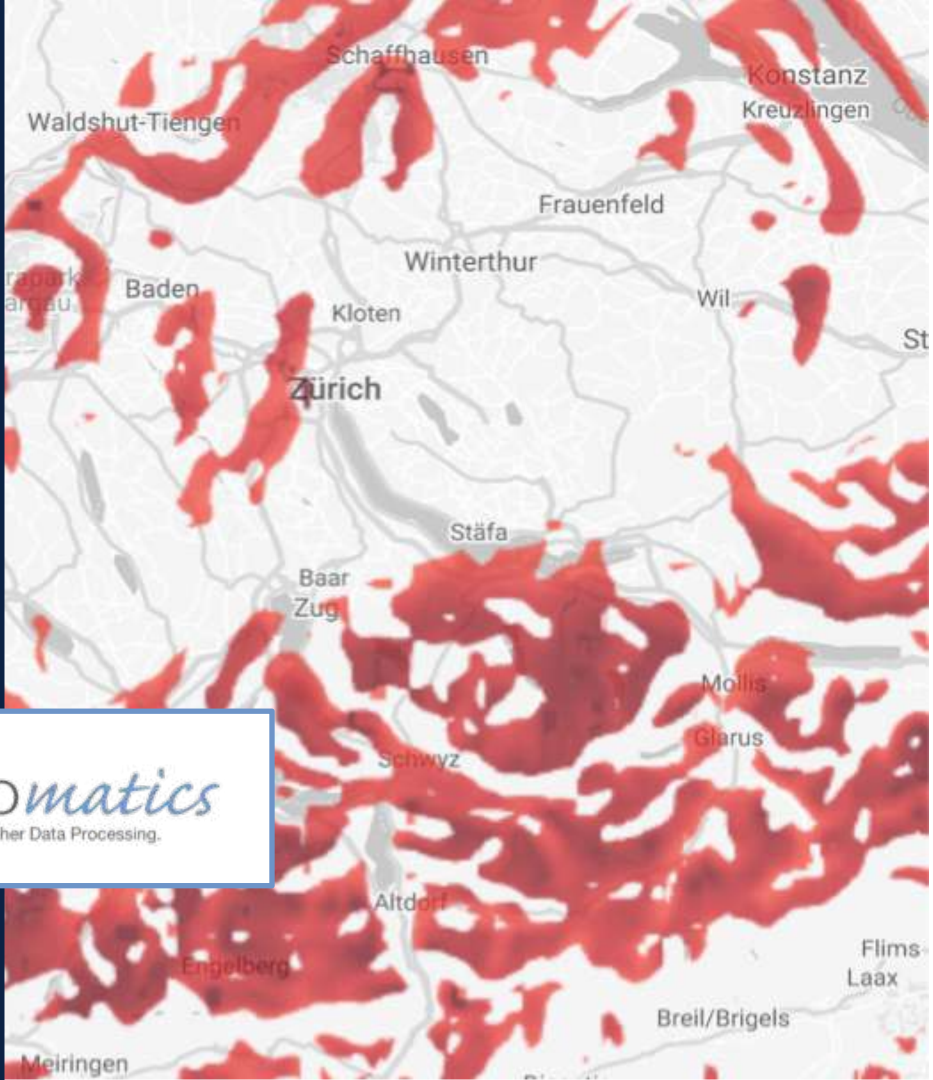


meteomatics
Your Experts in Weather Data Processing.

Project „SOPHIA-2“ – Final Report

(public version)

Meteomatics

St. Gallen

Meteomatics AG

Weather API

Worldwide Parameters

Model Data
Station Data
Satellite Data
...

Industry

Bespoke Solutions

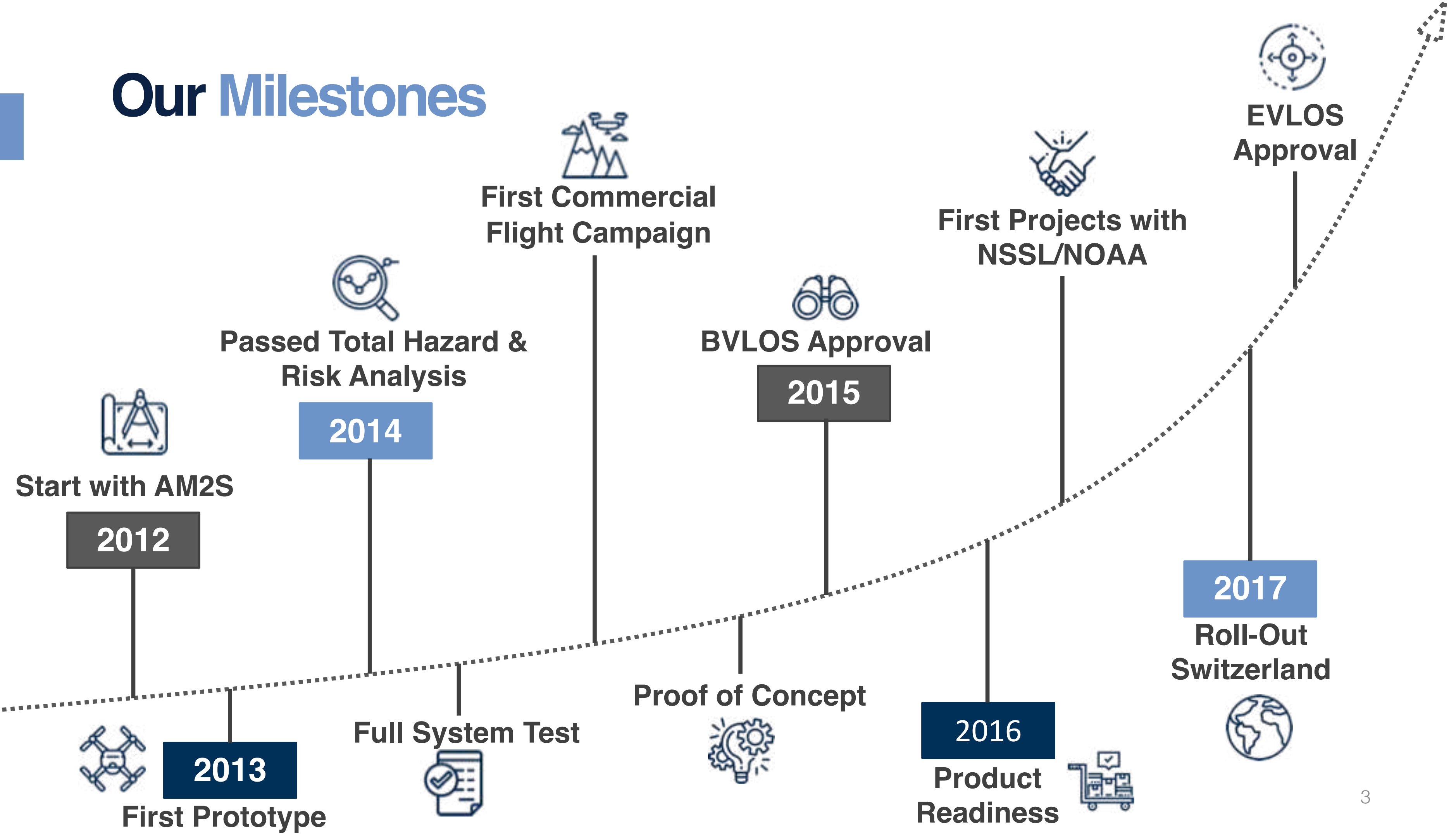
Wind Power
Solar Power
Hydro Power
...

Meteodrone

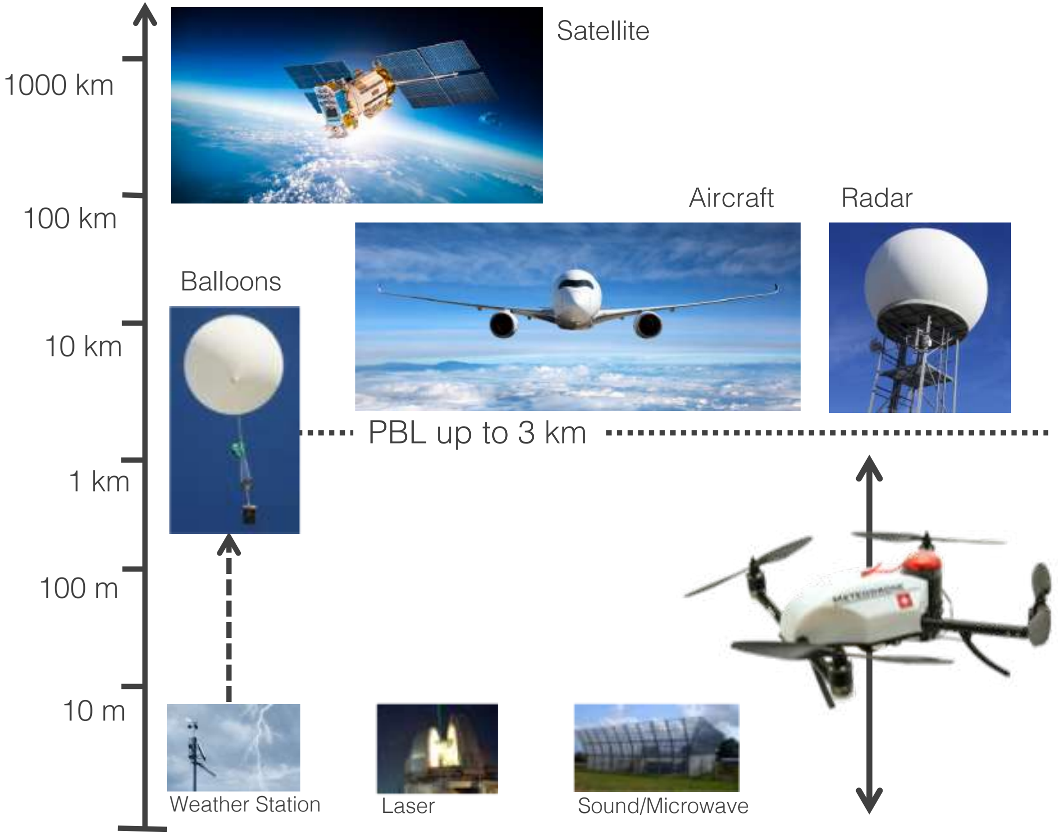
High-Resolution Weather Modeling

Better PBL Data
Improve Fog & Storm Forecasts
Customized Solutions

Our Milestones



Current Data Situation – and How to Improve



- Current forecasting models are quite insufficiently suited to forecast thunderstorms and fog
- Low stratus, fog, and triggers for storms develop in the planetary boundary layer
- Lack of adequate and accurate data in the lower atmosphere with traditional meteorological measuring systems
- **Meteodrones** – developed by Meteomatics – are a new kind of weather observation instrument
- Vision: Fully-automated, network of Meteodrones, running 24 / 7, which provide continuous information flow of the lower atmosphere
- Precision forecasting of fog and thunderstorms would improve significantly

Report Overview

1. Motivation and Project Goals
2. Current Project Status
3. Evaluation Design and Assessment Setup
4. Results
    1. Ice formation on propellers at different environmental conditions
    2. Effectivity of anti-icing propeller heating
    3. Icing impact on operational drone setup
5. Icing Forecast Model: Icing Index
6. Conclusions

Project Partners:

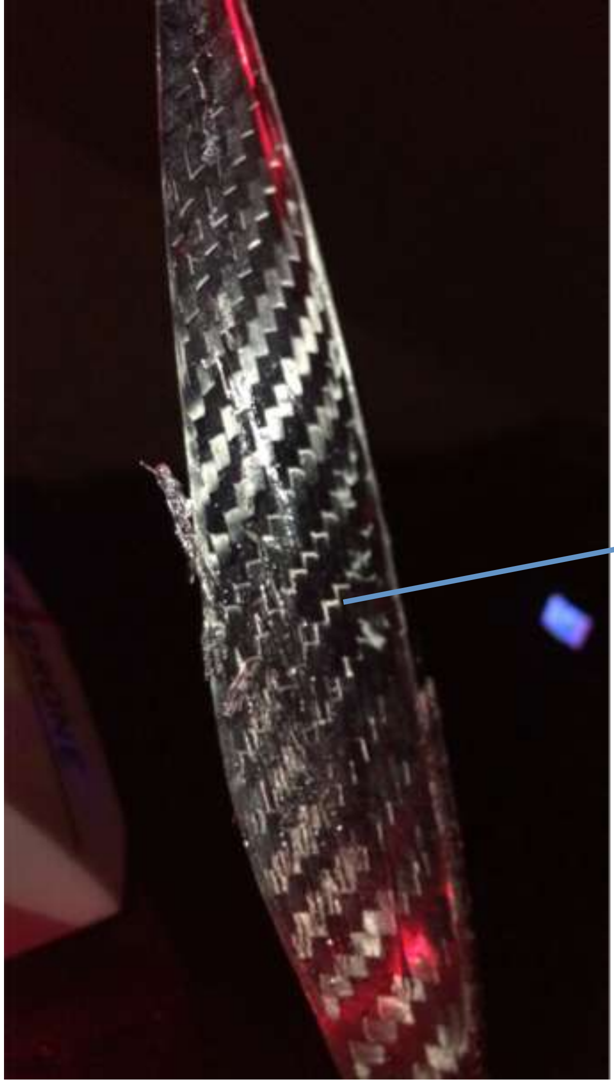
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

BAZL Bundesamt für Zivilluftfahrt

RAIL TEC ARSENAL

SOPHIA Project Motivation

- Meteodrones fly up to 3000 m and next generation Meteodrones will reach even higher altitudes
- During our operational flights (>2000 flight hours) in certain conditions we experienced ice accumulation on the propellers with negative impact on flight stability
- This “icing effect” is known from civil aviation like planes and helicopters and the frequency of icing incidences is expected to increase with flight height and length
- Growing utilization of unmanned aerial vehicles (UAVs) will intensify the importance of icing and anti-icing measures to ensure safety of the public in the future
- No study exists that analyzes icing and icing effects on UAV flights



1 mm thin clear ice formed during flights in icing conditions

SOPHIA Project Goals

Phase 1:

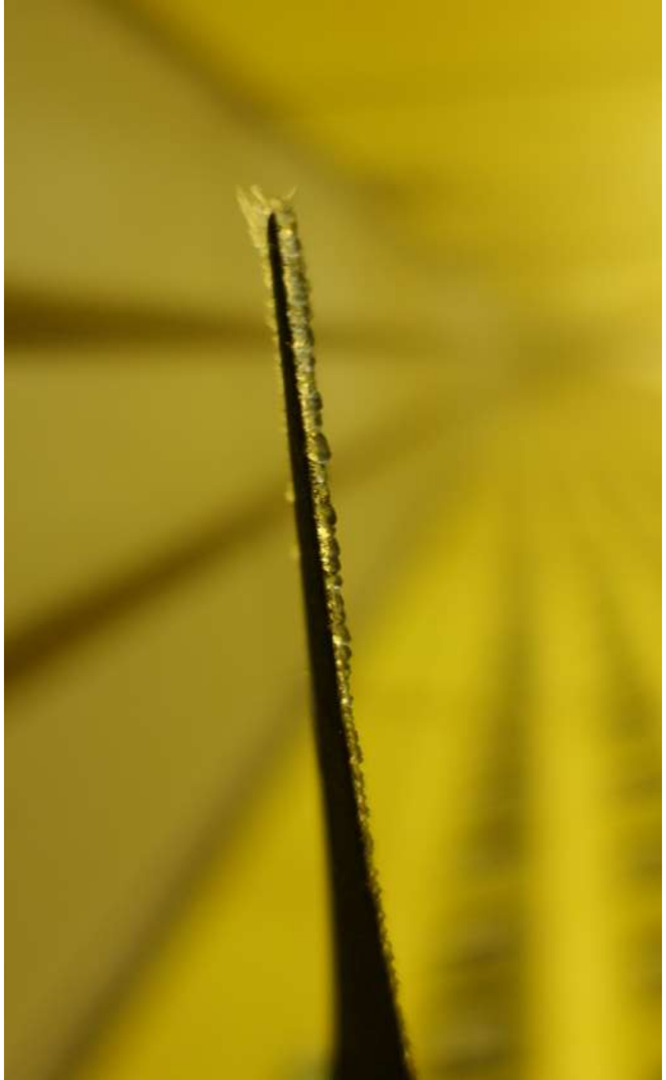
- Define test setup
- Examine ice accumulations on propellers and the body of the UAV during different icing conditions
- Test the effectivity of different anti-icing agents

Phase 2:

- Analysis of the tests
- Build a model that represents icing for different conditions
- Sketching further anti-icing strategies

Phase 3:

- Implement anti-icing strategies in prototype
- Validate the findings in field tests



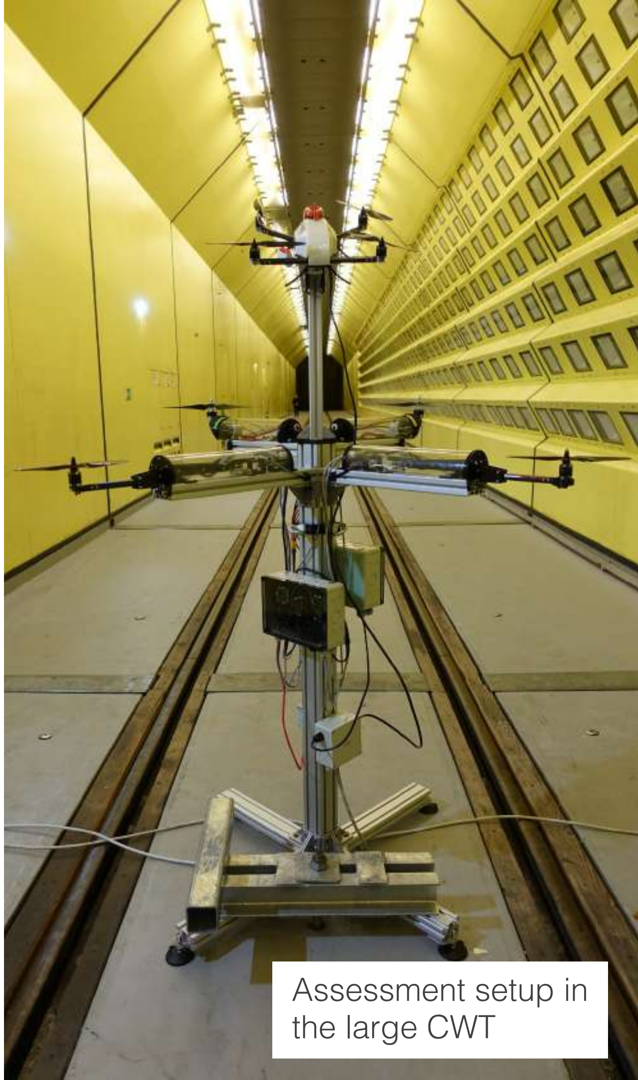
Formation of ice on propeller under specific set of laboratory conditions

SOPHIA Project Status

Overall status: Phase 3 accomplished

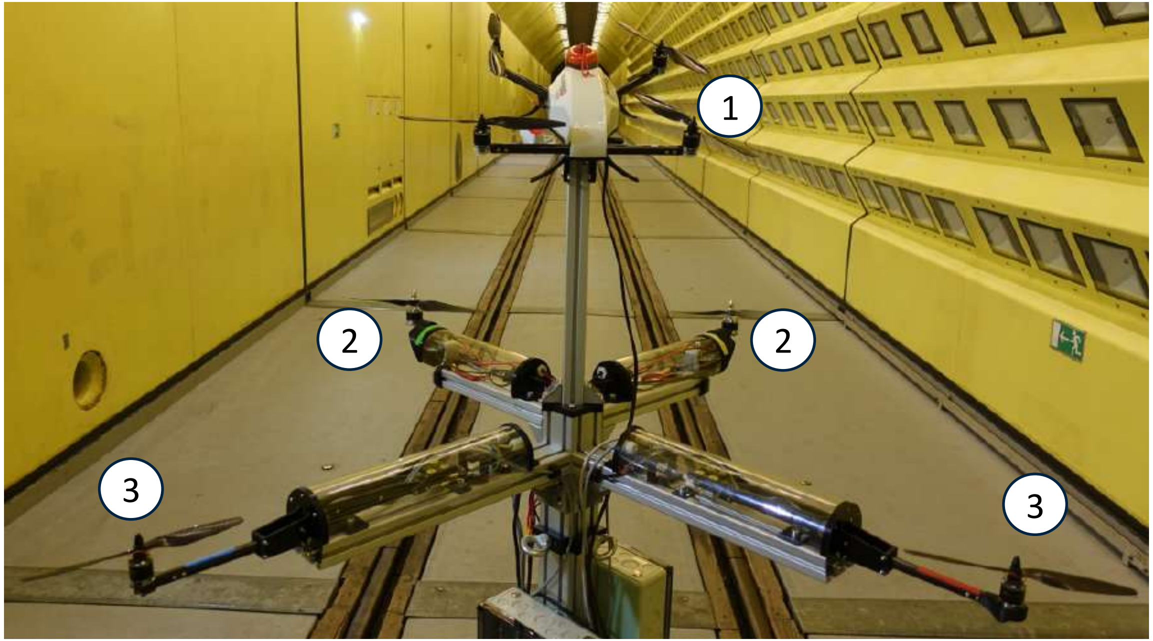
Achievements:

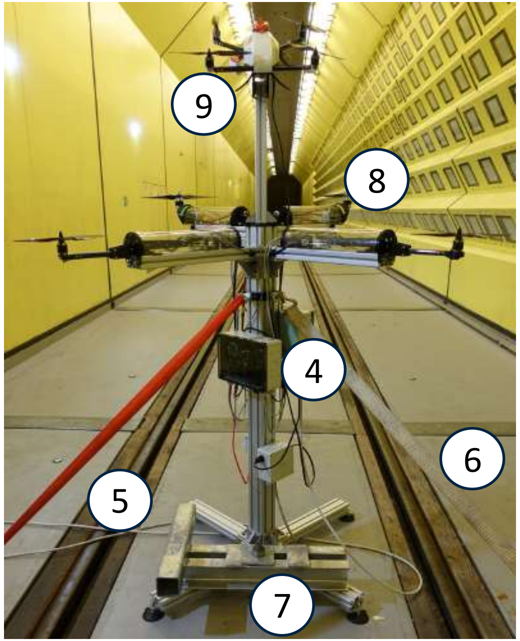
- ✓ We have designed and developed an icing assessment setup that allows to examine the impact of controllable and reproducible icing conditions on the flight parameters of the UAV
- ✓ The setup was verified and tested in different environments: outdoors in winter and at the RailTec Arsenal facilities in the large Climatic Wind Tunnel (CWT) in Vienna
- ✓ Different icing conditions were evaluated according to the EASA CS25/CS29 Appendix C guidelines as allowed by the facilities
- ✓ The setup considered two different propeller types of varying material and size, two propellers armed with an anti-icing heating system and a fully operational Meteodrone
- ✓ The effects on propeller efficiency were analyzed for different propellers, for the operational Meteodrone setup and the propellers with the anti-icing heating system in controlled conditions
- ✓ The anti-icing heating system was further validated and evaluated under real-life conditions in winter



Assessment setup in the large CWT

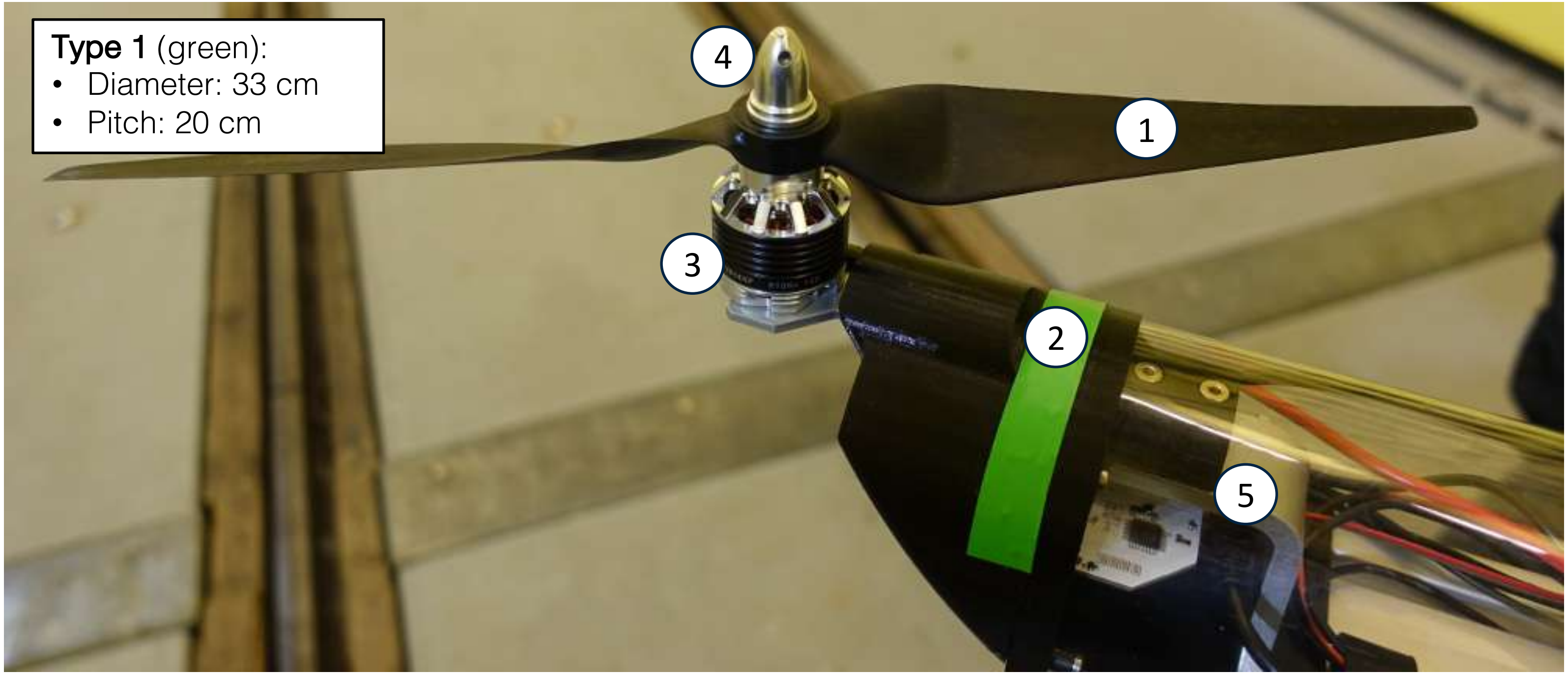
Assessment Setup





1 – operational drone setup with functional Meteodrone; **2 –** two propeller test stations with an alternative set of propellers with larger propeller work angle for comparison; **3** – two propeller test stations with custom-made anti-icing propeller heating; **4** – control unit; **5** – connection cable (30 m to control room); **6** – straps to setup mounting points; **7** – additional fixture; **8** – water proof cover; **9** – adjustable angle for Meteodrone to simulate different orientations towards the air flow – allowing for identification of the most critical flight modes

