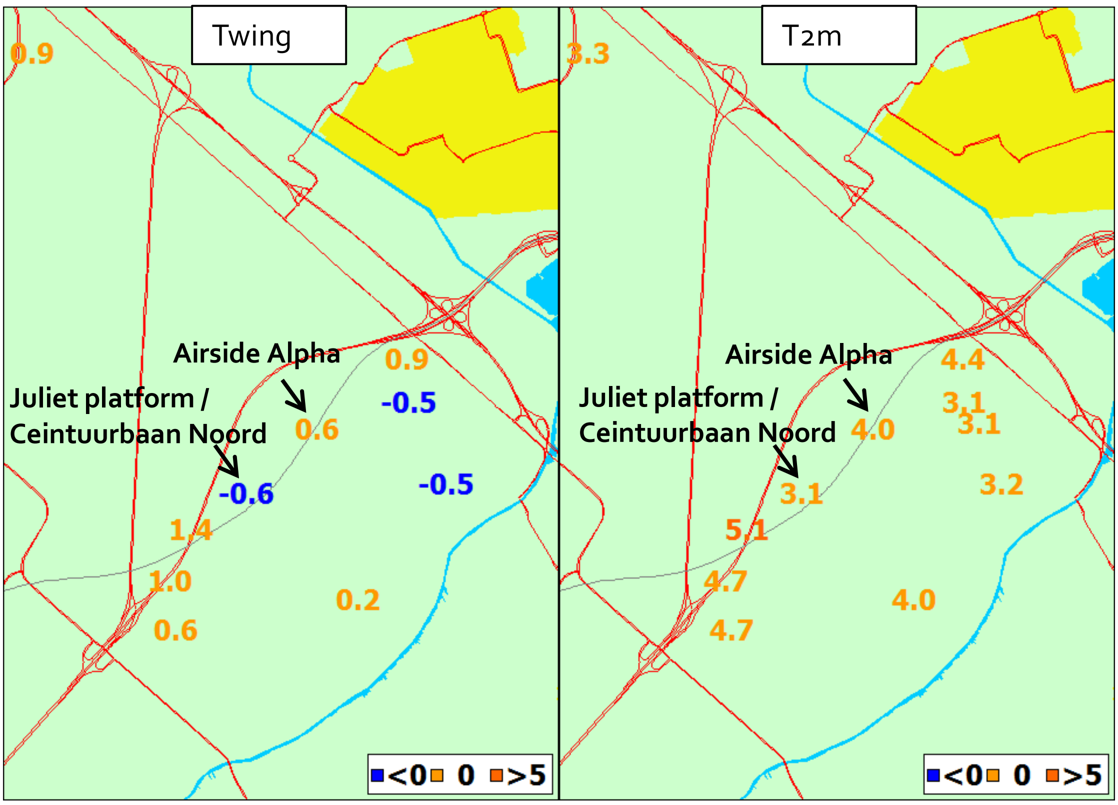

Figure 5.5: Map of Schiphol with simulated wing temperatures left and air temperatures right for March 14th 23 UTC. The dew point temperature is high enough to produce hoarfrost or condensation. At the locations where wing temperatures are below 0 °C, hoarfrost is expected.

5.2.3 Snow case 5-7 December 2012

At the west side of a low pressure system above Scandinavia, cold upper air is transported over the North Sea (Figure 5.6A). This results in several snow – and rain showers at December 5th and the night of December 6th. At day time for Schiphol this was predominantly rain and varied possibly with periods of hail and wet snow. Hail was recorded in this period in the near surrounding of Schiphol. After an almost dry period at daytime of December 6th a new low pressure system from the northwest enters the North Sea with accompanying frontal lines (Figure 5.6B). The precipitation falls merely as snow, which is supported by the colder land wind from the south. No or hardly any hoarfrost or rime formation occurred during this event.