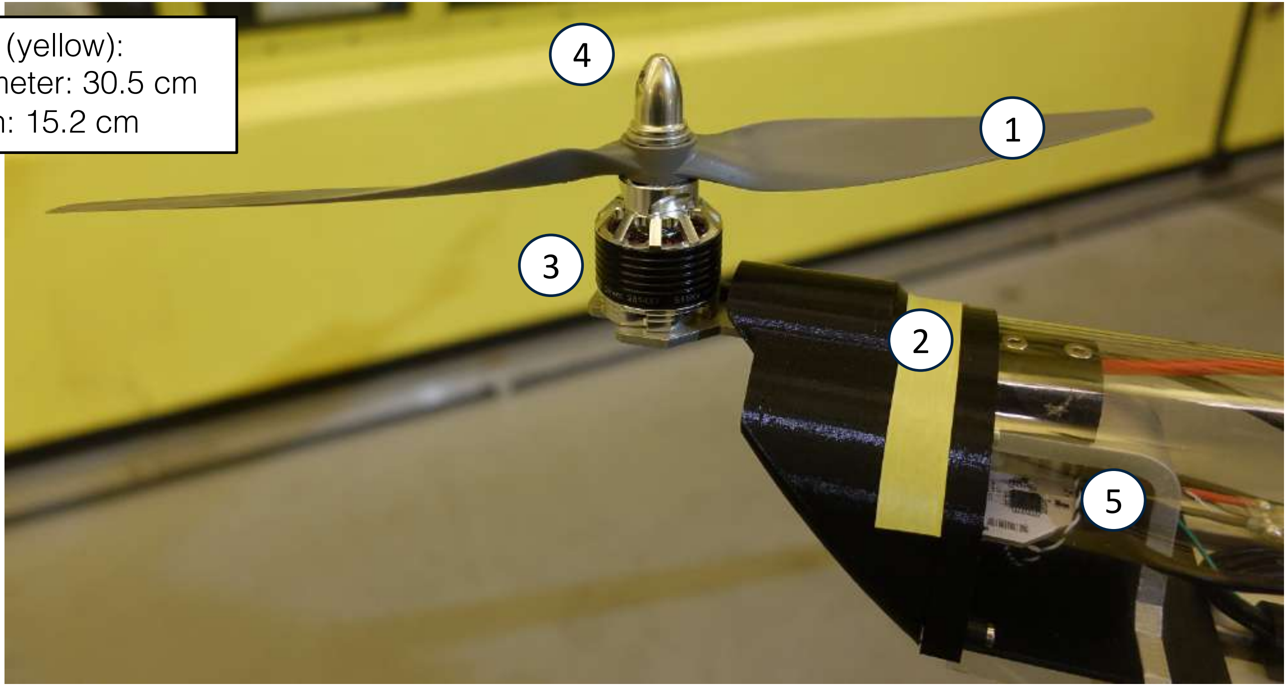
Assessment Setup Propeller Types



1 – propeller blade; **2** – color scheme for propeller test station; **3** – motor; **4** – propeller cap; **5** – setup for measuring rounds per minute (RPM), thrust, power

Assessment Setup Propeller Types

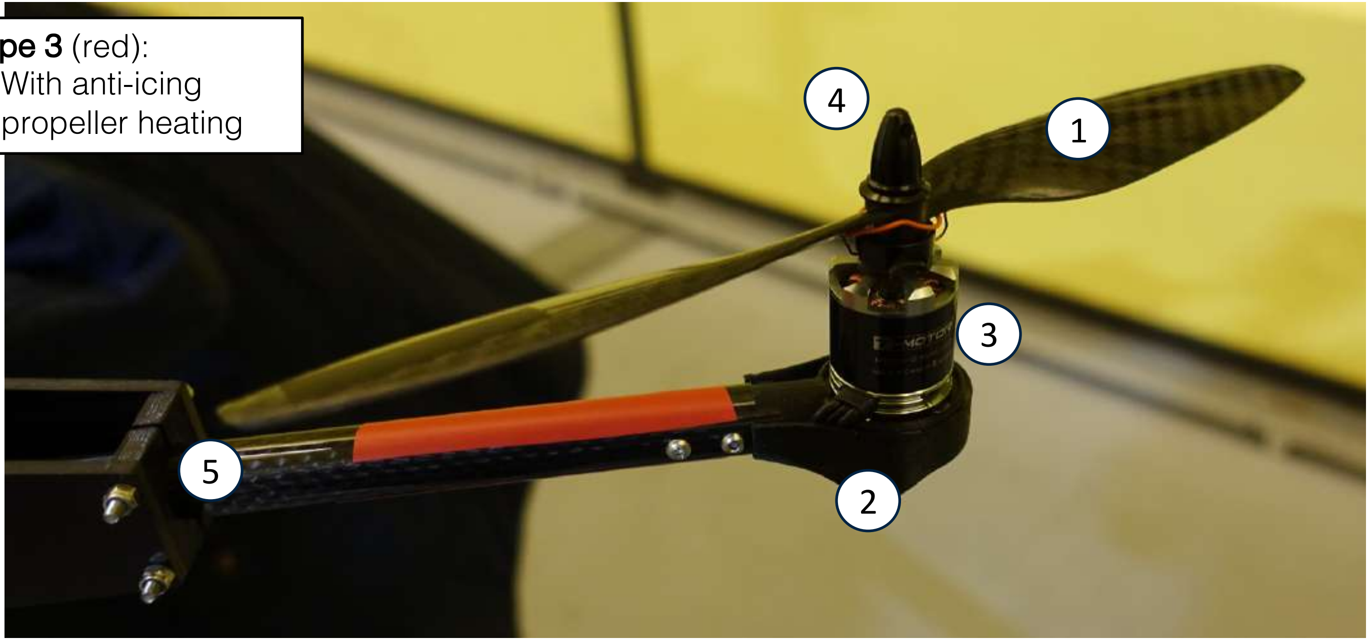
Type 2 (yellow):
- Diameter: 30.5 cm
- Pitch: 15.2 cm



1 – propeller blade; **2** – color scheme for propeller test station; **3** – motor; **4** – propeller cap; **5** – setup for measuring rounds per minute (RPM), thrust, power

Assessment Setup Propeller With Heating

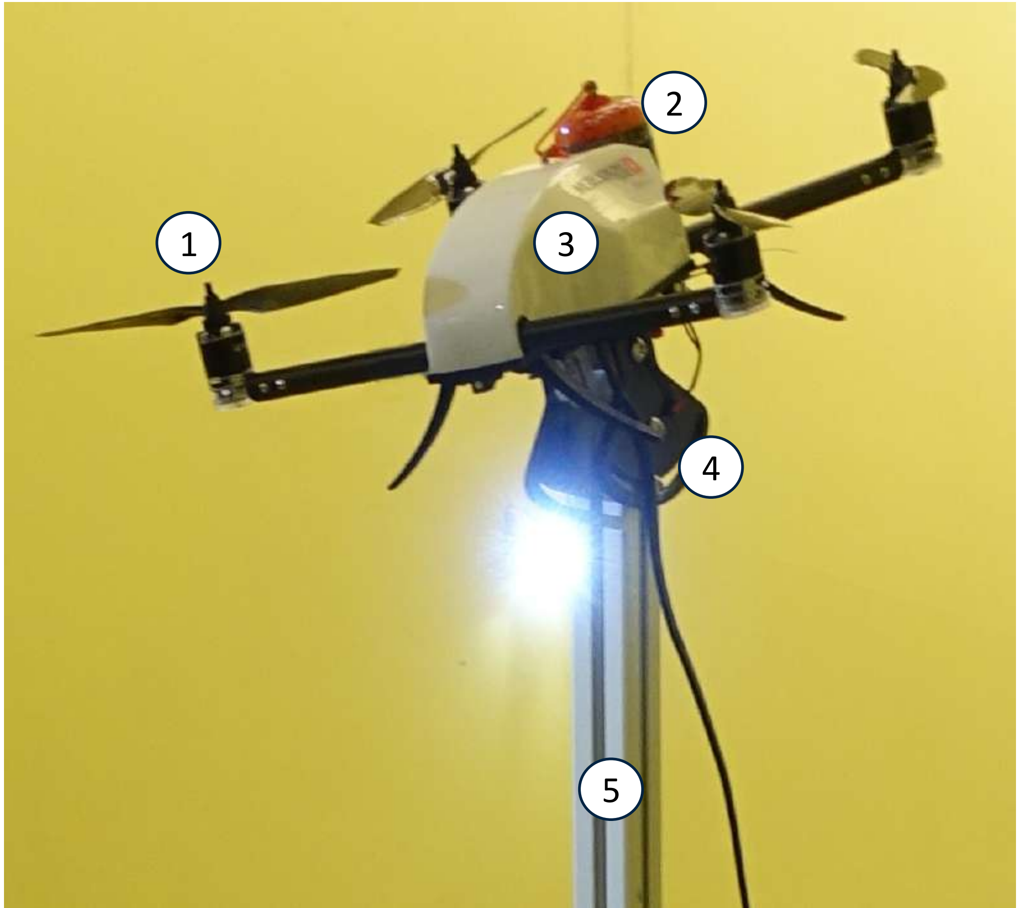
Type 3 (red):
- With anti-icing propeller heating



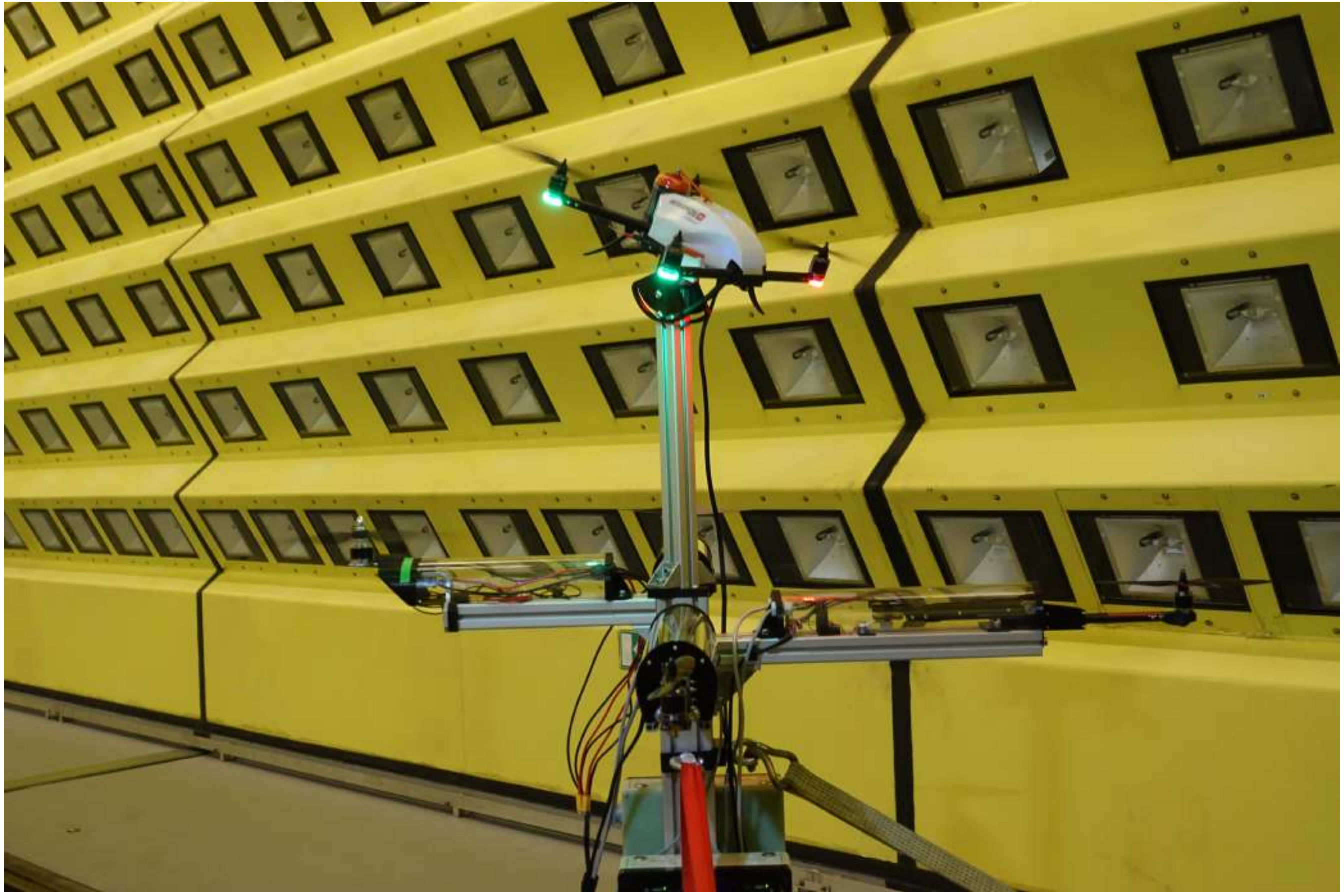
1 – propeller blade with propeller heating; **2** – custom made propeller mount; **3** – motor, accommodating propeller heating system; **4** – propeller cap; **5** – propeller arm with test stand (not shown in image) for measuring motor properties

Assessment Setup Meteodrone

1 – propellers, mounted on fully operational Meteodrone Classic; **2** – rescue parachute; **3** – hull with weather sensors; **4** – adjustable angle for facing Meteodrone front towards air flow between 0 - 90 degrees; **5** – adjustable height



Assessment Setup In the Large CWT



- Final setup in the large Vienna Climatic Wind Tunnel (CWT)
- Meteodrone operating on top with rotating propellers and strobe lights turned on
- Icing studies were conducted during two days from 25th to 26th of April 2019

Environmental Test Cases and Outline

We have investigated 6 different cases corresponding to real-world environmental conditions:

1. During one of our operational flights we have encountered a strong drop in electrical power, very similar to icing at +5 °C while flying through a cloud. We evaluate this test case by simulating a cumuliform cloud at +5 °C.
2. It is an open question if icing can occur at low temperatures above freezing temperature. We have examined this case for conditions of +2 °C and the same cloud conditions as under point 1.
3. We examine the impact of icing on different propellers and their makes and observe the direct influence on the electrical power. The latter allows for extrapolation of the icing condition potency and the resulting imposed limits for flight.
    1. Two different propellers and their performance are analyzed during various environmental test conditions of temperature (-2, -5, -10 °C) and clouds (cumuliform, stratiform)
    2. The impact of icing on an operational drone is examined for different flight angles towards air-flow allowing for assessing the severity of icing on the propellers and the hull of the drone during flight operation
    3. Our in-house developed state-of-the-art anti-icing propeller heating is assessed during the most harsh conditions the CWT allows for

The next page shows the exact matrix for the conditions feasible to create in the Vienna CWT

Environmental CWT Test Matrix

No.	Condition	Air Temperature [°C]	Wind Speed [m/s]	MVD [μm]	LWC [g/m³]
1	APP_C Cumuliform	+ 5.0	10.0	20	2.5
2	APP_C Cumuliform	+ 2.0	10.0	20	2.5
3	APP_C Stratiform	- 2.0	10.0	20	0.6
4	APP_C Cumuliform	- 2.0	10.0	20	2.5
5	APP_C Cumuliform	- 2.0	10.0	40	0.85
6	APP_C Stratiform	- 5.0	10.0	20	0.5
7	APP_C Cumuliform	- 5.0	10.0	20	2.3
8	APP_C Cumuliform	- 5.0	10.0	40	0.85
9	APP_C Stratiform	-10.0	10.0	20	0.48
10	APP_C Cumuliform	-10.0	10.0	20	2.2
11	APP_C Cumuliform	-10.0	10.0	40	0.85

- The CWTs capabilities allow for cumuliform and stratiform conditions
- Limitations are to wind speeds; The lowest wind speed available is 10 m/s
- Creating other conditions requires unfeasibly high wind speeds not practicable for testing
- Studies at positive temperatures were conducted to assess at which conditions icing occurs exactly

Results Setup 1 No. 1: Cloud Impact at 5 °C

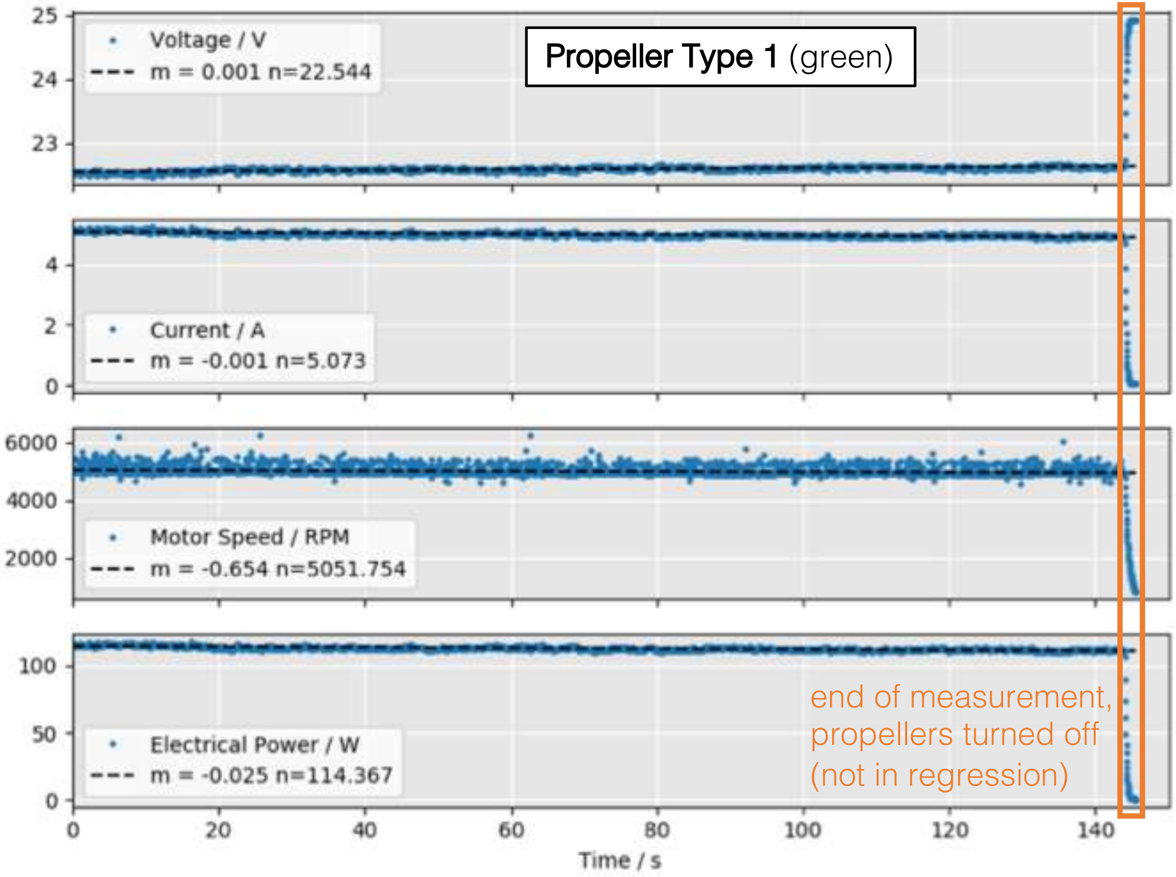
Test Case 1:

- Propeller Type 1

Environmental Conditions

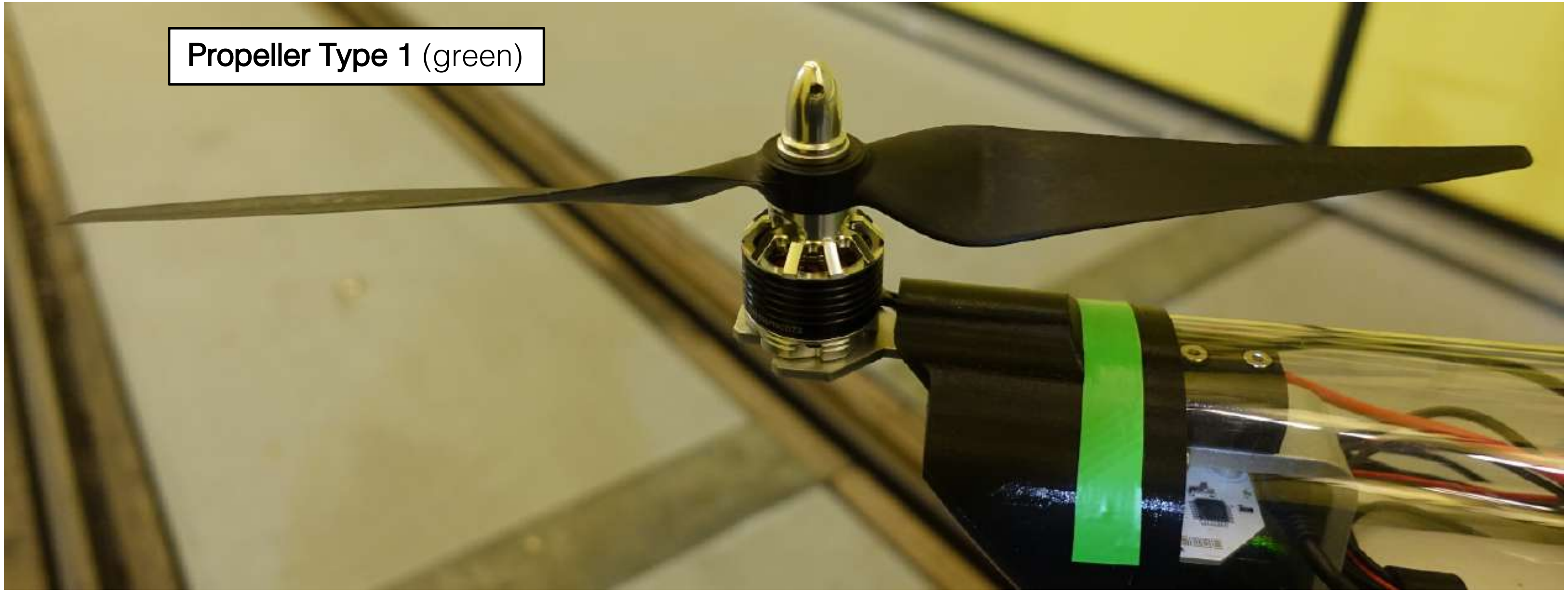
- Temperature: +5.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 µm
- LWC: 2.5
- Corresponds to thunderstorm conditions

Results Setup 1 No. 1: Cloud Impact at 5 °C



- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line, y = m*x + n)
- Voltage during load is constant at 22.5 V
- Current is constant at 5 A
- Motor speed is constant at about 5000 rpm
- Electrical power is constant at 114 W
- The measured results show **no impact** of test conditions of setup 1 on the propeller performance at 5 °C and heavy cloud

Results Setup 1 No. 1: Cloud Impact at 5 °C



- Results of visual analysis confirm no visible impact of rain droplets on propeller
- As expected from operational observations, no icing is formed under these conditions
- Under these conditions a drone will be able to fly to its full capacity

Results Setup 2 No. 2: Icing Occurrence at 2 °C

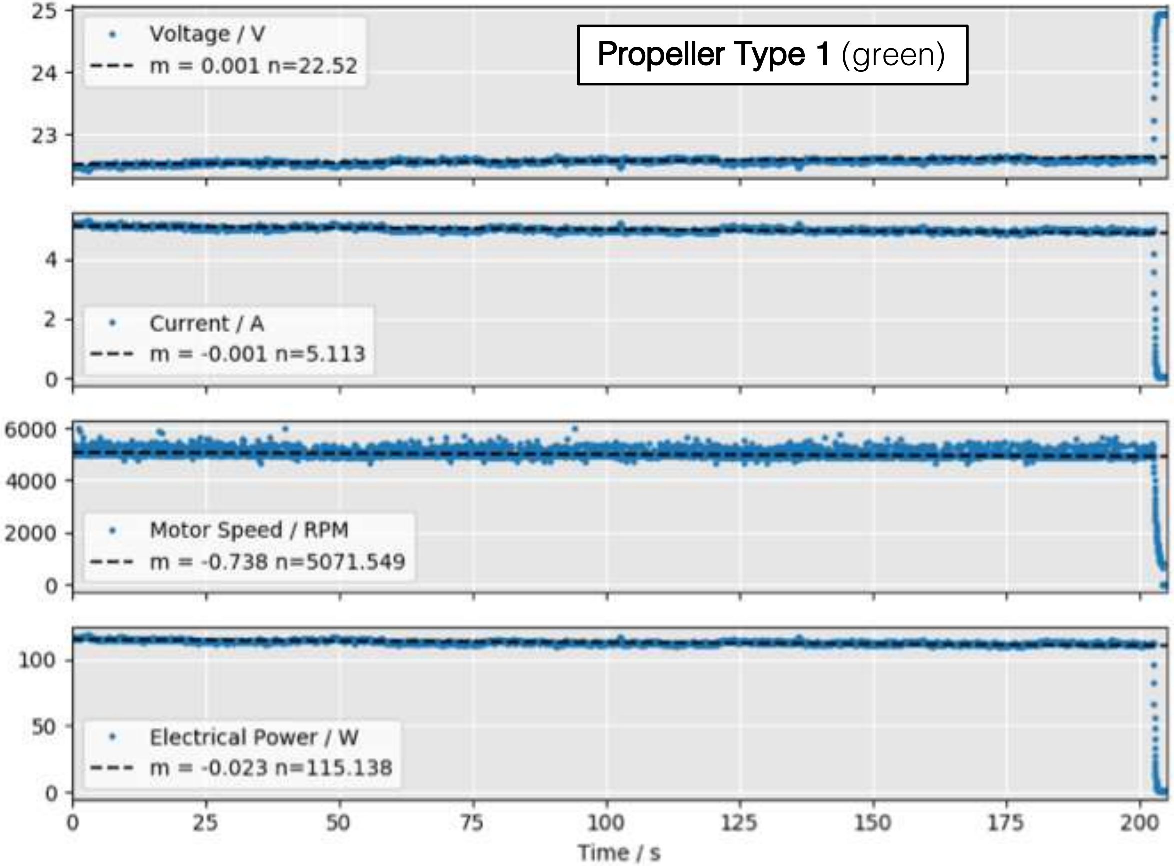
Test Case 2:

- Propeller Type 1

Environmental Conditions

- Temperature: +2.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 µm
- LWC: 2.5
- Corresponds to thunderstorm conditions

Results Setup 2 No. 2: Icing Occurrence at 2 °C



- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line, y = m*x + n)

- Voltage during load is constant at 22.5 V

- Current is constant at 5 A

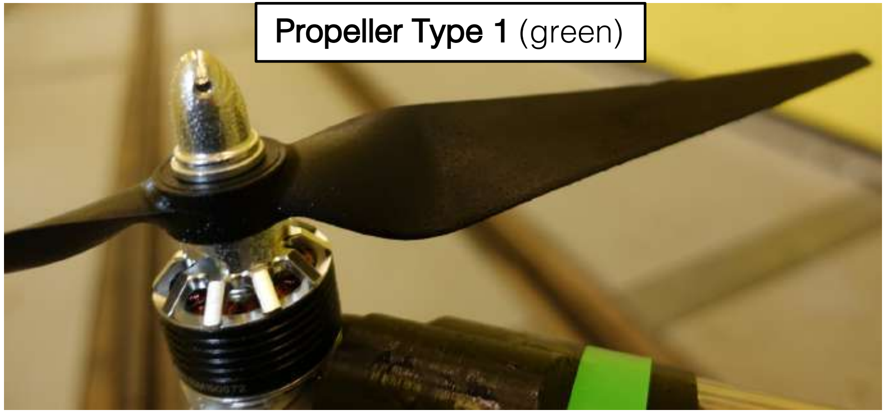
- Motor speed is constant within the error margin at about 5000 rpm

- Electrical power is constant at 115 W

- The measured results show **no significant impact** for test conditions of setup 2 on the propeller at 2 °C and heavy cloud

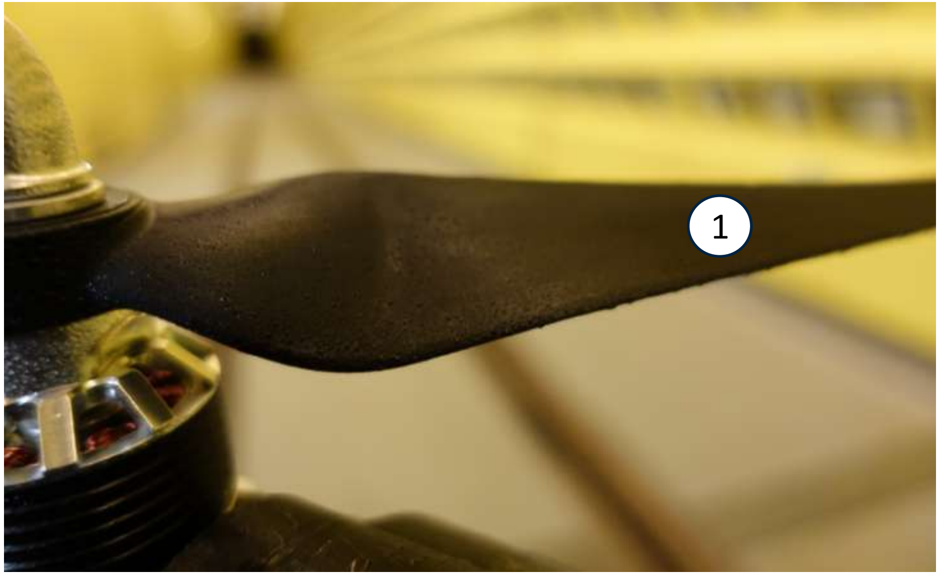
- We therefore expect no icing at temperatures above freezing level

Results Setup 2 No. 2: Icing Occurrence at 2 ºC



- No formation of icing on propeller is confirmed by visual analysis
- Propellers have been kept running for several minutes without showing any signs of icing
- Under these conditions a drone will be able to fly to its full capacity

Close up on propeller



1 – formation of rain droplets on the propeller blade due to cumulus cloud simulation

Results Setup 3.1 No. 3: Stratiform Cloud

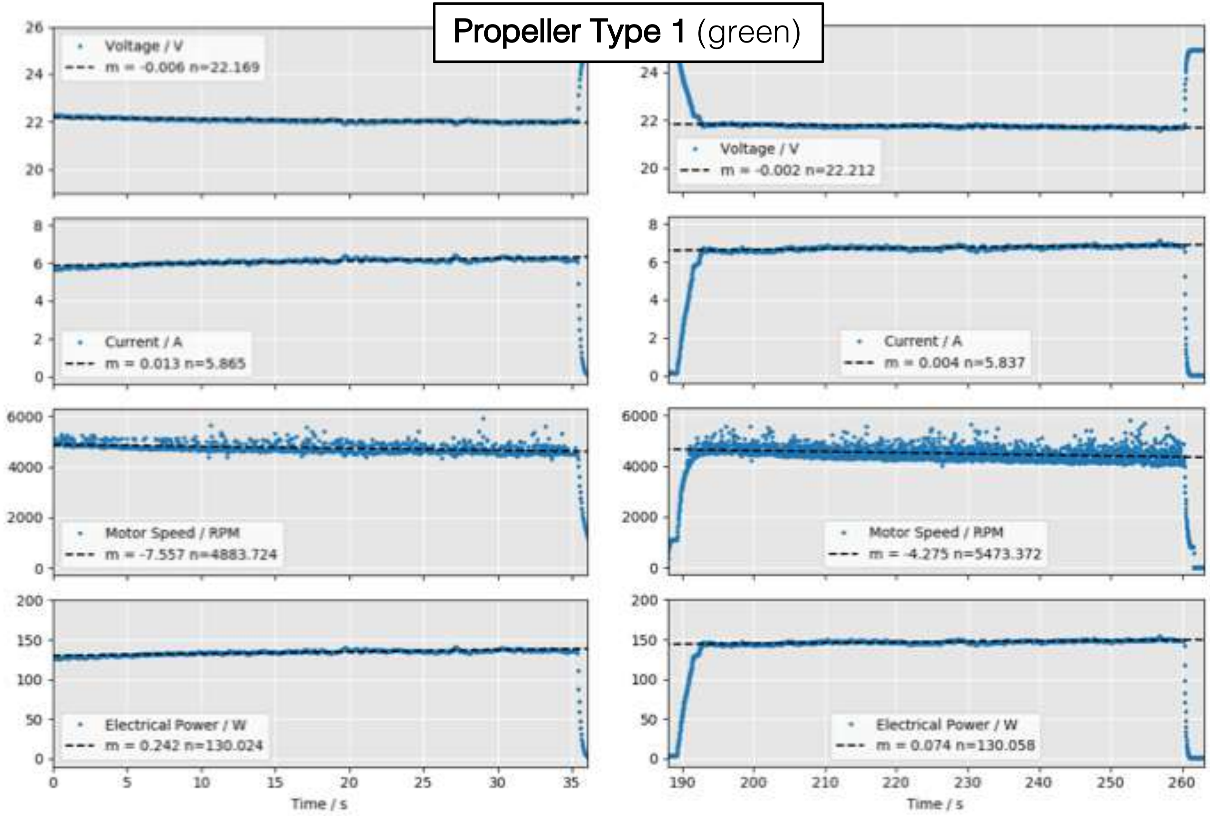
Test Case 3.1:

- Propeller Type 1
- Propeller Type 2

Environmental Conditions

- Temperature: -2.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 µm
- LWC: 0.6
- Corresponds to stratiform cloud

Results Setup 3.1 No. 3: Stratiform Cloud

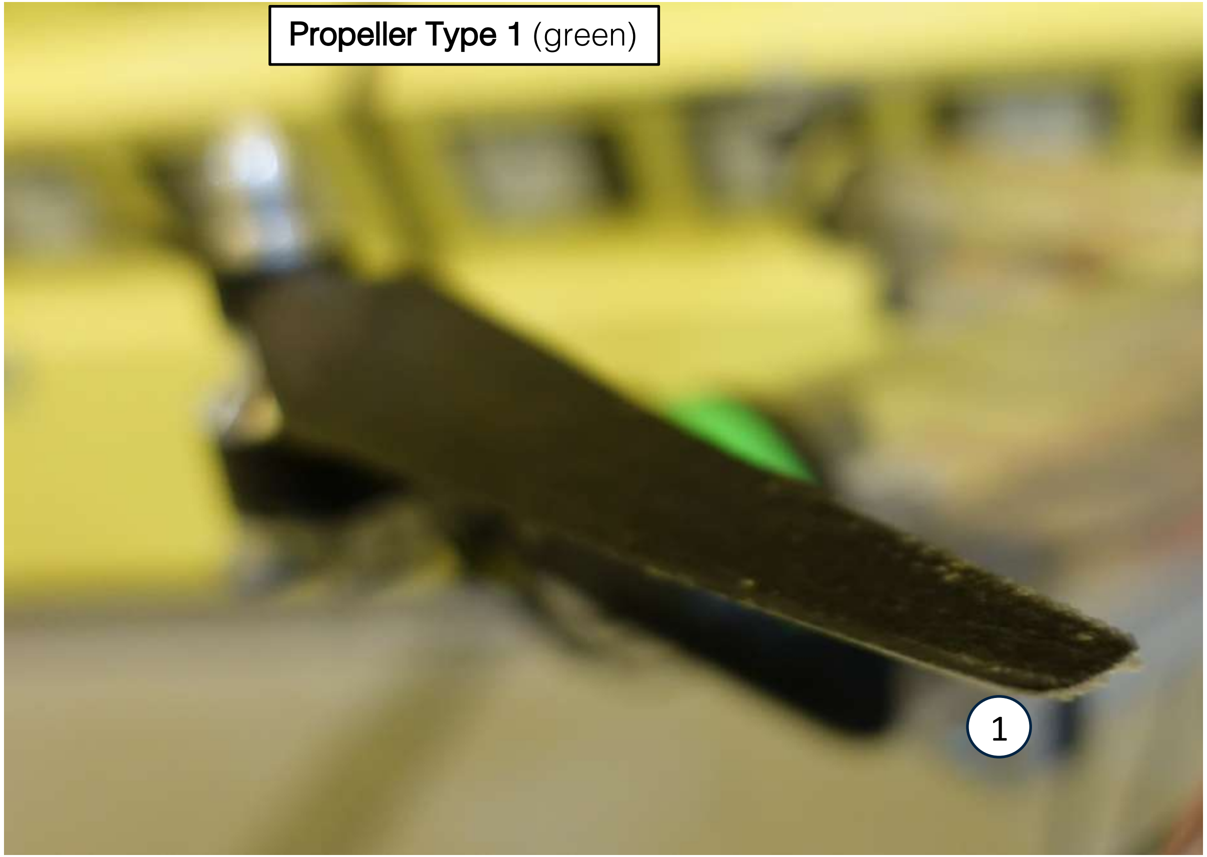


Propeller run for 30 sec

Propeller run for additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Voltage during load shows a small but constant linear drop from 22.5 to 22 V, while the current constantly rises from 6 to 7A
- Motor speed drops accordingly slightly, while the electrical power consumption rises slowly to 150W
- According to the measurements, thin ice formation is expected
- At this level, flight time of our operational drone drops by 20 %

Results Setup 3.1 No. 3: Stratiform Cloud



- Visual checks confirm a thin ice layer has formed on the propeller blade
- Ice accumulates at the blade edges
- Under these conditions a drone will still be able to fly but with a decreased range

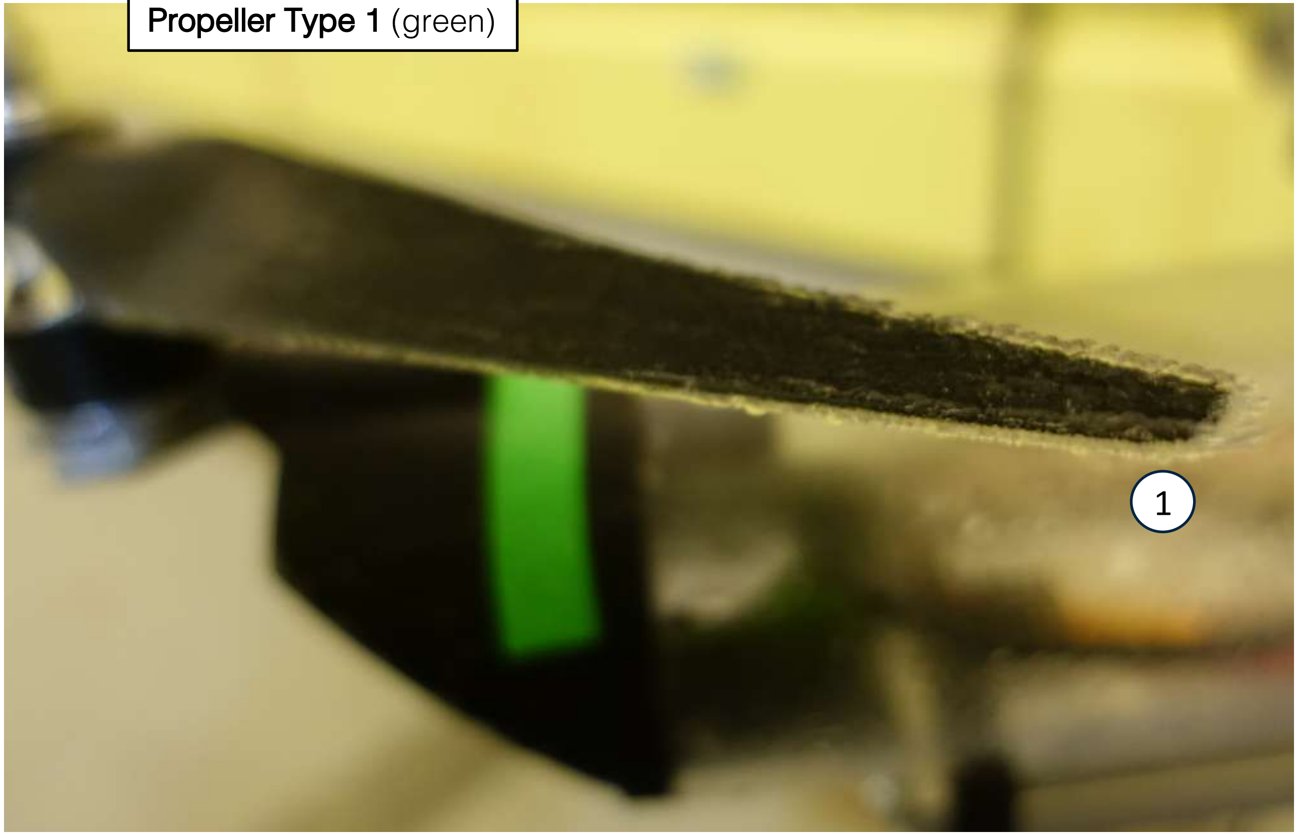
1 – after 30sec: formation of thin ice layer on propeller, stronger formation on the edges

Results Setup 3.1 No. 3: Stratiform Cloud

- After an additional 1 minute of exposure time, the ice is grown to a thicker layer on the blade
- Ice accumulates strongly at the blade edges
- Under these conditions - and given the ice amount stays roughly constant over longer exposure times - a drone has a decreased range of about 20 %.
- Though it would still be maneuverable, this limits the drone flight duration significantly

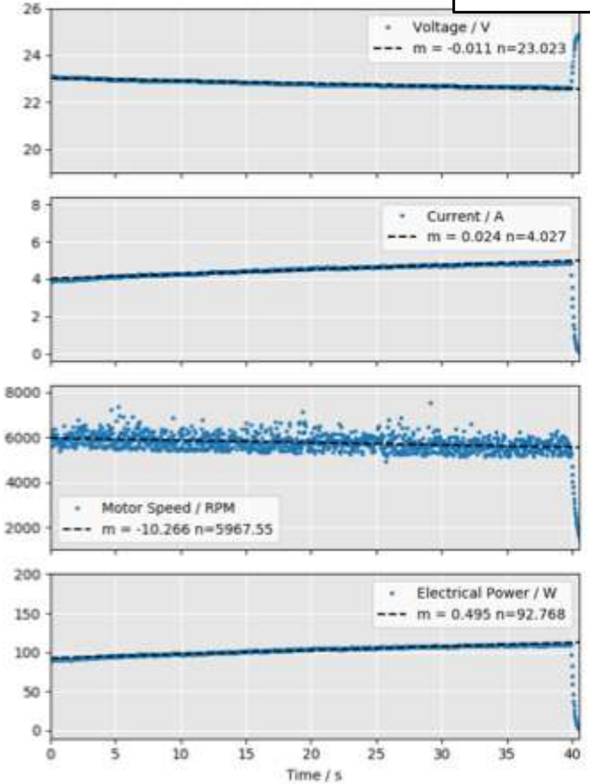
1 – icing after additional 1 min: much stronger formation of thin ice layer especially at the front and edges

Propeller Type 1 (green)

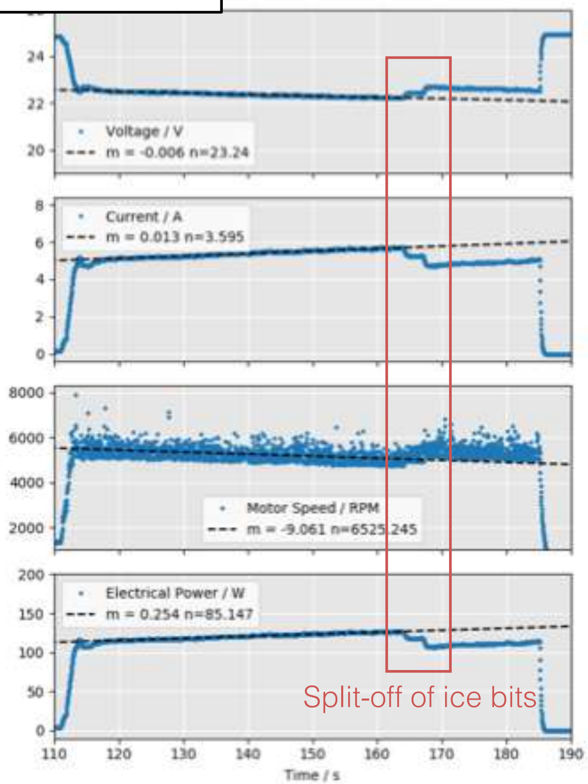


Results Setup 3.1 No. 3: Stratiform Cloud

Propeller Type 2 (yellow)



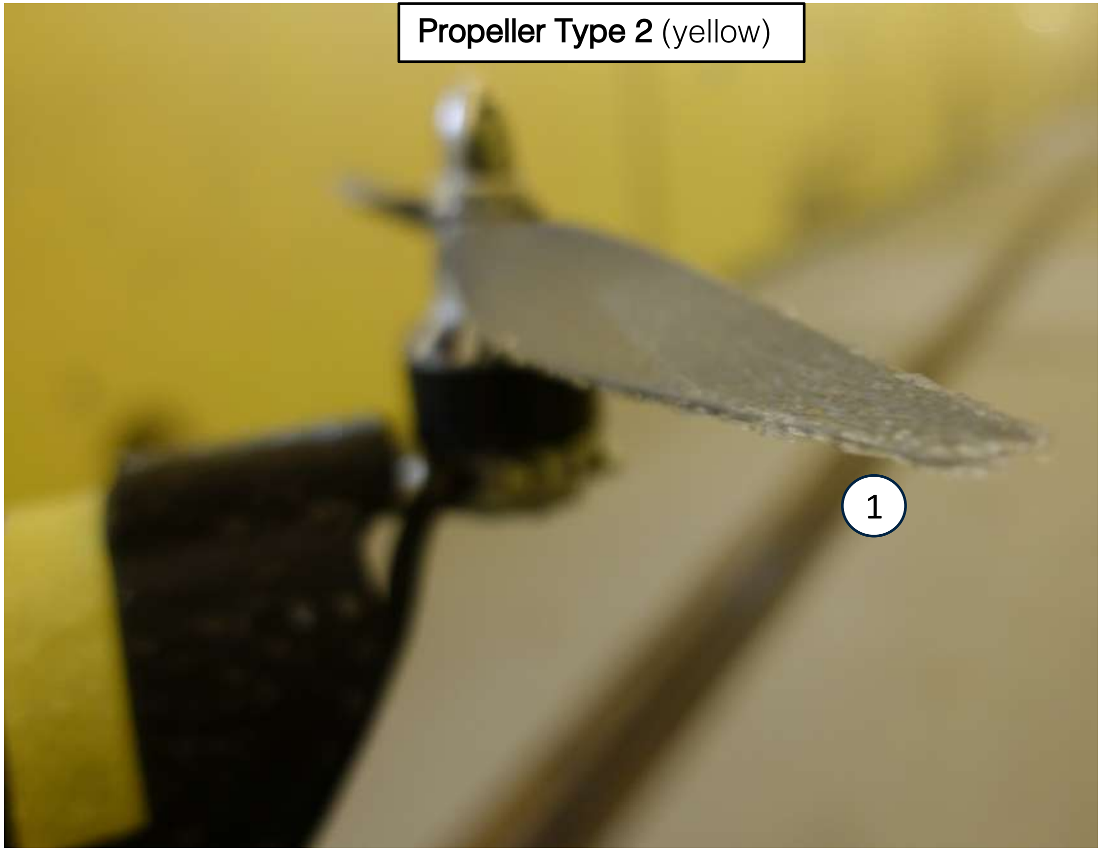
Propeller run for 30 sec



Propeller run for additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Voltage during load drops slowly but constantly and linearly from 23 to 22.5 V, while the current rises from 4 to 5.5 A
- Motor speed drops slowly from 6000 to 5000 rpm, while the electrical power rises roughly from 90 to 110 W
- The measurements show a steady rise of power consumption
- At 165 sec into the measuring time the electrical power drops abruptly, which is an indication for ice falling off from the propeller (red frame)