According to Figure 5.7B and C, the first showers at 14-15 UTC are recorded as snow with temperatures and simulated wing temperatures well above 0 °C. Also the dew point temperature is slightly above 0 C°, which means that it is impossible for snow to freeze on the wings (Figure 5.7A). Thereafter the snow turned into rain and the T2m increases with a half degree. The simulated wing temperature remains above 0 °C, so that no ice is expected on wings. Hardly any de-icing (Type 1) took place. So, this corresponds with the indications of the model.

The night of December 6th started with a bit of freezing rain and thereafter solely snow occurred (Figure 5.7C). Simulated wing temperatures and T2m were well below 0 °C, so ice on the wings is expected. The de-icing events (Type 1) show clearly the presence of ice on the wings. For some airplanes much de-icing fluid was needed which suggests that it was a recalcitrant layer of ice. This is supported by the occurrence of freezing rain at the start of the night.

During the frontal passage with snow from 4 UTC onwards on December 7th the T2m and wing temperature were slightly above 0 °C. Based on the de-icing events (Figure 5.7C), the relative small amounts of de-icing fluid suggest that the wet snow did not freeze on the wing, which is indicated by the positive simulated wing temperature. In such weather situations with negative Td it is possible that wing temperatures drop below 0 °C due to the heat loss of evaporation. The single de-icing events in afternoon on December 6th cannot be declared with the rain spike at 15 UTC and positive temperatures.

Precipitation is compared to other icing types as hoarfrost not the main added value for de-icing forecasts, because solid precipitation can lead to de-icings regardless of wing temperature. However the nights of 6 and 7 December show that wings above 0°C have less de-icings and less used de-icing fluid than wings below 0 °C.

Also for wing temperatures above 0 °C we see de-icings which imply that solid precipitation is a hazard regardless of wing temperature. However, the number of de-icings and the amount of de-icing fluid is substantially lower in case wing temperatures are simulated above0 °C.