Results Setup 3.1 No. 3: Stratiform Cloud



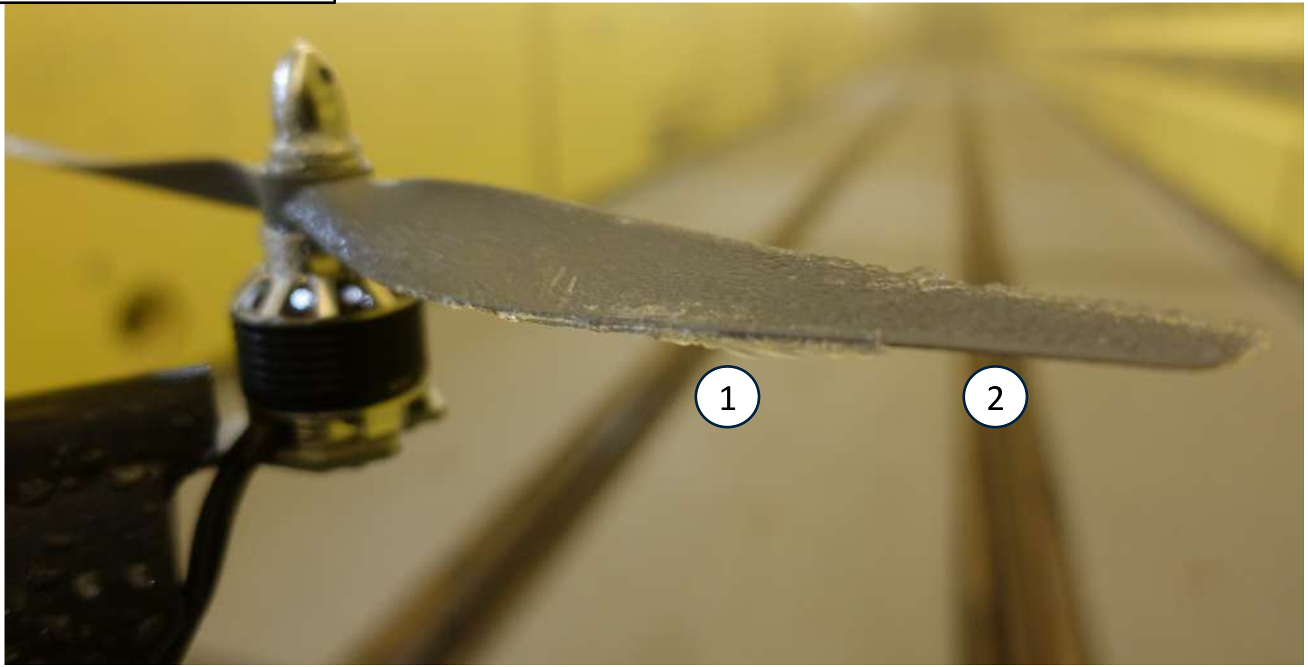
- After about 30 sec of exposure time the propeller shows clear signs of icing
- A thin ice layer forms on the blade and again a slightly stronger formation on the propeller edges
- Under these conditions a drone would still be capable of flying but to a limited range

1 – after 30sec: formation of thin ice layer stronger on the whole blade compared to Prop. Type 1

Results Setup 3.1 No. 3: Stratiform Cloud

Propeller Type 2 (yellow)

- Icing accumulates heavier after an additional minute of exposure time
- The propeller edge shows a clear sign of broken off ice at the edge (sharp and clear break point)
- Under these conditions a drone will lose about 27 % of its capacity and in consequence flight range and time is strongly limited
- However, the drone will still be maneuverable - at least for a given time - at these conditions



1 – after additional 1 min: much stronger formation of thin ice layer especially at the front and edges

2 – sharp ice edge where ice split off from the blade during rotation

Results Setup 3.1 No. 4: Cumuliform Cloud

Test Case 3.1:

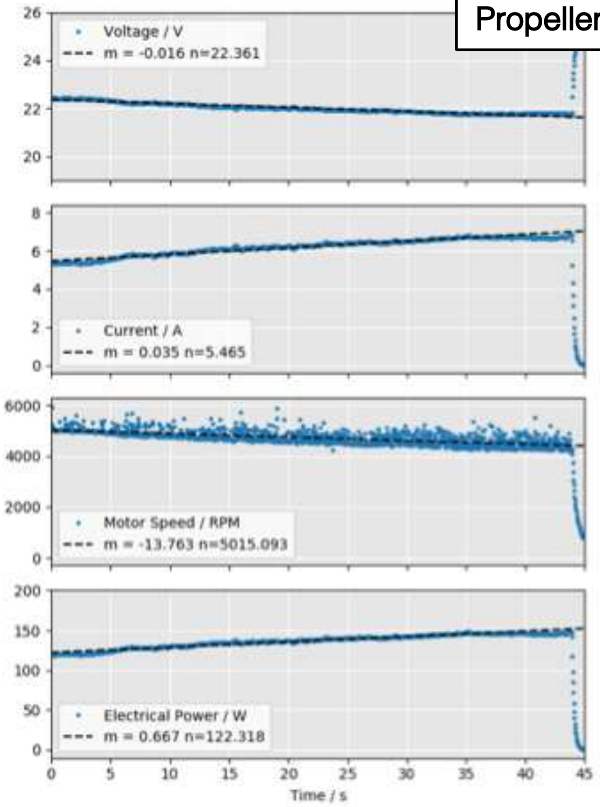
- Propeller Type 1
- Propeller Type 2

Environmental Conditions

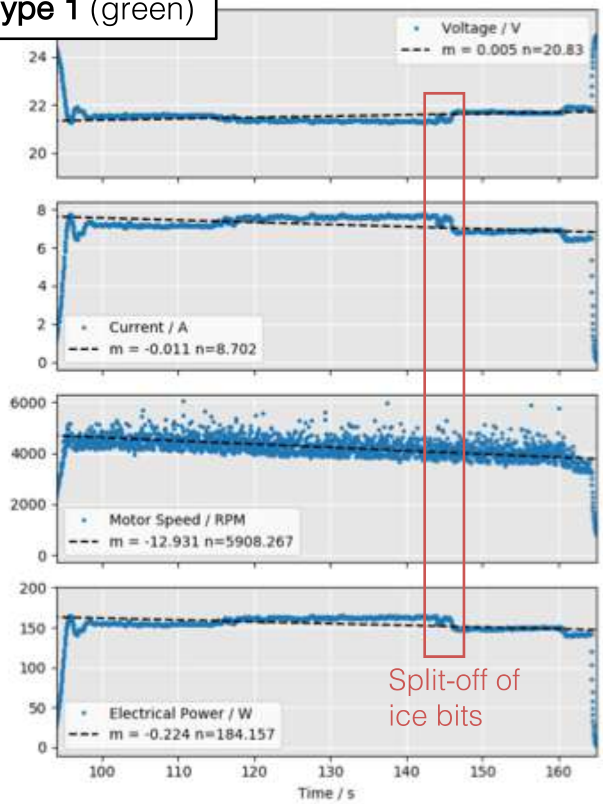
- Temperature: -2.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 μm
- LWC: 2.5
- Corresponds to thunderstorm cloud, extreme conditions

Results Setup 3.1 No. 4: Cumuliform Cloud

Propeller Type 1 (green)



Propeller run time 30 sec

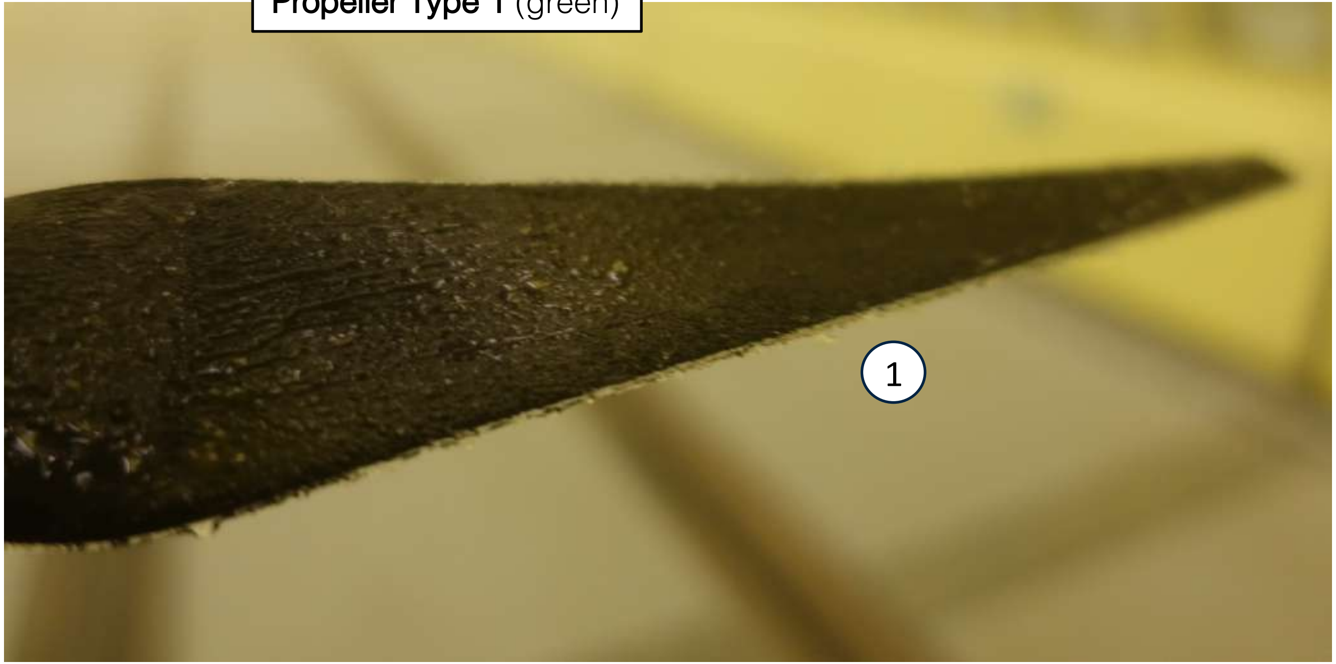


Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , $y = m*x + n$)
- During the first 30 seconds of exposure time, the voltage drops significantly faster than for stratiform clouds, which correlates to a faster ice growth; the electrical current rises accordingly
- In agreement with current and voltage, the motor speed drops, while the electrical power rises significantly – a strong sign for fast ice build up
- The results show again a sudden drop in electrical power consumption and current, which is a strong indication of split-off ice

Results Setup 3.1 No. 4: Cumuliform Cloud

Propeller Type 1 (green)

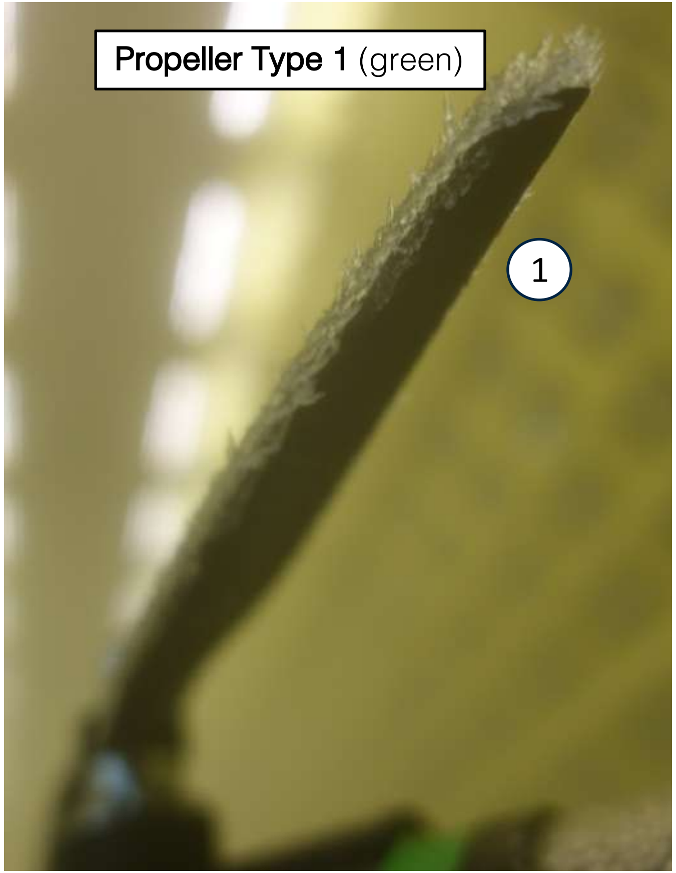


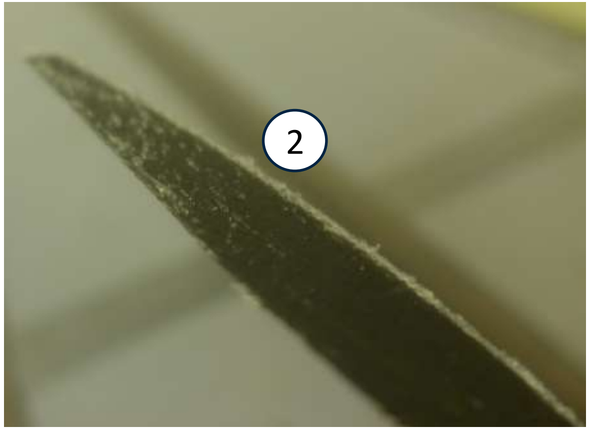
1 – after 30sec: thin ice layer covers the complete propeller with again a slightly stronger formation on the edges

- Thin layer of icing covers the whole propeller rather evenly
- The edges show an increased growing speed for the ice and therefore start to accumulate more ice mass
- Although such a layer of icing deteriorates the flight properties noticeably, controlled flying would still be possible

Results Setup 3.1 No. 4: Cumuliform Cloud

- Heavy formation of ice on propeller blade after an additional 1 min of exposure time
- The dynamics of ice growth show enhanced kinetics at the edges
- Clear break point on the other side of propeller where ice flew off during rotation
- Under these conditions a drone's capacity will be drastically reduced by about 30 % and maneuverability is in question



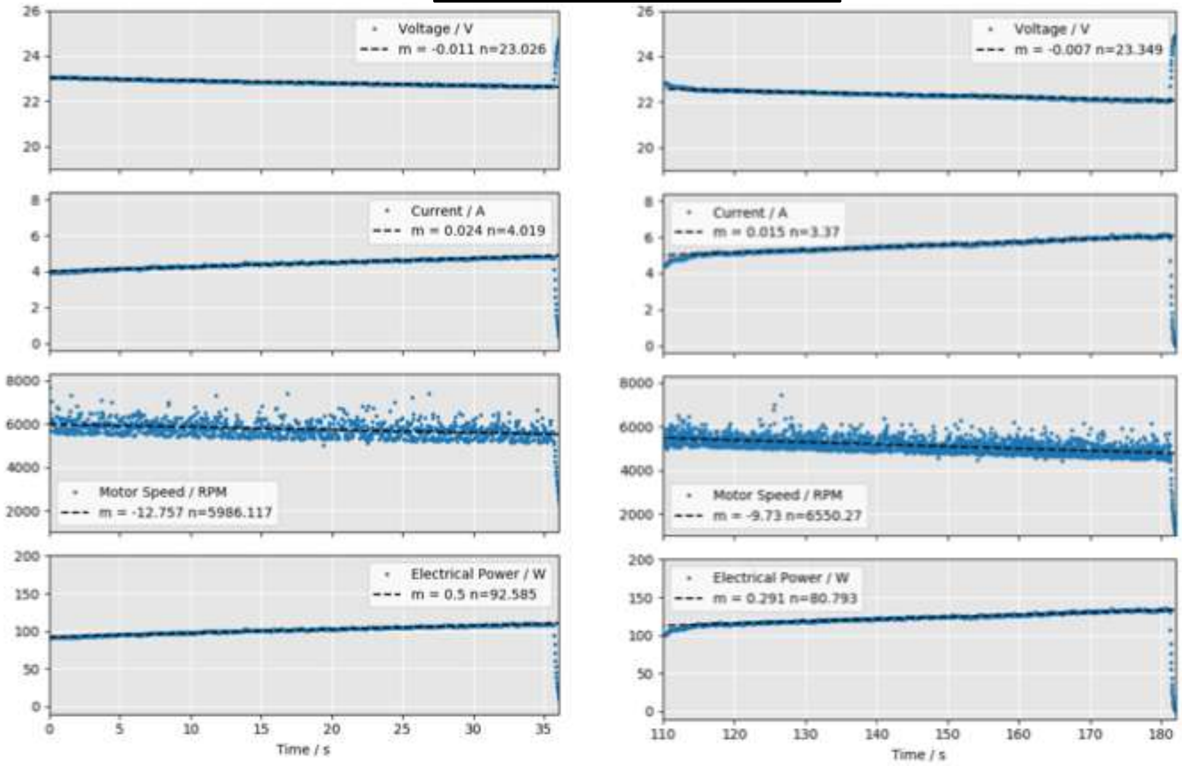


1 – heavy icing, strongly developed at the edges, growing lengthily towards the centrifugal force

2 – the clean edge shows signs of ice breakup on other side of propeller

Results Setup 3.1 No. 4: Cumuliform Cloud

Propeller Type 2 (yellow)

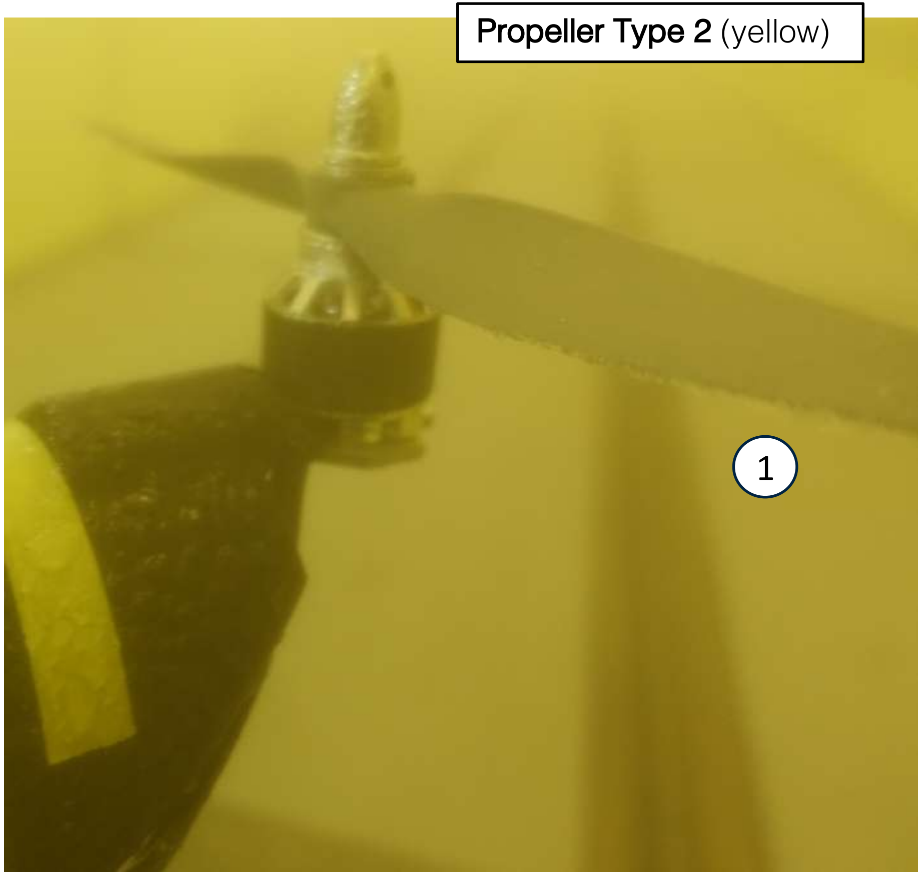


Propeller run time 30 sec

Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Voltage during load drops constantly and linearly from 23 to 22 V, while the current rises steadily from 4 to about 6 A
- In consequence the electrical power consumption rises from about 90 to 130 W, while the motor speed drops at the same time from an average 6000 to an average 5000 rpm
- The measured results show a large impact on the flight properties

Results Setup 3.1 No. 4: Cumuliform Cloud



- Substantial formation of ice after about 30 sec with a strongly increased growth for an additional 1 min exposure time
- Ice growth is proceeding slowly on the propeller blade and heavily on the exposed propeller edges
- Under these conditions a drone's capacity to fly will be reduced by at least 30 % assuming maneuverability is still given

1 – after 30sec: as before formation of thin ice layer especially on the edges

Results Setup 3.1 No. 5: Cumuliform Cloud

Test Case 3.1:

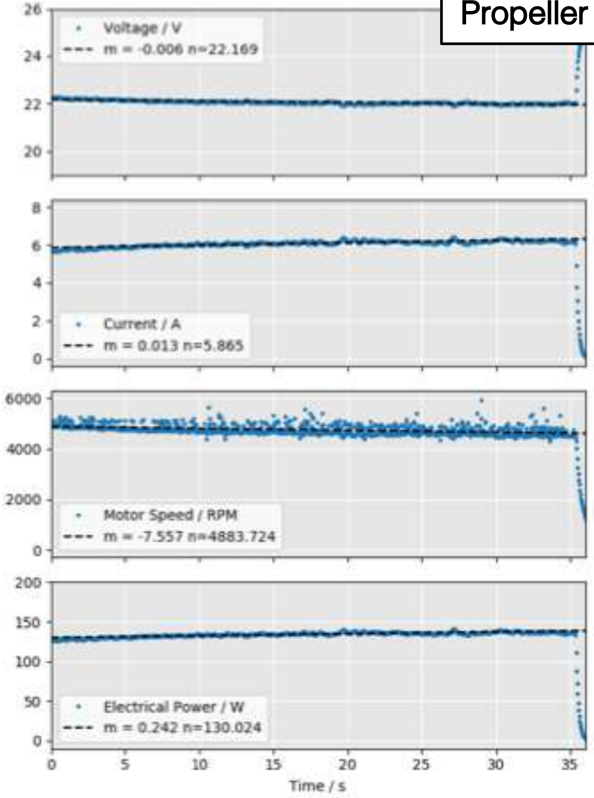
- Propeller Type 1
- Propeller Type 2

Environmental Conditions

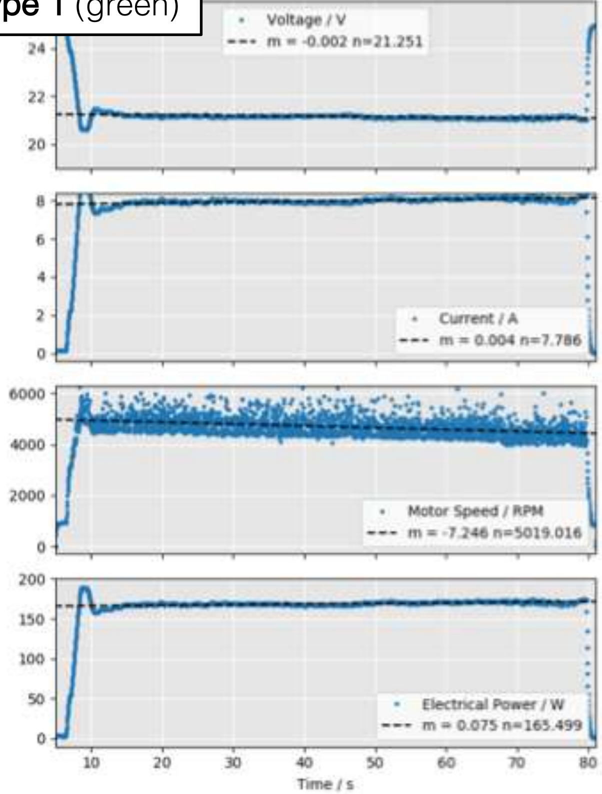
- Temperature: -2.0 °C
- Wind Speed: 10.0 m/s
- MVD: 40 µm
- LWC: 0.85
- Corresponds to medium conditions

Results Setup 3.1 No. 5: Cumuliform Cloud

Propeller Type 1 (green)



Propeller run time 30 sec



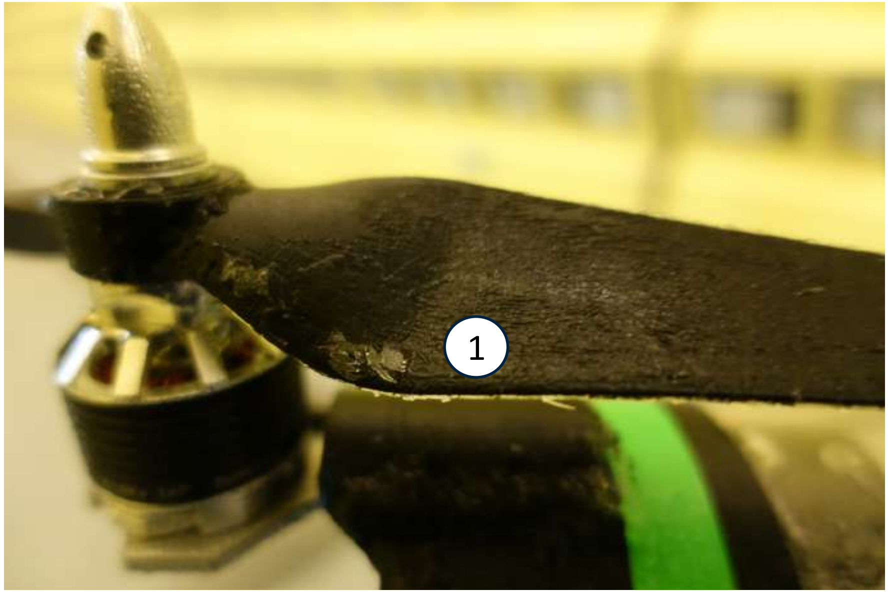
Propeller run time additional 1 min

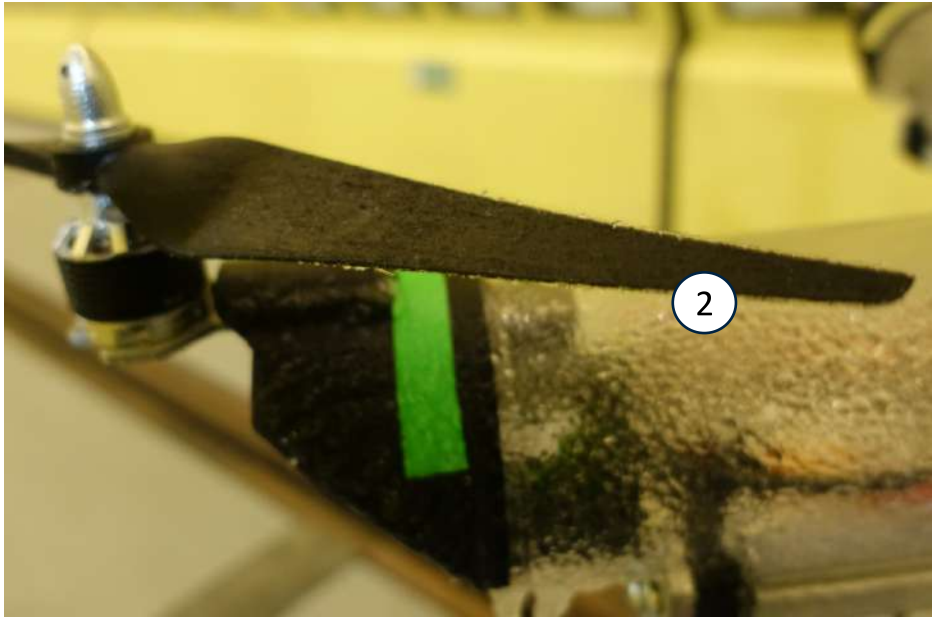
- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- The measured voltage during load falls from 22.5 to 21 V, while the current increases at the same time from 5.5 to about 8 A
- Due to icing the average motor speed is reduced significantly from 5000 to above 4000 rpm, while the electrical power consumption rises from 115 to about 170 W
- The measured results show significant impact on propeller performance by icing
- The spread in the propeller speed increases strongly indicating an unstable flight

Results Setup 3.1 No. 5: Cumuliform Cloud

- Only a thin layer of ice forms after 30 sec of exposure to the cumuliform cloud with larger ice particles but lower water content

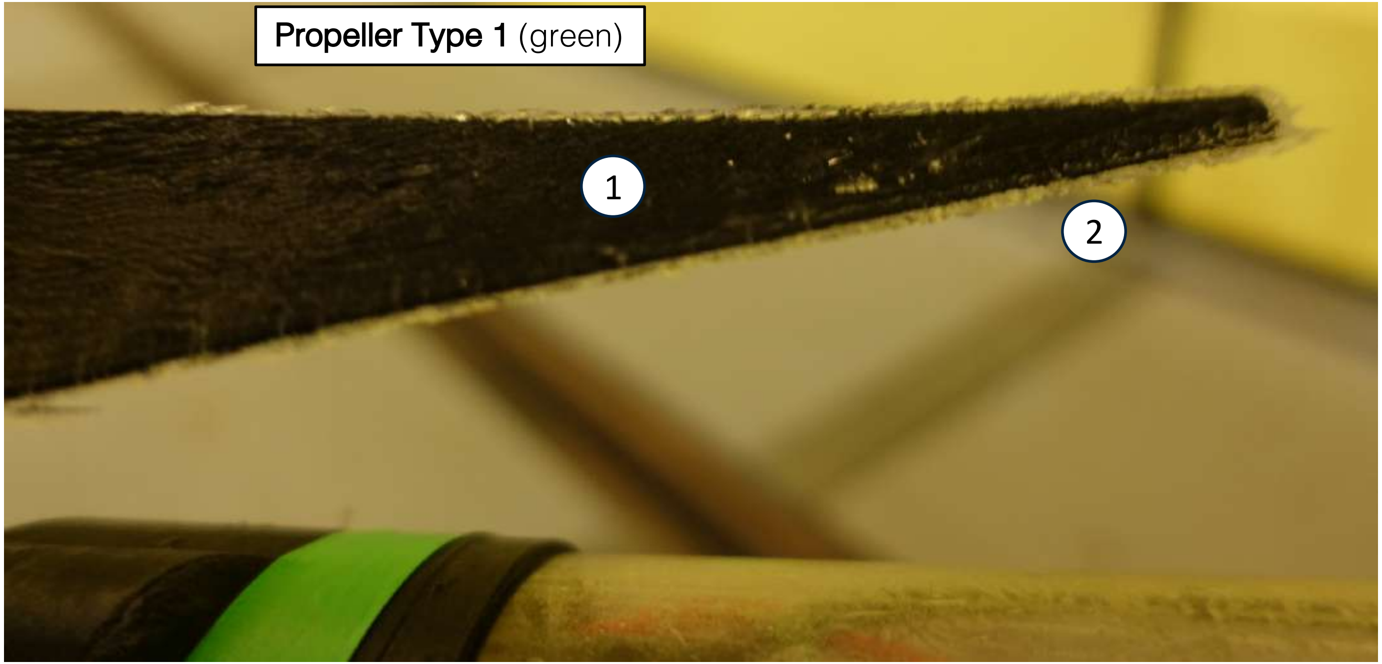
Propeller Type 1 (green)





1 – after 30 sec: fine thin layer of ice on propeller blade
2 – only thin formation of ice at the edges

Results Setup 3.1 No. 5: Cumuliform Cloud

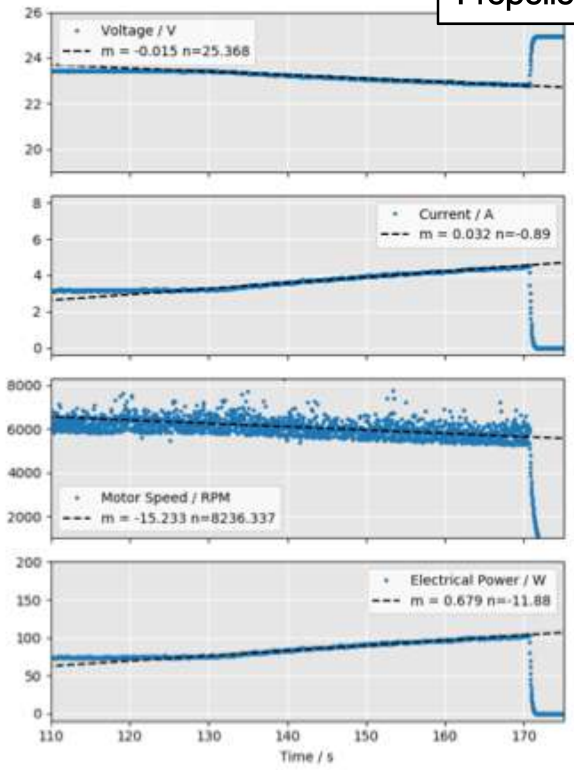


1 – after additional 1 min: thicker ice layer forms on the propeller and 2 - accumulates on the edges

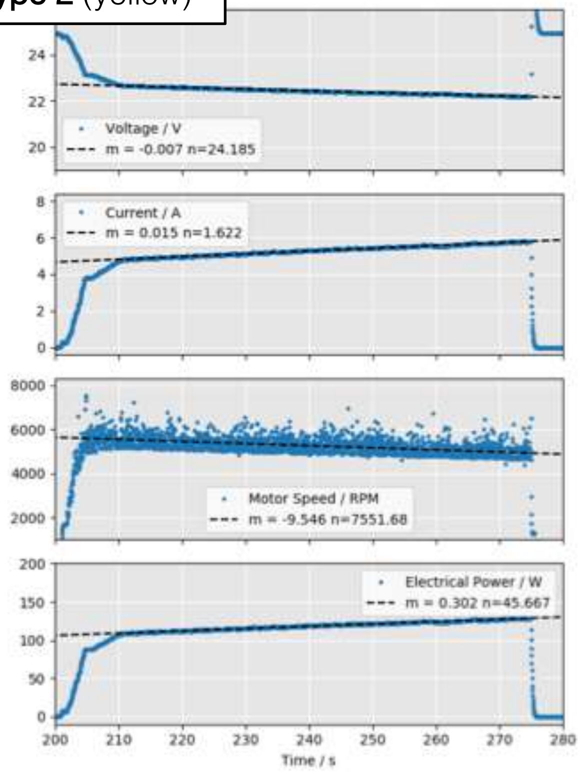
- Thickened layer of ice forms on top of propeller blade
- Growth kinetics is again much higher at the propeller edges
- These conditions will lead the drone to demand at least 30 % more power and with unclear consequences to controllability

Results Setup 3.1 No. 5: Cumuliform Cloud

Propeller Type 2 (yellow)



Propeller run time 30 sec



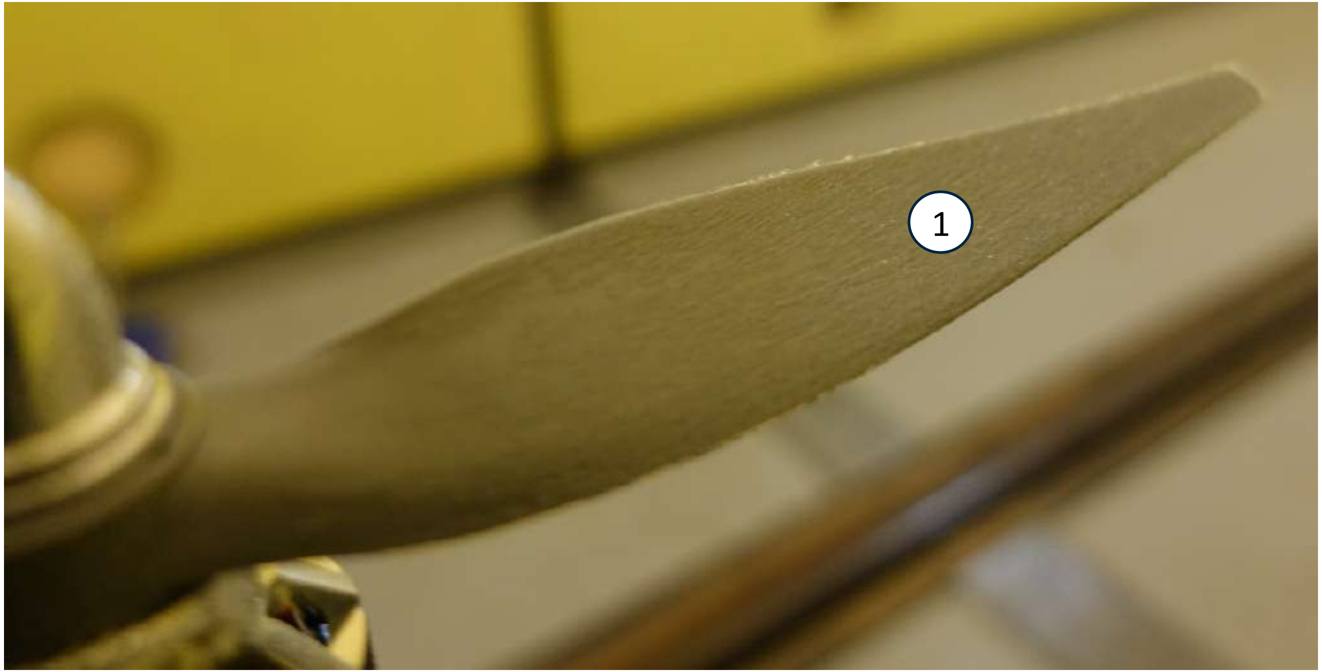
Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- The measurements show a linear drop of voltage from 23.5 to about 22 V, while the current rises compared to the background measurement from 3.5 to about 6 A
- The motor speed decreases steadily from average 6000 to 5000 rpm, while the electrical power is steadily increasing with the amount of accumulated ice
- While the aircraft might still be operable, its performance decreases rapidly with ice amount

Results Setup 3.1 No. 5: Cumuliform Cloud

- After 30 sec a thin layer of ice growth slowly and evenly on top of propeller blade
- The growth is slowly but uniformly and steadily proceeding

Propeller Type 2 (yellow)

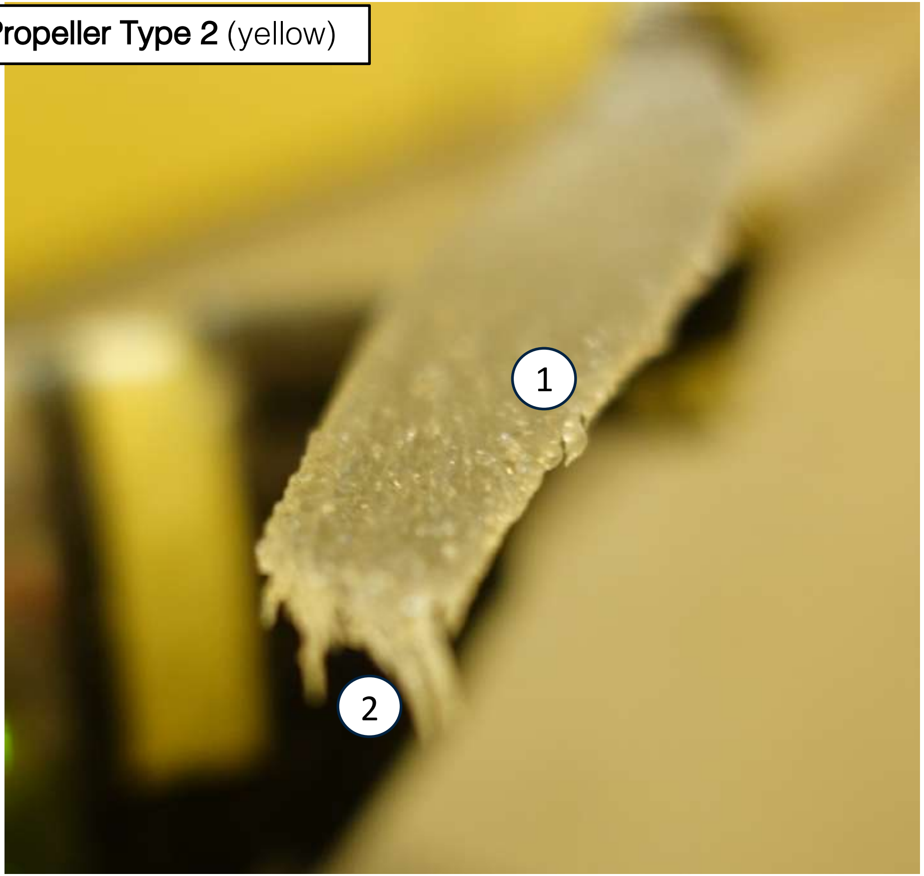


1 – after 30 sec: formation of only very thin layer of ice on propeller blade

Results Setup 3.1 No. 5: Cumuliform Cloud

- Formation of total ice cover on propeller as a layer
- Formation of ice needles at the tip of the propeller after another one minute of exposure time
- Under these conditions a drone’s capacity – if still maneuverable – is drastically reduced by about 50 %

Propeller Type 2 (yellow)



1 – after additional 1 min: thick ice layer grows on the propeller blade and **2** - accumulates to long needles on the edges

Results Setup 3.1 No. 6: Stratiform Cloud

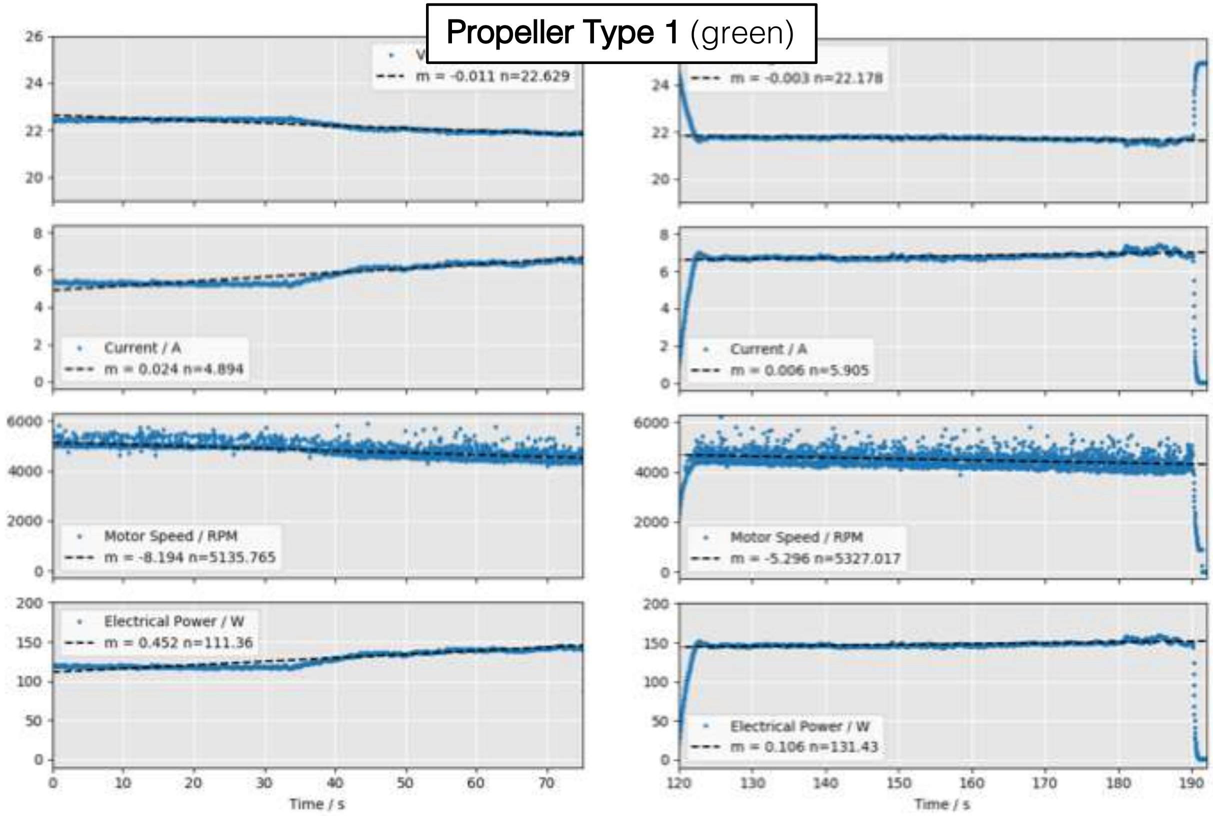
Test Case 3.1:

- Propeller Type 1
- Propeller Type 2

Environmental Conditions

- Temperature: -5.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 µm
- LWC: 0.5
- Corresponds to stratiform cloud

Results Setup 3.1 No. 6: Stratiform Cloud



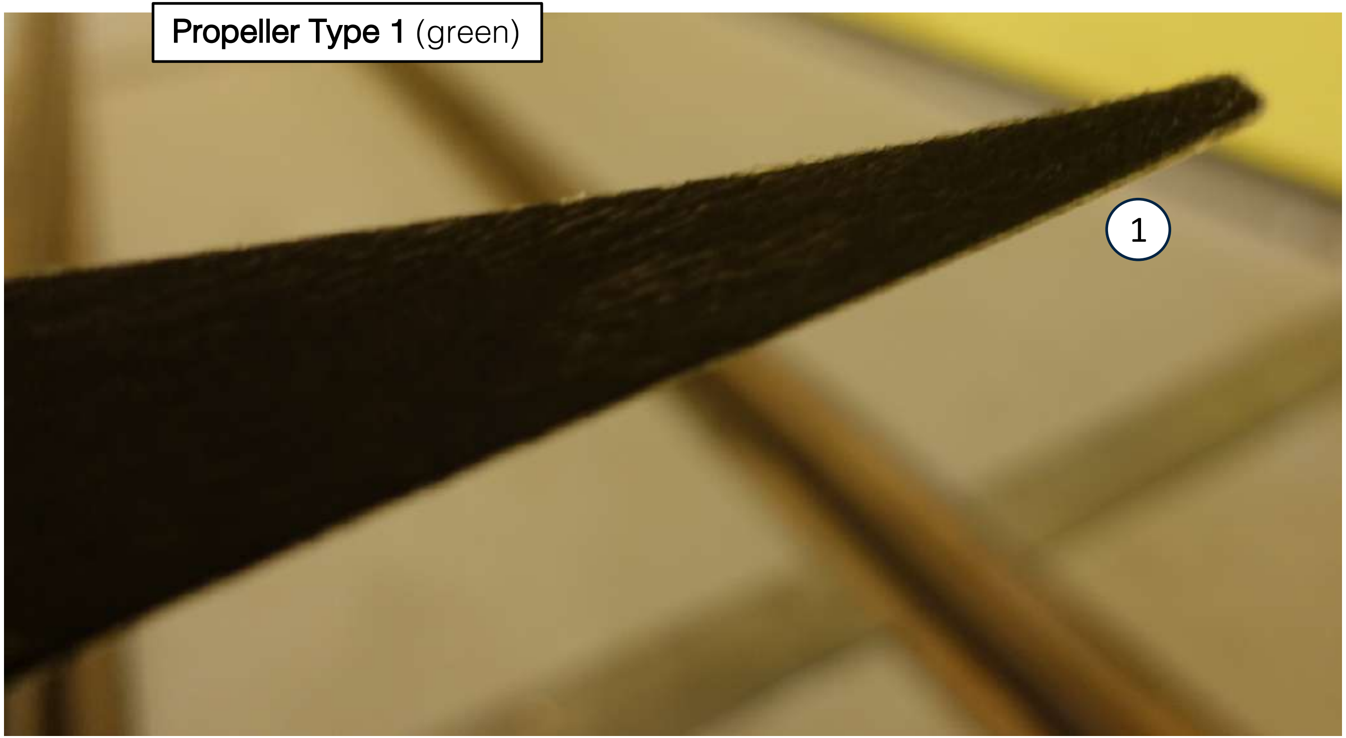
Propeller run time 30 sec

Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- The voltage drops significantly compared to background measurements (0-35 s), while the current increases accordingly
- As before the motor speed is steadily decreasing with an increased speed variation leading to a less stable flight
- Electrical power rises abruptly compared to background measurement to about 150 W
- The results show significant impact by the icing, yet less so than for cumuliform clouds

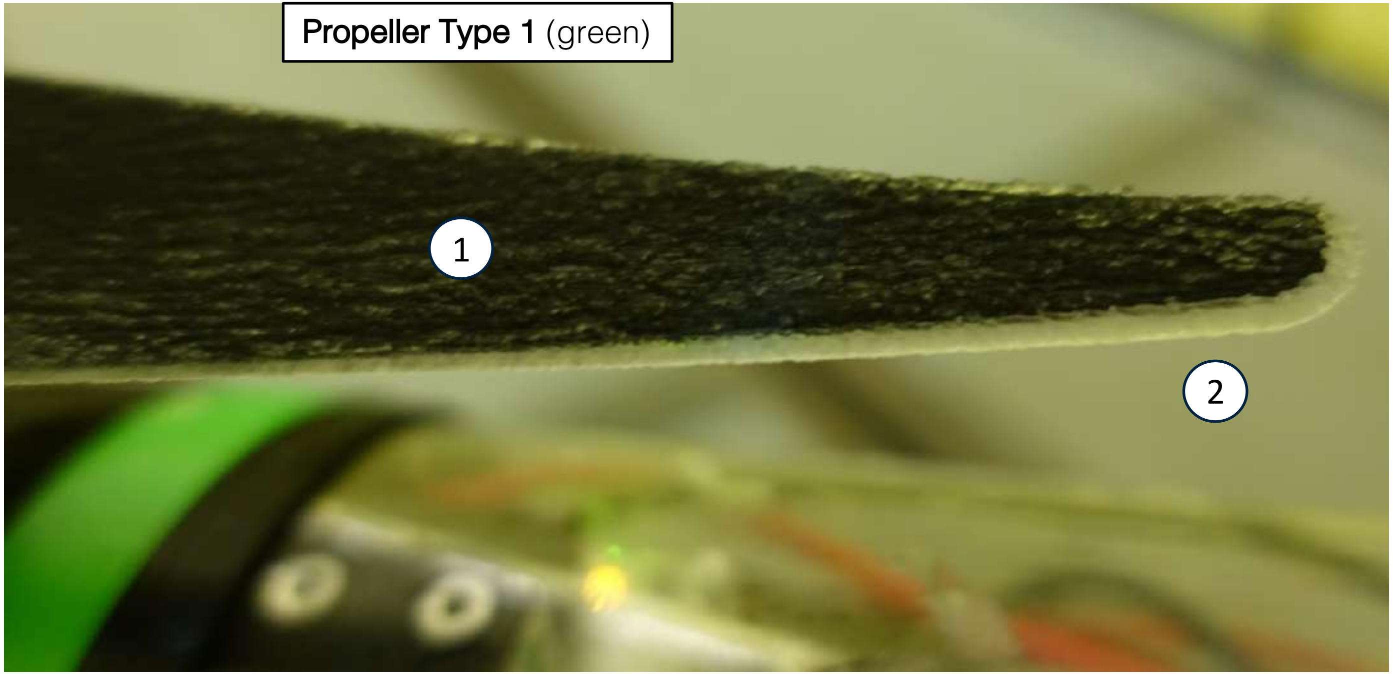
Results Setup 3.1 No. 6: Stratiform Cloud

- Thin layer of ice grows on top of propeller blade
- Thin rounded ice grows at the edge of the propeller for stratiform cloud with small LWC amount



1 – after 30 sec: only thin ice layer forms on propeller blade with a thin rounded ice edge on the propeller edges.