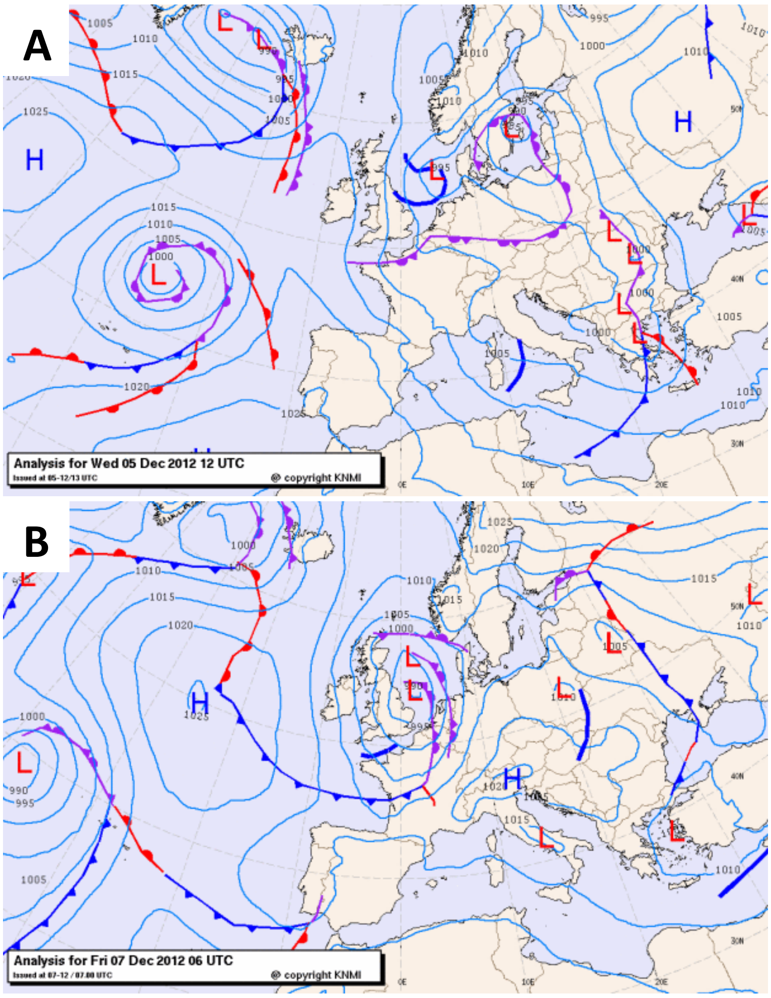

Figure 5.6: (A) Synoptic weather maps of Europe December 5th 2012), (B) 12 UTC and December 7th, 6 UTC