Results Setup 3.1 No. 6: Stratiform Cloud

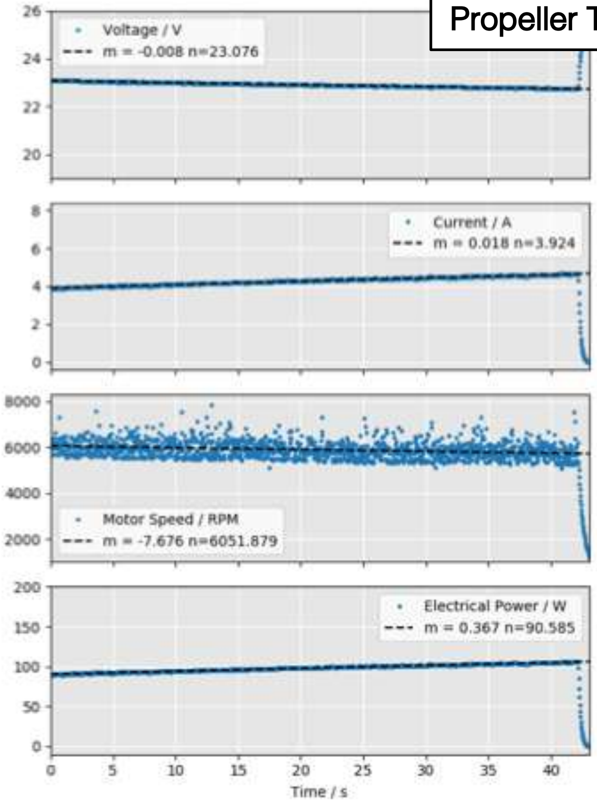


1 – after additional 1 min: thicker ice layer forms on the propeller and again **2** - accumulates on the edges more rapidly towards centrifugal forces

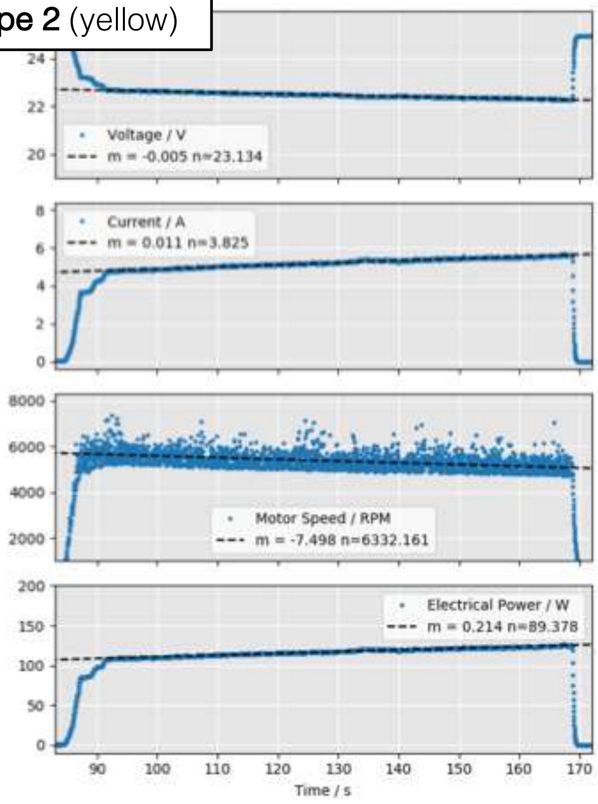
- Strong formation of ice although growth is slower than for cumuliform clouds
- Ice edge grows to a rounded edge
- Under these conditions a drones range is reduced by more than 25 % and flight controllability will decrease with time

Results Setup 3.1 No. 6: Stratiform Cloud

Propeller Type 2 (yellow)



Propeller run time 30 sec



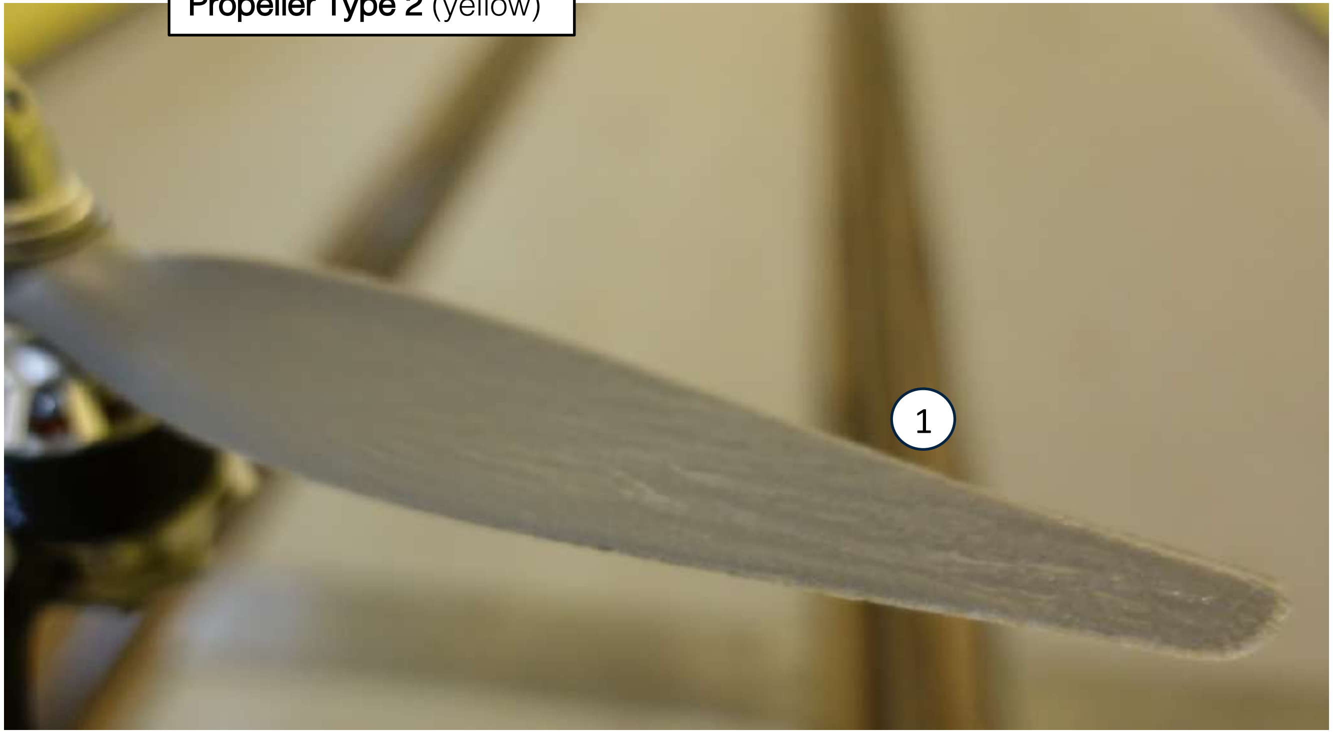
Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- The measurements show a clear drop in voltage with an increase in current, which – as shown before – is a clear sign of icing
- The motor speed decreases steadily from 6000 to 5000 rpm on average, while the electrical power consumption rises linearly up to about 130 W
- Although the impact of icing is severe, the drone will likely be still maneuverable, however for a strongly reduced time

Results Setup 3.1 No. 6: Stratiform Cloud

- Uniform formation of ice on propeller blade after about 30 sec of exposure time
- Ice grows evenly over the whole propeller with a slightly enhanced growth rate at the propeller tips

Propeller Type 2 (yellow)

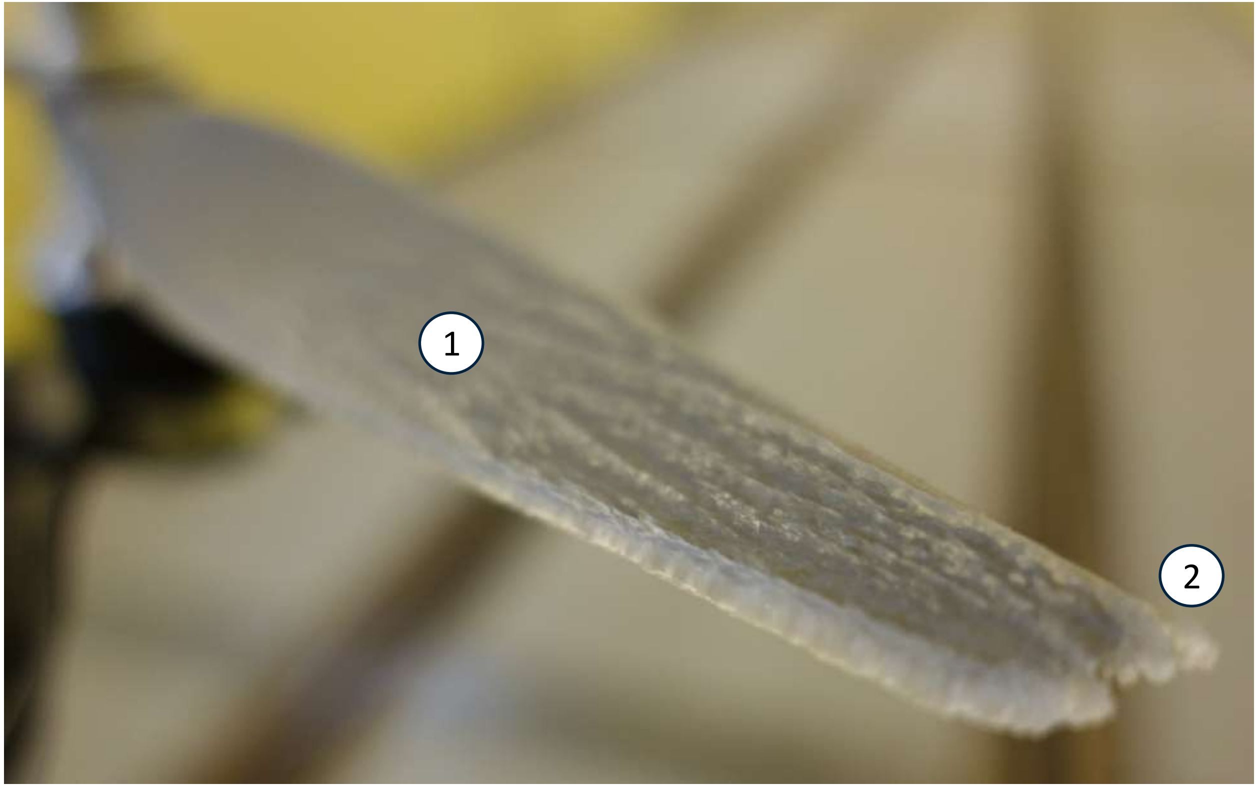


1 – after 30 sec: formation of thin layer of ice on propeller blade

Results Setup 3.1 No. 6: Stratiform Cloud

Propeller Type 2 (yellow)

- Thick layer of ice grows on the propeller blade leading to reduced flight performance
- While the drone might still be operational the performance time is greatly reduced by about 40 %
- Under these conditions an aircraft will only fly for a certain amount of time, however, the exact flight behavior would need to be evaluated



1 – after additional 1 min: thick ice layer grows on the propeller blade and **2** – accumulates on the blade edges

Results Setup 3.1 No. 7: Cumuliform Cloud

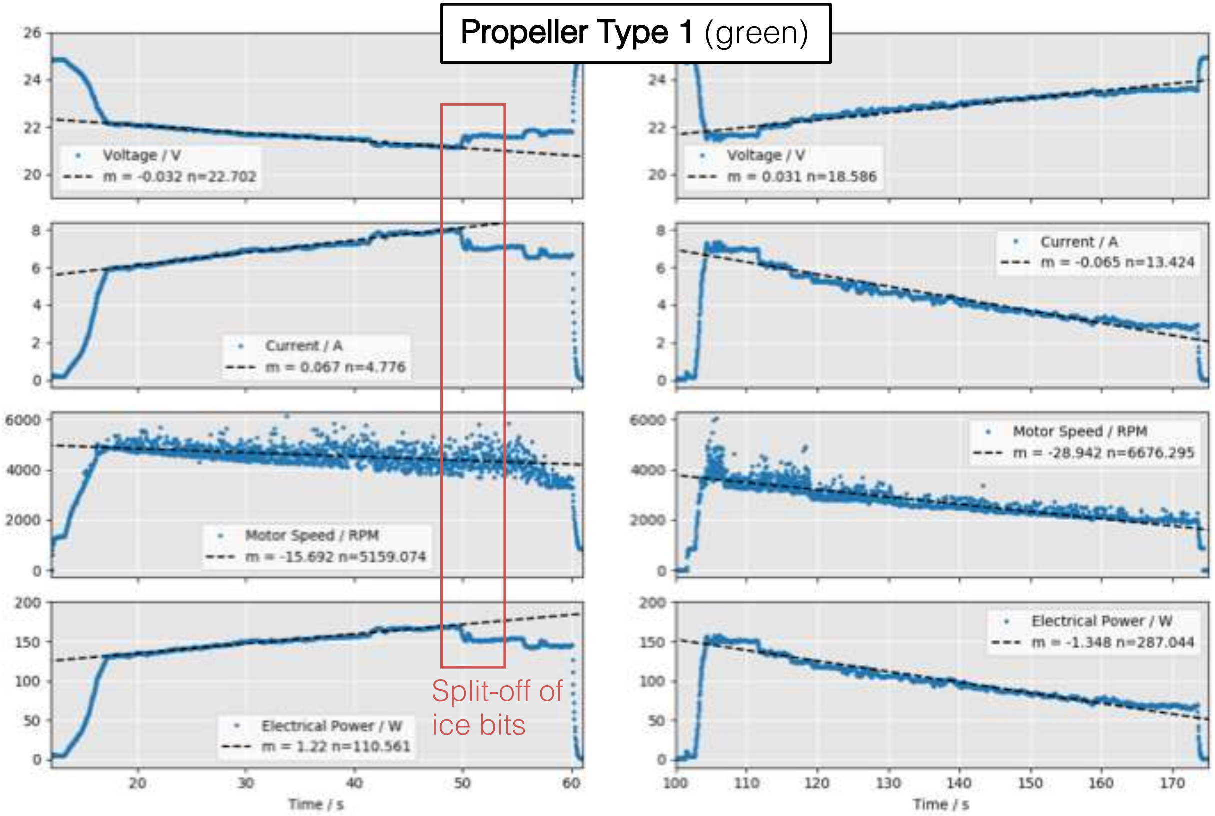
Test Case 3.1:

- Propeller Type 1
- Propeller Type 2

Environmental Conditions

- Temperature: -5.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 µm
- LWC: 2.3
- Corresponds to thunderstorm cloud, extreme conditions

Results Setup 3.1 No. 7: Cumuliform Cloud



Propeller run time 30 sec

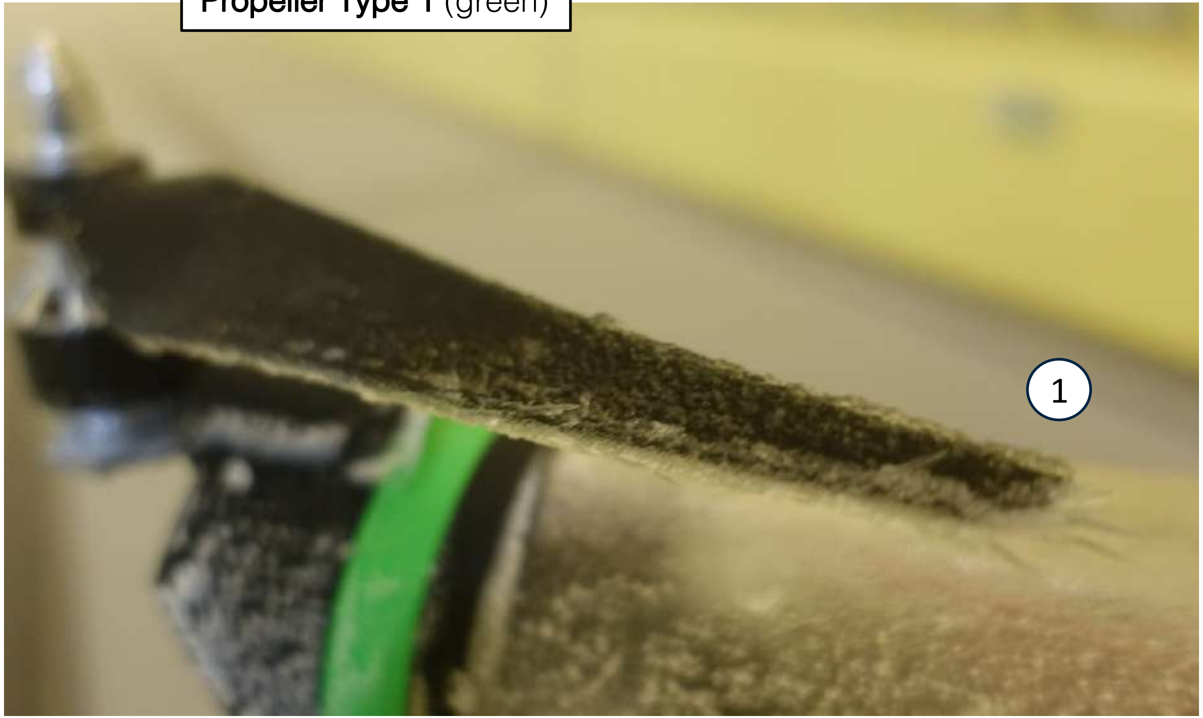
Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- The voltage first drops massively and increases again for the additional 1 min exposure time, while the current behaves reciprocal
- The motor speed decreases constantly and rapidly, while at the same time the power first rises trying to overcome the resistance due to icing but then surrenders and drops within seconds
- In these conditions flying is impossible after only about 30 sec of flight time the system will shut down and a return is inevitable

Results Setup 3.1 No. 7: Cumuliform Cloud

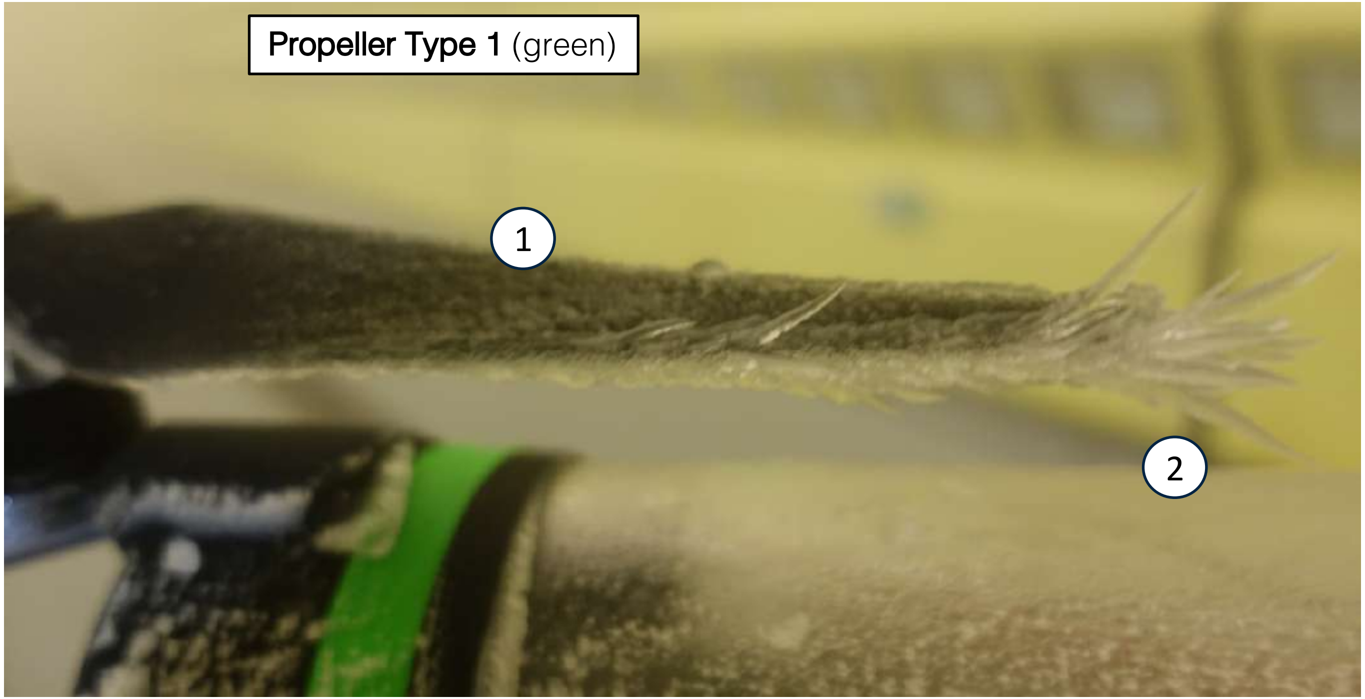
- After only 30 sec of exposure time long ice needles grow at the tip of the propeller interfering strongly with flight performance
- Ice needles might break from time to time, but new ice accumulates rapidly again
- Propeller blades are heavily covered in ice

Propeller Type 1 (green)



1 – after 30 sec: heavy formation of ice with long needles at the propeller tip, that break easily from time to time

Results Setup 3.1 No. 7: Cumuliform Cloud

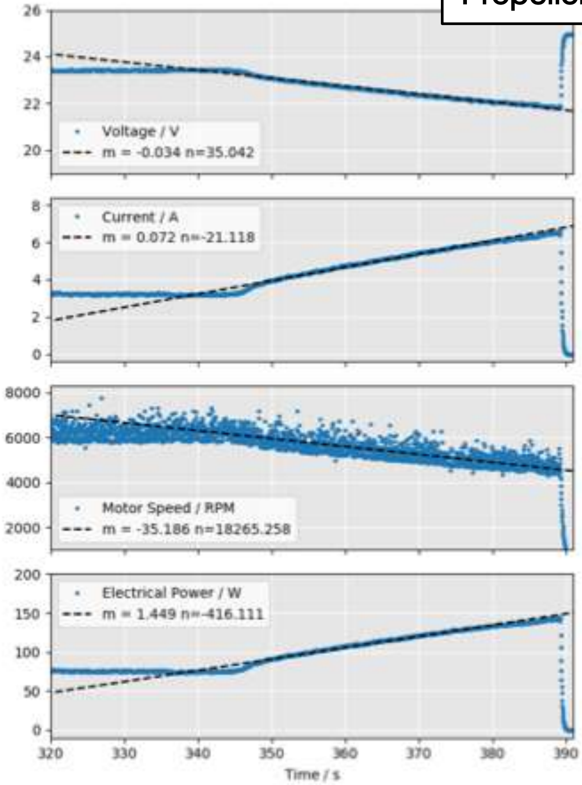


1 – after additional 1 min: thicker ice layer forms on the propeller and **2** – ice/water run-off at the tip forms beautiful needle patterns

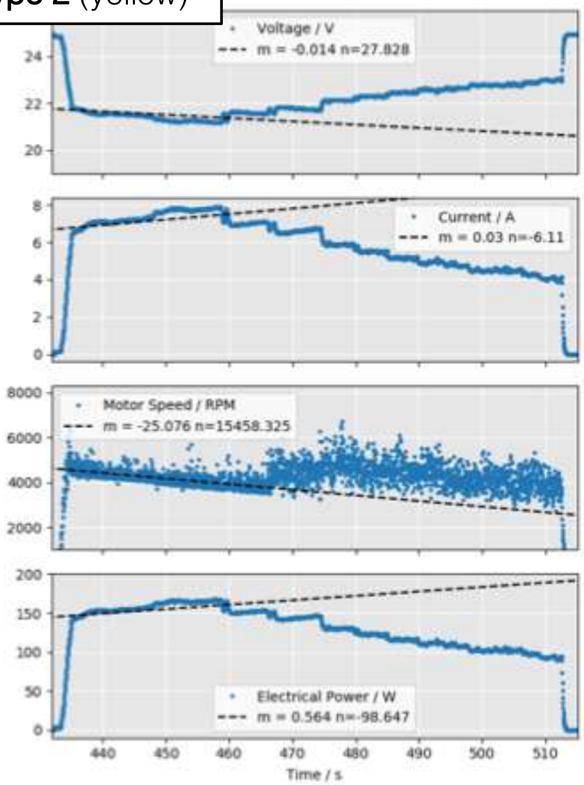
- The largest amount of ice seen so far is formed after only another additional minute of exposure to the thunderstorm-like cloud conditions
- Beautiful – but for flight performance deadly – long needles form at the propeller tip
- Under these conditions a drone operator has about 30 secs before he will lose control over the system

Results Setup 3.1 No. 7: Cumuliform Cloud

Propeller Type 2 (yellow)