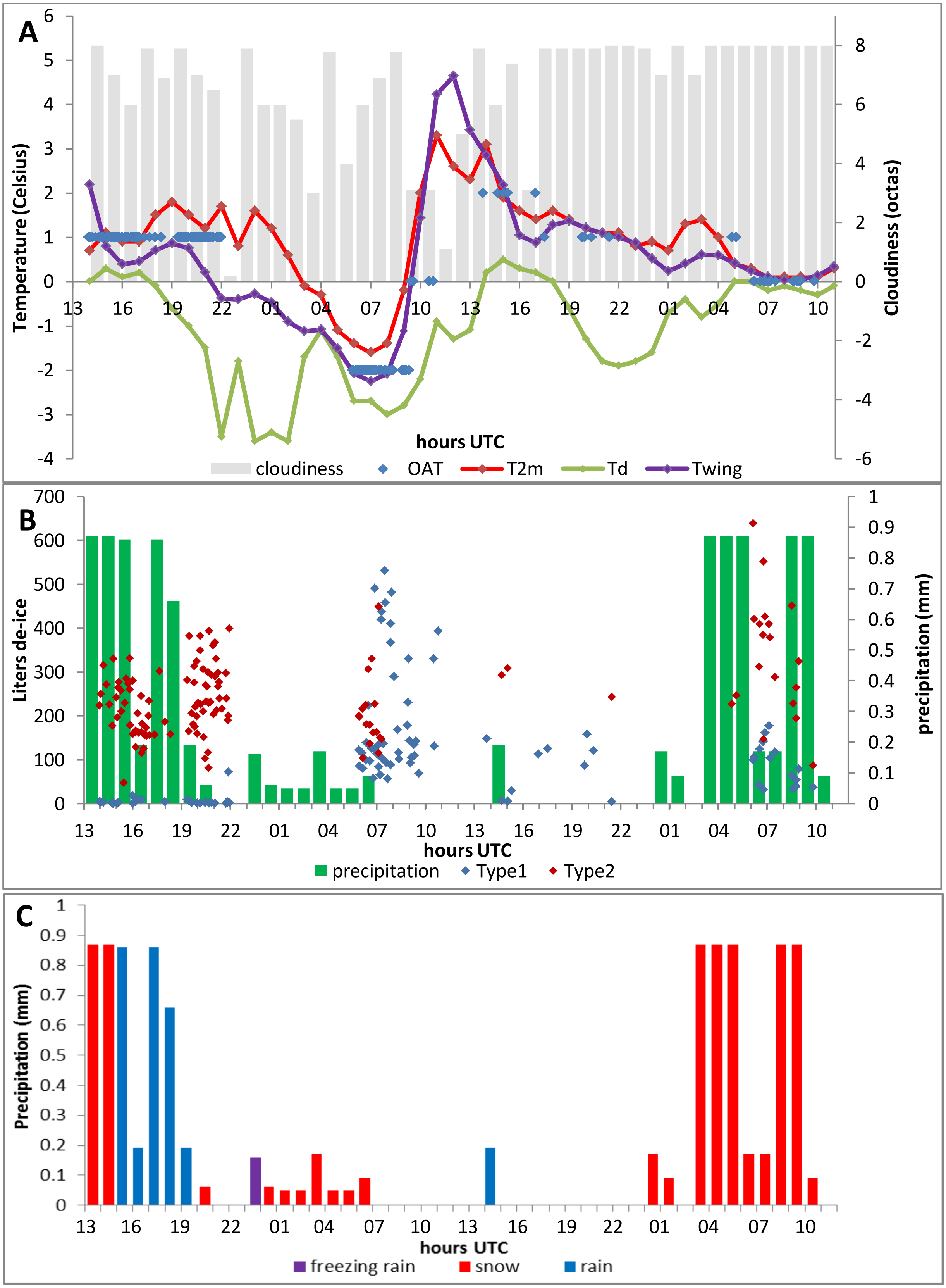

Figure 5.7: Weather panels representing the period 5-7 December 2012. (A) This panel shows temperature and cloud cover observations and simulated wing temperature. (B) Precipitation amounts are displayed together with the de-icings and anti-icings. Only narrow airplanes (category 1 and 2) are considered. (C) The precipitation is subdivided in freezing rain, snow and rain.

5.2.4 Fog case 19 November 2012

A ridge of high pressure is covering the Netherlands in the night of 19 November. The air is from the start of the evening very humid, which is indicated by a high relative humidity. Until 3 UTC there are predominantly clear conditions and with low wind speed the simulated wing temperature drops well below 0 ^oC and the dew point temperature. In Figure 5.8A it can be seen that hoarfrost is expected. The air cools down such that the dew point temperature is reached and fog is formed from 3 UTC. The relative humidity is near 100 % then. While little oversaturation might occur (RH > 100 %), the value of 102 % is not reliable and is caused by an uncertainty of the measurement device (Vaisala, 2013) (Figure 5.8B).

In a situation with fog the wing temperature is very close to the air temperature, which is also true for this case (Figure 5.8A). Same as for a cloud cover, this is because long wave radiation is emitted back towards the wing. At the onset of the fog the simulated wing temperature rises above 0 ^oC. At 6 UTC the fog becomes thinner and the related extra outgoing long wave radiation causes the wing to freeze again. Because it is fog the ice deposition is classified as freezing fog (Figure 5.8A). In the morning warm humid air is advected from the south. The fog remains, but Td, T2m and wing temperature rises well above 0 ^oC from 8 UTC.

In the frost interval between 6 UTC and 8 UTC we find also de-icing events (Figure 5.8C). In the clear conditions before the fog no de-icing events are registered. It is unknown if no airplanes departed in the late evening, or the airplanes did not suffer from icing. After 8 UTC when the temperature is above 0 ^oC, the de-icing abruptly stops. Condensation is very effective in removing the ice of the wings, because water is an effective conductor of heat. At this day 36 planes have been de-iced, which is quite a lot. The amount of used de-icing fluid increases towards the end of the period, which might be an indication of a growing ice layer on the wings. The rime due to the freezing of supercooled water droplets gives a thicker stubborn layer of ice compared to hoarfrost. Type 2 anti-icing might have been used, because freezing fog has a low hold-over-time similar to precipitation on a frozen wing also. In addition, snow and rain felt at 7 and 8 UTC.