Propeller run time 30 sec



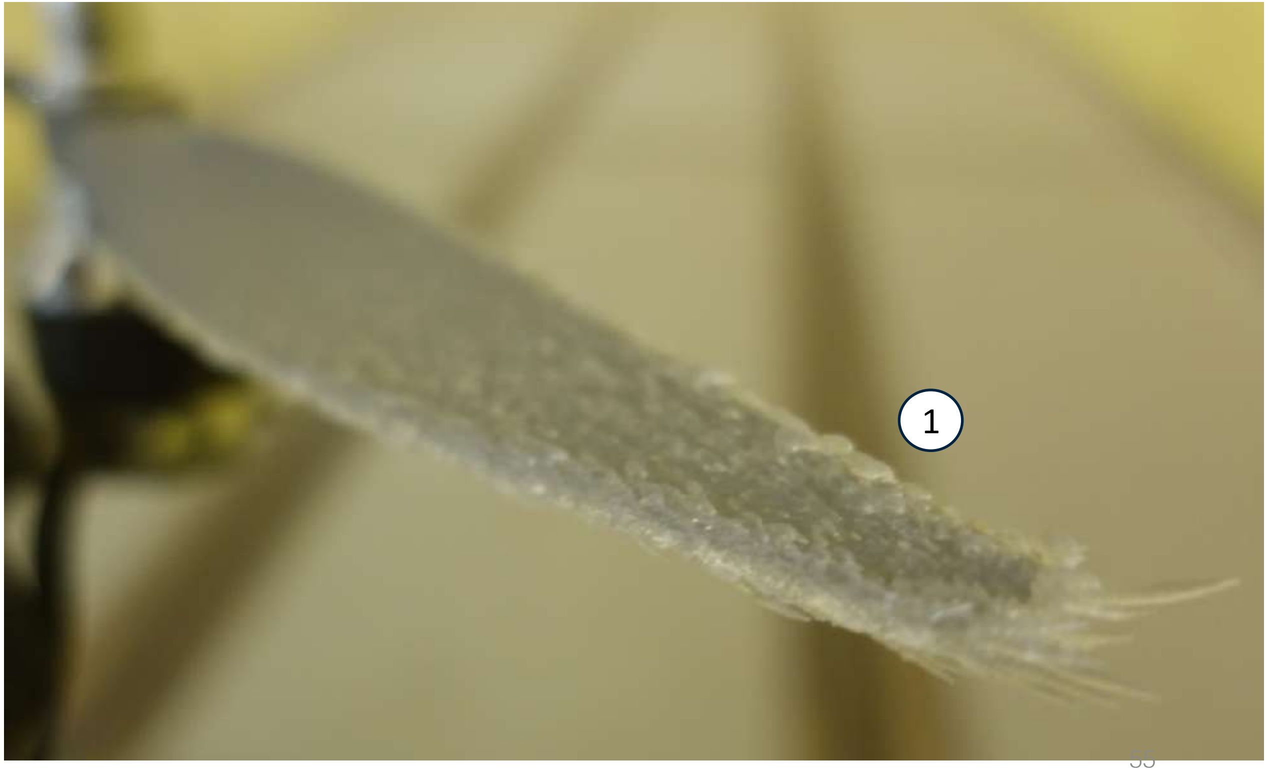
Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- As in the cases before the voltage drops rapidly and constantly compared to the background measurements, while the current increases steadily over the first 30 sec
- The system breaks down at about 460 s of measuring time which corresponds to about 90 sec of exposure time
- This is reflected in the motor speed data as well as in electrical power consumption

Results Setup 3.1 No. 7: Cumuliform Cloud

Propeller Type 2 (yellow)

- Even after only 30 sec of exposure time to the heavy rain cumuliform cloud heavy icing on the propeller blade can be detected
- Large ice spikes form along the centrifugal forces on the blade at the tip
- A thick layer of ice builds up on propeller blade

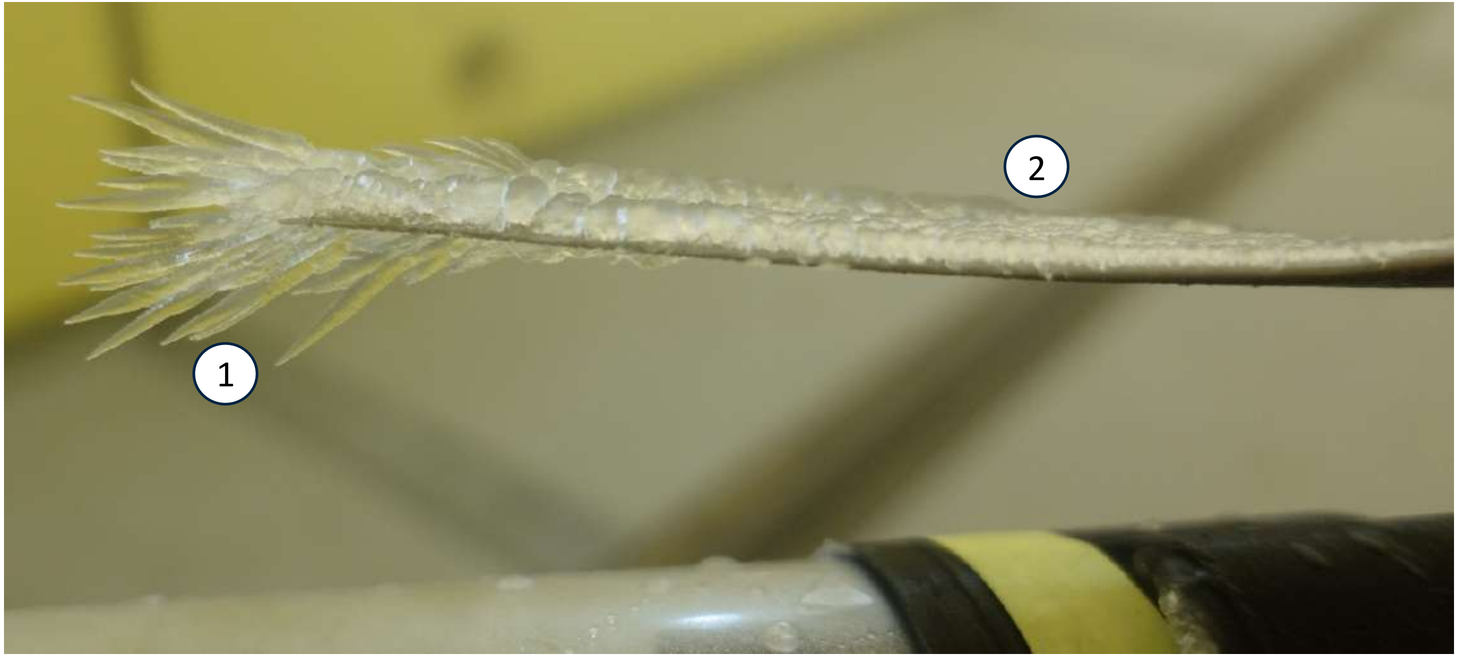


1 – after 30 sec: heavy icing with rapidly decreasing flight performance properties

Results Setup 3.1 No. 7: Cumuliform Cloud

Propeller Type 2 (yellow)

- After an additional minute a heavy and thorough ice layer has formed on the propeller blade
- Beautiful but for flight performance deadly thick ice needles build up at the tip
- A drone operator has maximal 90 seconds to get the aircraft out of those conditions, otherwise a loss of control is inevitable



1 – after additional 1 min: thick ice layer grows on the propeller blade and
2 – thick ice needles grow at the top

Results Setup 3.1 No. 8: Cumuliform Cloud

Test Case 3.1:

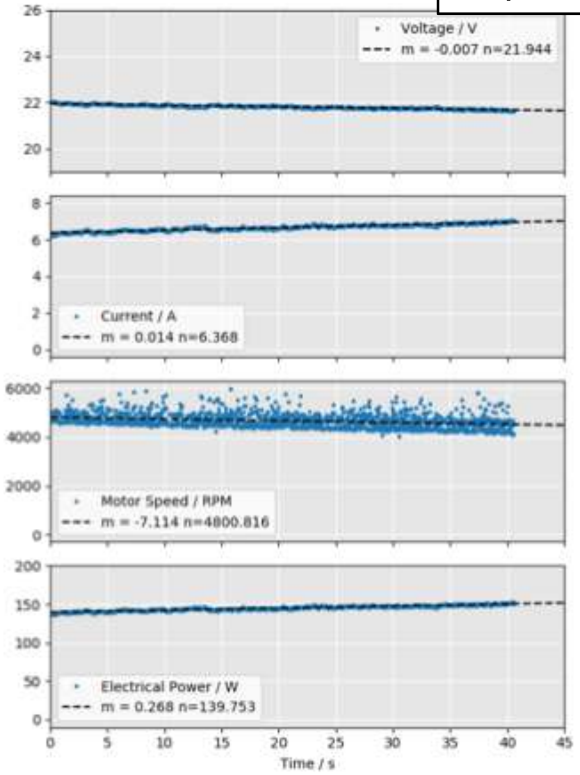
- Propeller Type 1
- Propeller Type 2

Environmental Conditions

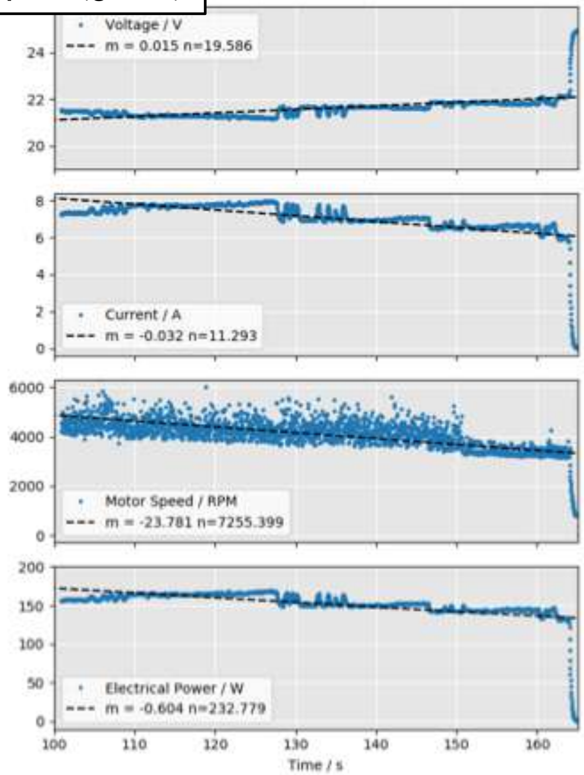
- Temperature: -5.0 °C
- Wind Speed: 10.0 m/s
- MVD: 40 µm
- LWC: 0.85
- Corresponds to medium conditions

Results Setup 3.1 No. 8: Cumuliform Cloud

Propeller Type 1 (green)



Propeller run time 30 sec

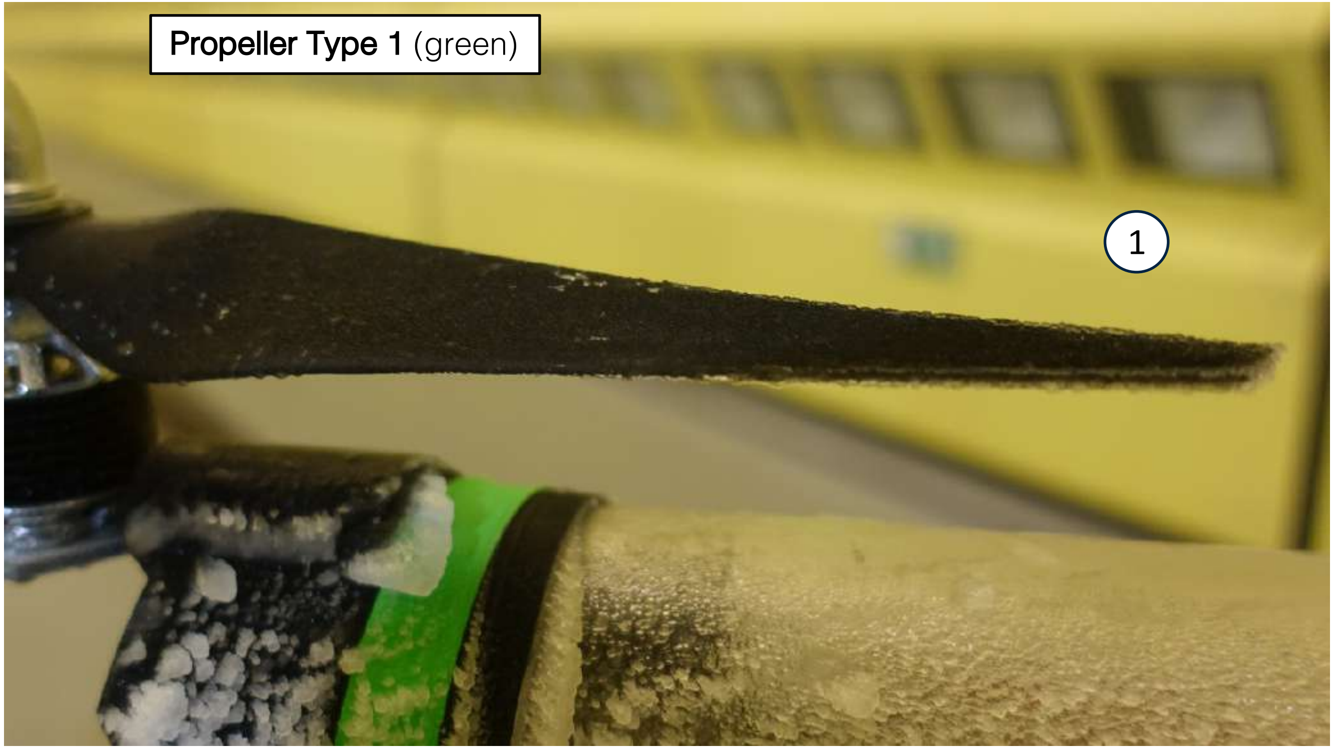


Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Unsteady conditions for the voltage leads to an unsteady drop, while the current first rises after breaking down at about 130 sec
- Motor speed is steadily decreasing, while electrical power increases before it breaks down after about 130 sec
- While these conditions are less severe then the cumuliform from Setup 3.1 No. 7 they are still too heavy to make a continuous flight feasible

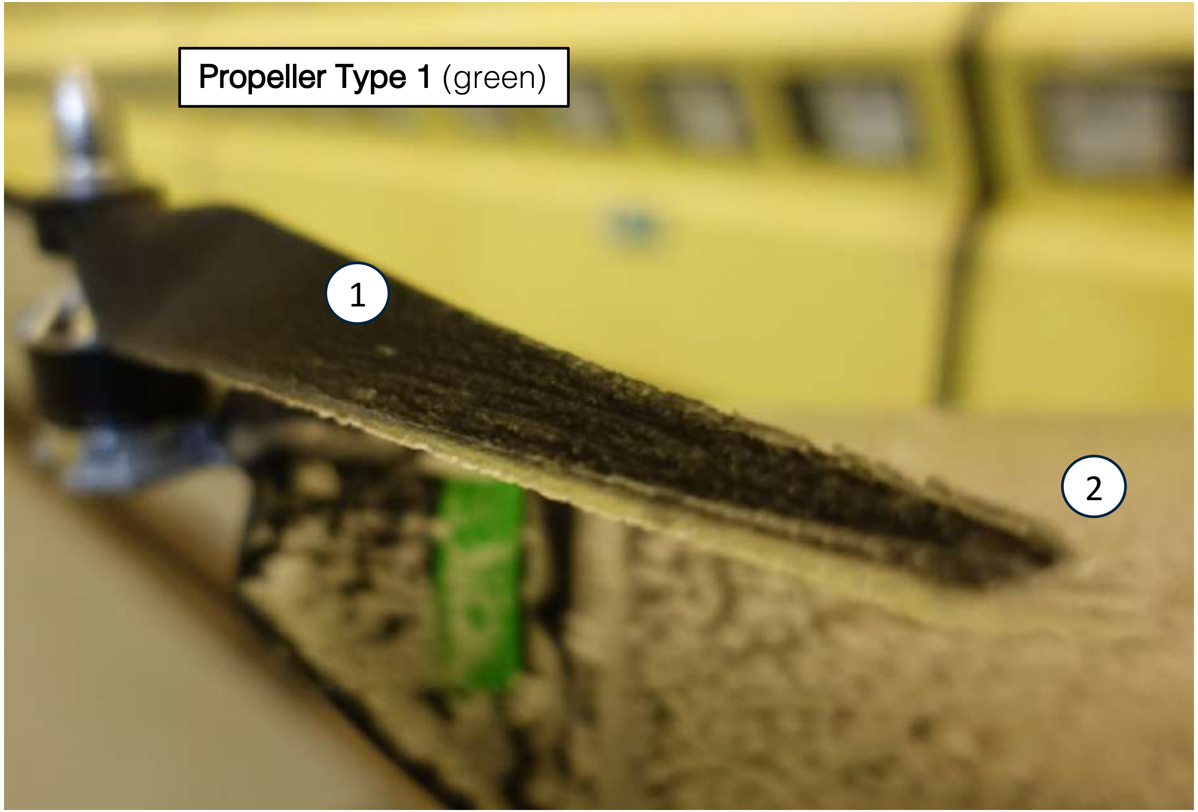
Results Setup 3.1 No. 8: Cumuliform Cloud

- Substantial but less ice formation compared to prior case
- Ice layer forms quite uniformly over the whole propeller with a slight stronger growth on the edges



1 – after 30 sec: uniform ice film has already grown on propeller

Results Setup 3.1 No. 8: Cumuliform Cloud

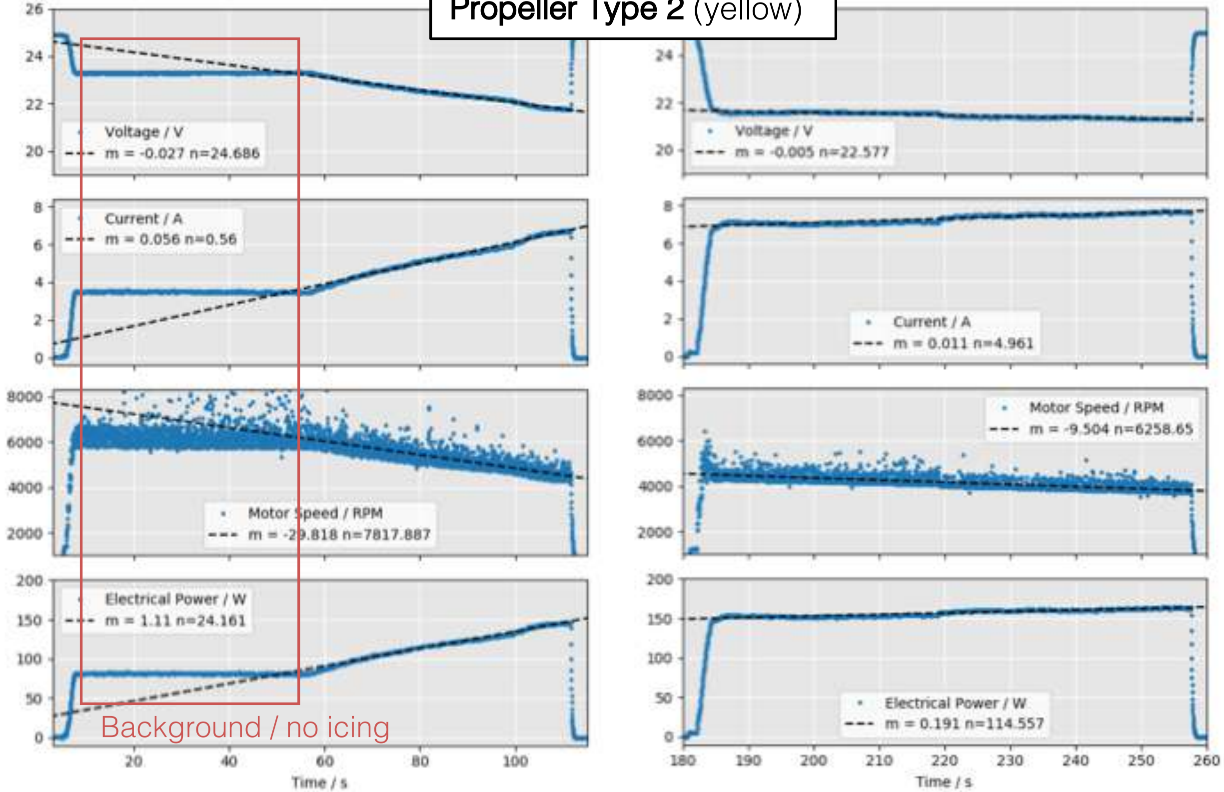


- Heavy icing occurrence after long enough exposure time for these less intense conditions compared to prior cumuliform cloud
- Needles form again at the tip of the propeller
- Under these conditions the drone operator has about 130 sec to maneuver the drone out of the cloud to safer grounds, otherwise a loss of control is highly likely

1 – after additional 1 min: thicker ice layer forms on the propeller and **2** – ice needles form again after additional minute of exposure

Results Setup 3.1 No. 8: Cumuliform Cloud

Propeller Type 2 (yellow)



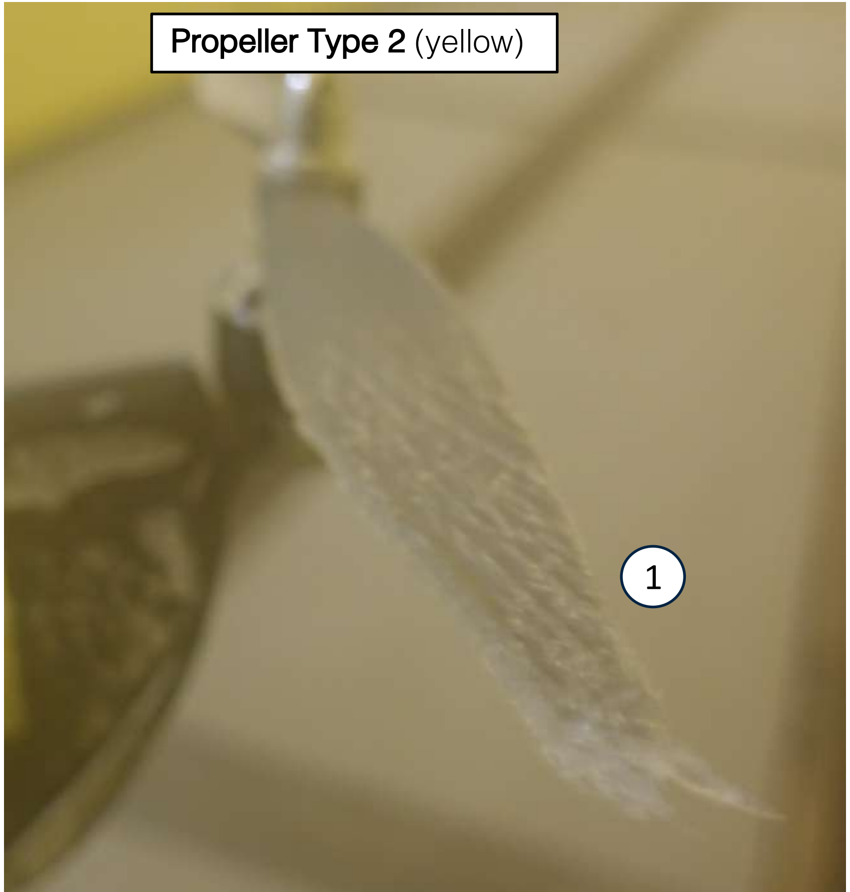
Propeller run time 30 sec

Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Similar to the conditions in the test case before, flight parameters go down rapidly, although current, voltage, electrical power consumption and motor speed seem to reach a saturation after the first 30 seconds at which ice growth is proceeding much slower than before
- For these results it is unlikely that the aircraft will be operational much longer, however, if it is, the flight time is reduced by at least 60 %

Results Setup 3.1 No. 8: Cumuliform Cloud

- Heavy ice formation already after 30 sec of exposure time
- Strong tendency to formation of lengthy needles at propeller blade tip

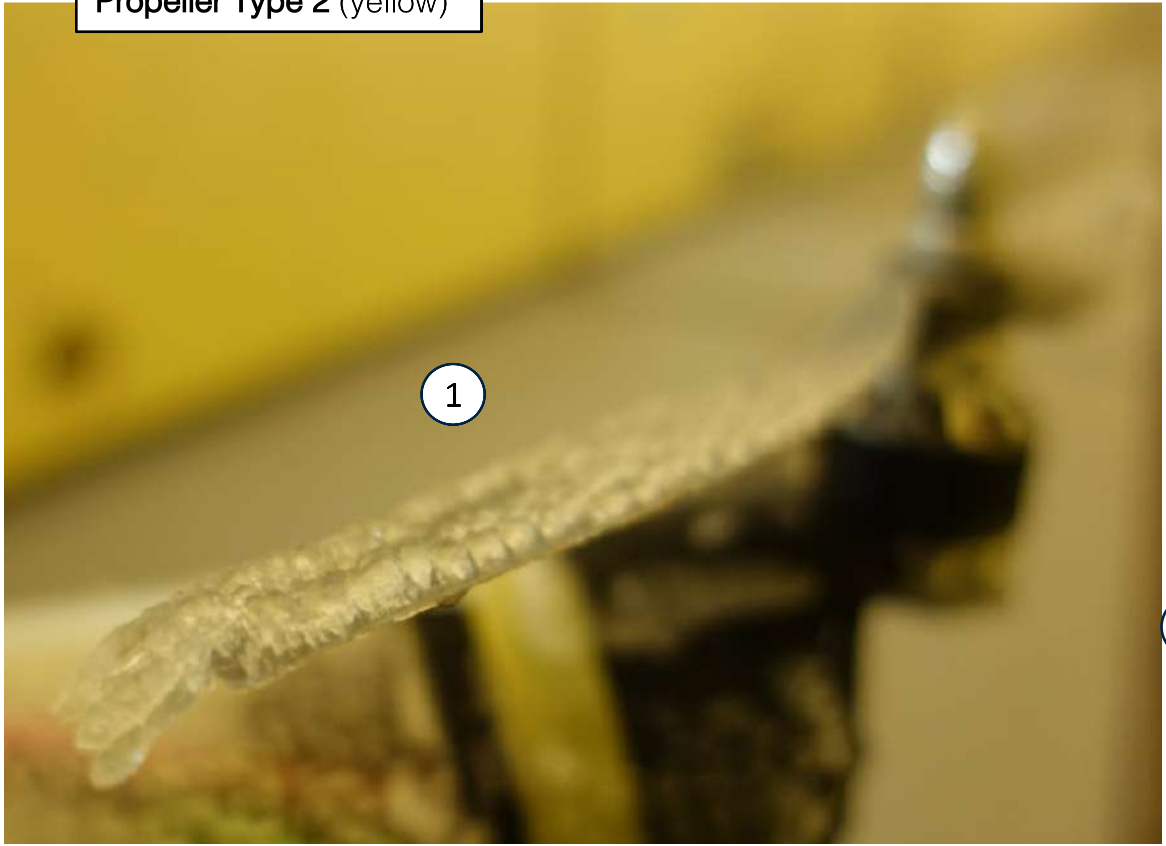


1 – after 30 sec: strong formation of ice already with building of needles at the tip