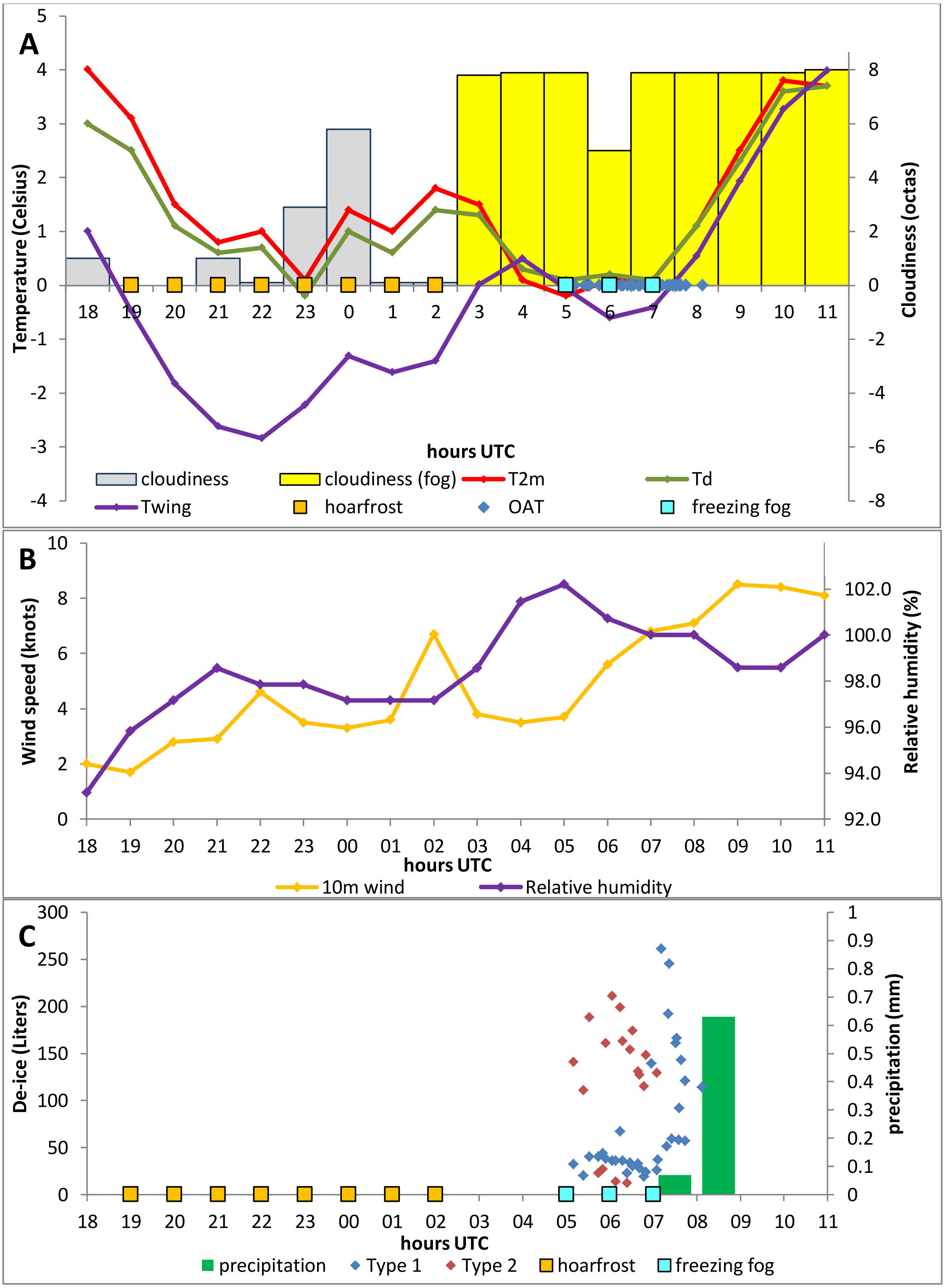

Figure 5.8: (A) This panel shows temperature and cloud cover observations and simulated wing temperature. Also hoarfrost and freezing fog are indicated. (B) Relative humidity and wind speed are displayed. (C) The dots labelled with Type 1 and Type 2 indicate de-icing records of one airplane. Only narrow airplanes (category 1 and 2) are considered. Snow felt at 7 UTC and rain felt at 8 UTC.

6. Conclusions and recommendations

6.1 Model validation

The validation of the wing model has shown that there is a good correlation between de-icing events and modelled icing hazards. As expected the model shows that the wing temperature is strongly related to cloud cover. During clear nights the modelled wing temperature dropped several degrees below air and dew point temperature resulting in hoarfrost. Although the air temperature was sometimes above 0 °C, these nights often resulted in a significant number of de-icing events.

Based on the de-icing events it is only possible to do a raw validation. The time of de-icing strongly depends on flight schedule. It is therefore difficult to compare the model results on an hourly base to the de-icing events. Furthermore it is not clear if all de-icing events are necessary. It could be possible that pilots request de-icing while there is no ice on the wing. This is supported by the fact that we found some de-icing events during situations with frost, but with a low relative humidity. With the model one can prevent these unnecessary de-icings, which is estimated to 9 cases over two seasons.

The best way to verify the model is by comparing results with observations. This winter temperature sensors will be placed on a test wing at Schiphol. Based on these observations a more detailed validation of the model will be done. Ideally after two winter seasons, because one winter season is often not representative in the occurrence different icing types.

6.2 Model improvements

Based on the validation we have some ideas to improve the model.

- Hoarfrost is now modelled in a qualitative way. You can have either hoarfrost or heavy hoarfrost. We advise a more quantitative approach with the possibility to accumulate hoarfrost over a period resulting in an amount of hoarfrost. Ad hoc manual observations by taking pictures for example, could help to understand the process.
- The hazards (e.g. snow, hoarfrost, freezing rain) calculated by the model are focused on the type of weather. It is however more important to know the amount and how ice is attached to the wing than the source. We recommend therefore to model these parameters and to define classes based on severity.
- Most false alarms occur during spring. In this time of the year the runway is relatively warm during night time. Maybe the temperature of the runway has more impact on the wing temperature resulting in warmer wings and less ice than expected. We should therefore include the impact of the runway temperature in the model. However to draw firm conclusions we have to wait for wing temperature observations.

6.3 Spatial variation

This research showed that there can be a significant difference in air temperature in the area of Schiphol. Locations close to the gates are often warmer than locations next to the runway. This can be explained by heat that is emitted from surrounding buildings. If planes are parked close to the gates during night time, heat from buildings will have impact on the wing temperature and ice formation on the wings.

We therefore recommend doing an air temperature mapping on the different parking sites during a clear and stable night to discover the local variation in air temperature. This information will help to make a (parking) site specific forecast and give more detailed information about the expected number of planes that have to be de-iced.

6.4 Variation among planes

a) The current model validation was done for all categories and all airplane types. For a further distinction of de-icing sensitivity per airplanes type a flight schedule is needed. We expect that different wing and plane types will react different to the weather and will show quicker or slower icing. Therefore it would be good to have a flexible solution to measure the wing temperature of other airplanes. A solution could be to measure wing temperatures with a mobile infrared camera. However in a first stage the applicability of an infrared camera to measure the wing temperature has to be tested. For measuring air and dew point temperature we advise to install a mast that measures at larger heights corresponding to larger airplanes, up to 10 m. In a later stage this information could be used to develop a wing temperature and condition model for different wing types.

b) We will also explore the usefulness of a combination sensor that measures not only (runway/wing) surface temperature but also other elements like the thickness of the water layer on a wing.

c) Next to the de-icing platform, measurements can be performed at other locations at the airport.

6.5 Probability forecasting

The current version of the model produces the most likely wing temperature and condition forecast. However it is also possible to produce a forecast in terms of probabilities. For mid rang and long term forecasts (>1 days ahead) probabilities are often more indicative than the most likely values since the uncertainty of the weather forecast increases in time.

Probability forecasts are already used by the de-icing team. However this forecast is based on general weather parameters like air temperature and precipitation. We recommend to make a probability forecast based on a forecasted wing temperature and condition since the wing temperature can deviate strongly from the air temperature.

6.6 Decision support system

This research showed that there is a strong relation between weather and de-icing events. The wing model forecast can be used to make a capacity and hold-over time forecast. By linking these forecasts to decision trees and the flight schedule, a decision support system can be developed. A probability forecast could help to take decisions based on a cost-loss approach. This system can be used for resource and capacity planning.

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