Results Setup 3.1 No. 8: Cumuliform Cloud

Propeller Type 2 (yellow)

- Thick layer of ice forms after an additional minute
- Ice growth is more evenly than for larger LWC cumuliform cloud which results in measurements that show less severity for flight
- Under these conditions, however, staying operational is very unlikely and flying time will be at least reduced drastically by 60 % and is expected to increase over time



1 – after additional 1 min: thick ice layer grows on the propeller blade and **2** – accumulates heavily on the blade edges

Results Setup 3.1 No. 9: Stratiform Cloud

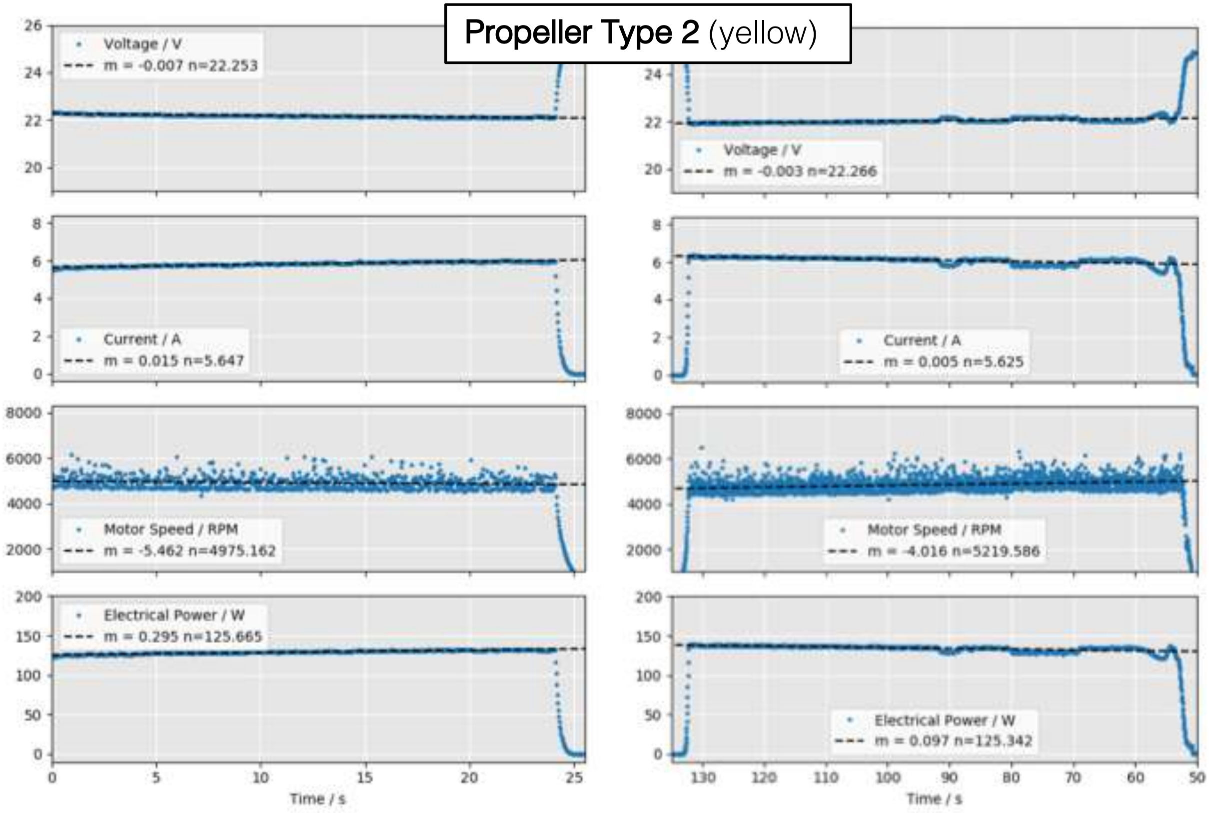
Test Case 3.1:

- Propeller Type 1

Environmental Conditions

- Temperature: -10.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 μm
- LWC: 0.48
- Corresponds to stratiform cloud

Results Setup 3.1 No. 9: Stratiform Cloud



Propeller run time 30 sec

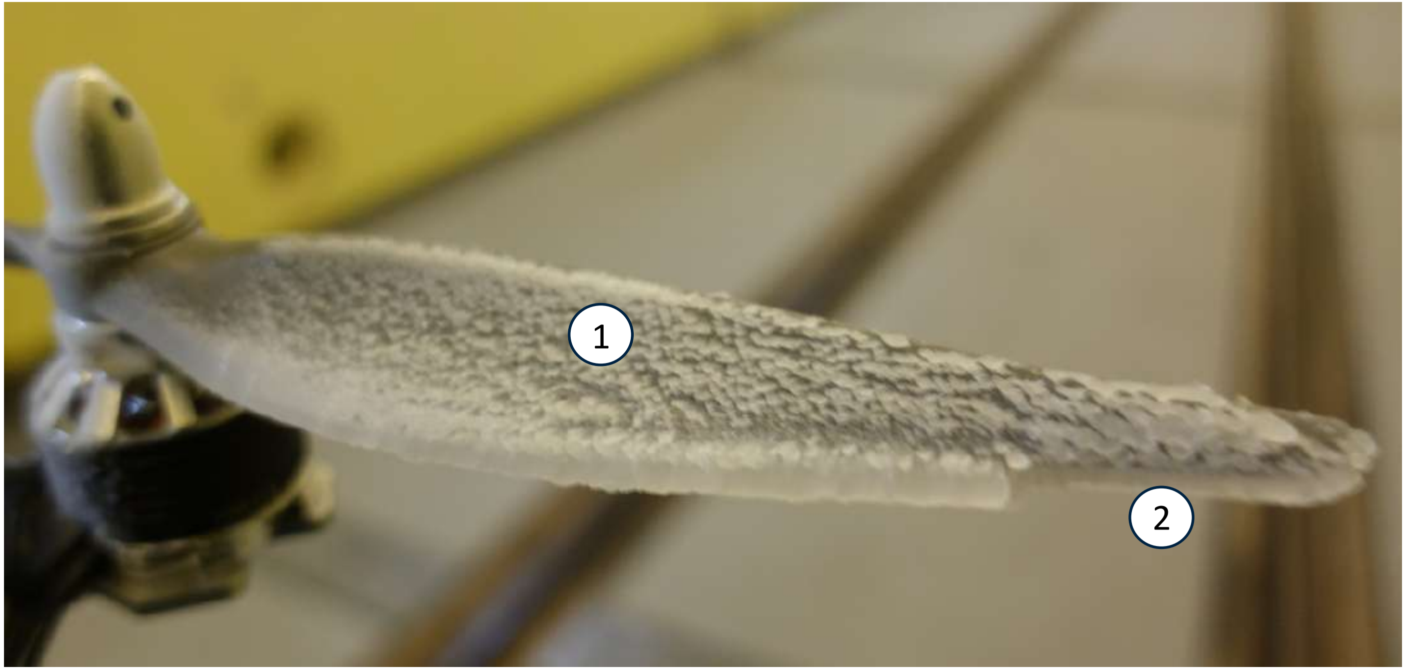
Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- As for higher temperatures before, in stratiform clouds voltage drops slowly over time, while current is steadily increasing
- The above is true till a certain moment, where ice breaks of and performance increases again
- This effect can be nicely seen for the motor speed – first declining then rising again – as well as for electrical power consumption
- This outcome would be fortunate for a drone operator leading to longer intervention time

Results Setup 3.1 No. 9: Stratiform Cloud

Propeller Type 2 (yellow)

- Ice grows quite evenly in the given conditions
- The propeller shows declining flight properties while the ice is growing and improving performance when the ice-edge broke off
- Under these conditions a drone is very unlikely to fly a long time in an operational mode, with an order of magnitude of around 90 seconds



1 – after additional 90 sec of exposure time, propeller shows heavy icing **2** – a clean cut off of ice at the propeller tip can be seen at propeller tip

Results Setup 3.1 No. 7: Cumuliform Cloud

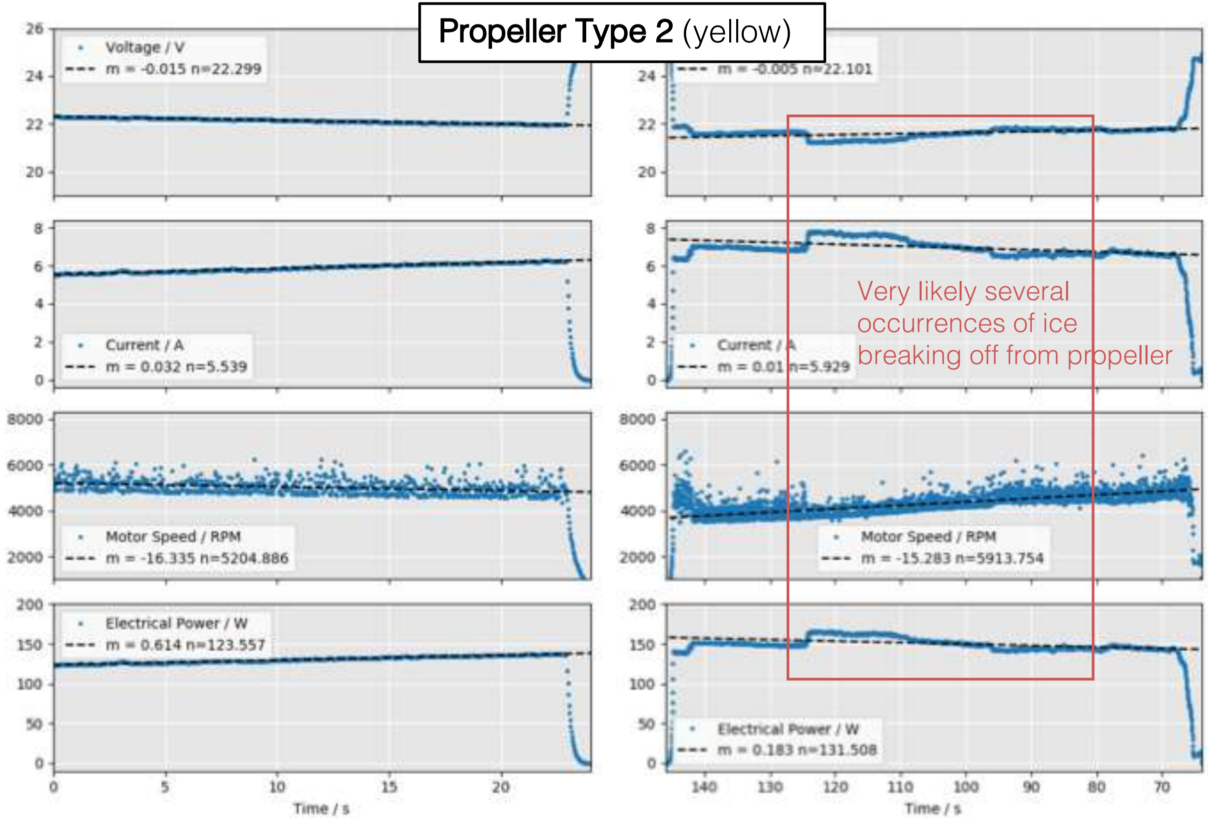
Test Case 3.1:

- Propeller Type 1

Environmental Conditions

- Temperature: -10.0 °C
- Wind Speed: 10.0 m/s
- MVD: 20 μm
- LWC: 2.2
- Corresponds to thunderstorm cloud, extreme conditions

Results Setup 3.1 No. 10: Cumuliform Cloud



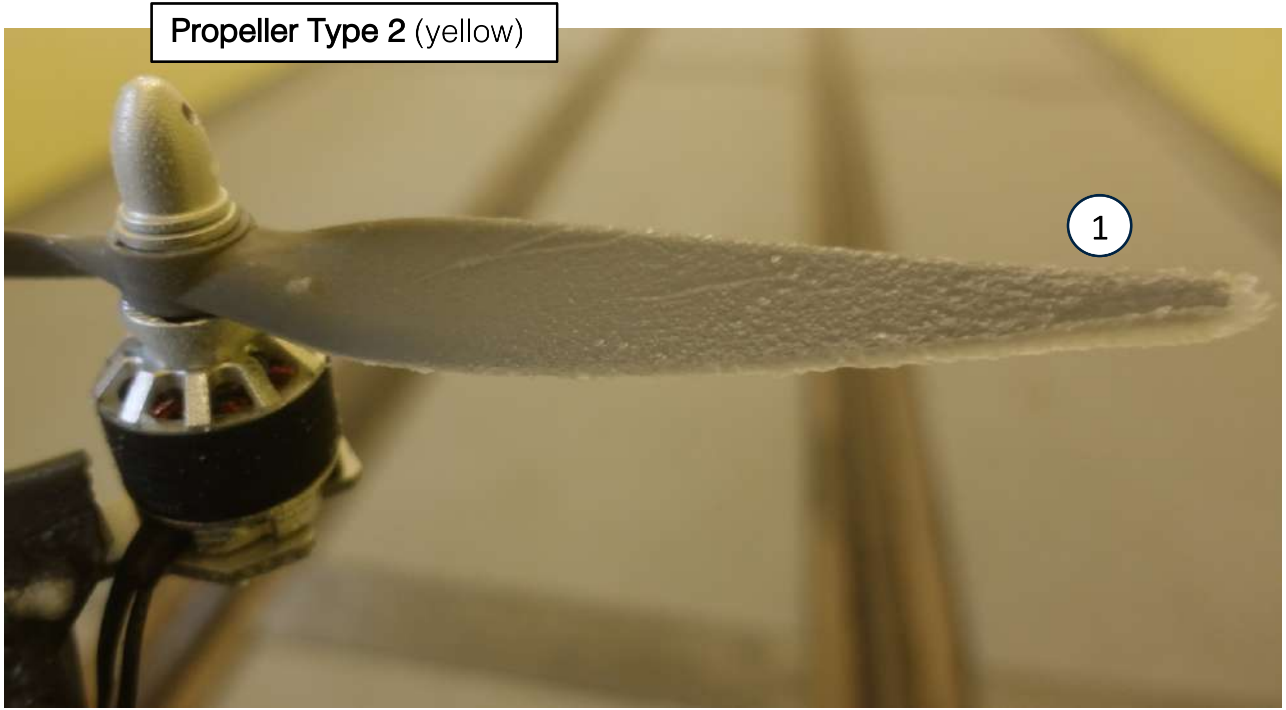
Propeller run time 30 sec

Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Voltage drops as expected with occasional interruptions most likely due to ice breaking off the propeller tip
- The trend from the voltage is recursively for the current, while motor speed shows first decrease and then an increase again
- Electrical power reflects the above interpretations of ice break offs
- Ice at -10 °C might be more brittle which might in turn lead to more ice chipping off

Results Setup 3.1 No. 10: Cumuliform Cloud

- Heavy icing forms on propeller already after 30 sec
- Ice build up is however smaller than for higher temperatures
- Ice growth is again quite uniformly distributed over the propeller blade

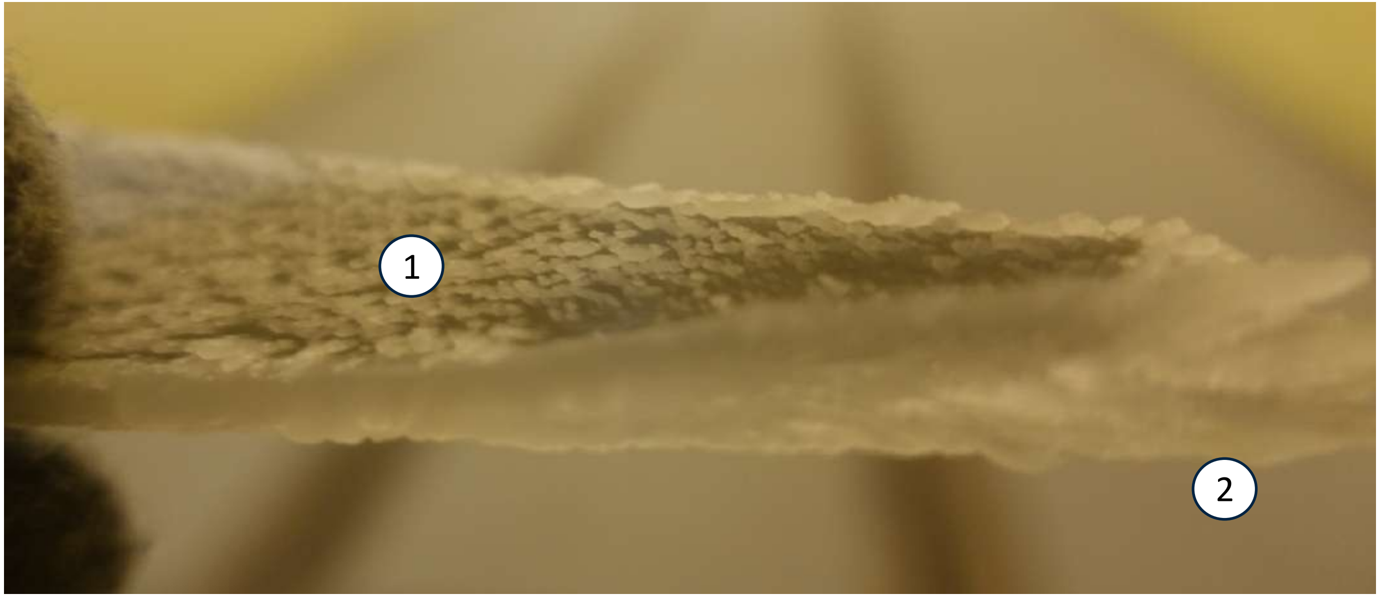


1 – after 30 sec thick layer off ice has formed with strong accumulatio at the tip

Results Setup 3.1 No. 10: Cumuliform Cloud

Propeller Type 2 (yellow)

- Extreme amounts of icing form at the tip of the propeller as well as on the propeller blade
- Under these conditions performing a flight is very unlikely and measurements indicate that heavily accumulated ice is breaking off frequently from the top
- A drone operator seems to have more response time to pull out of these conditions than for the same cloud at higher temperatures



1 – after additional 1 min: thick layer of ice on the blade
2 – beautiful formation of heavy ice needles at the propeller tip

Results Setup 3.1 No. 11: Cumuliform Cloud

Test Case 3.1:

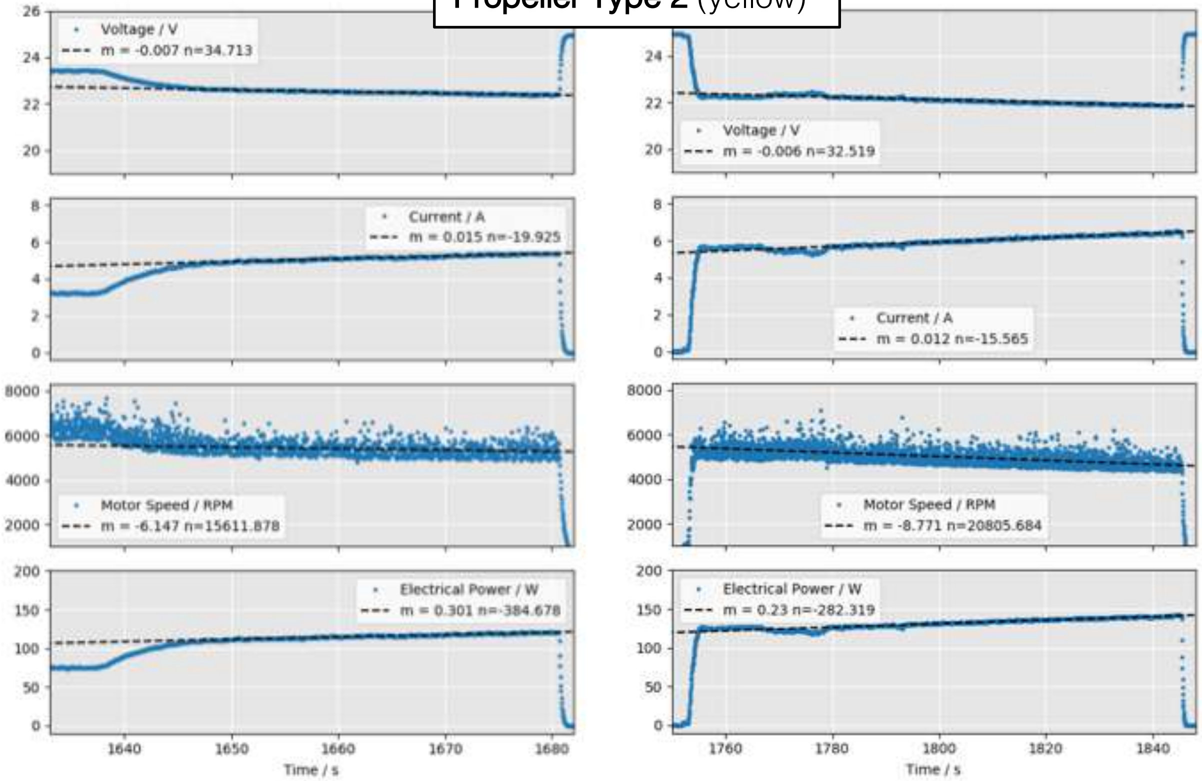
- Propeller Type 1

Environmental Conditions

- Temperature: -10.0 °C
- Wind Speed: 10.0 m/s
- MVD: 40 µm
- LWC: 0.85
- Corresponds to medium conditions

Results Setup 3.1 No. 11: Cumuliform Cloud

Propeller Type 2 (yellow)



Propeller run time 30 sec

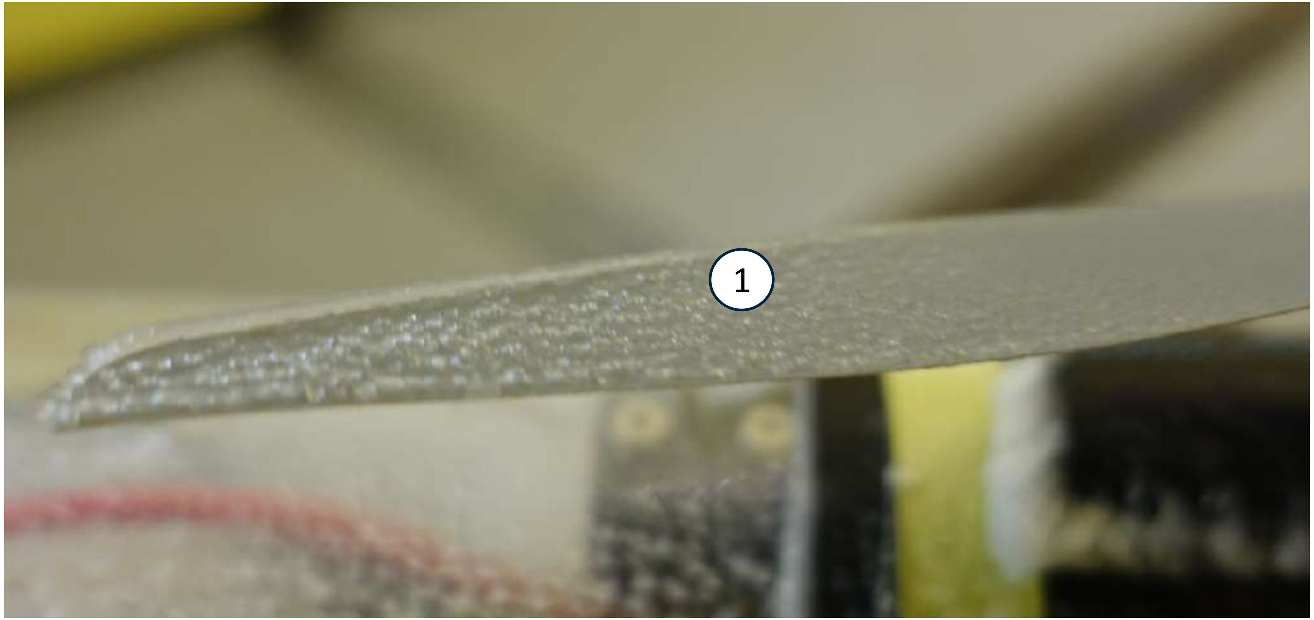
Propeller run time additional 1 min

- The plots show voltage, current, motor speed and electrical power of the stated propeller type (blue dots) together with the line of best fit (black dashed line , y = m*x + n)
- Voltage drops steadily again at the given conditions, while the current is increasing steadily
- As the motor speed is constantly declining, the electrical power consumption grows steadily
- In case an aircraft in such conditions is still controllable flight endurance will decrease by at least 50 %

Results Setup 3.1 No. 11: Cumuliform Cloud

Propeller Type 2 (yellow)

- Steadily growing ice layer with lower weight compared to the cumuliform with higher LWC

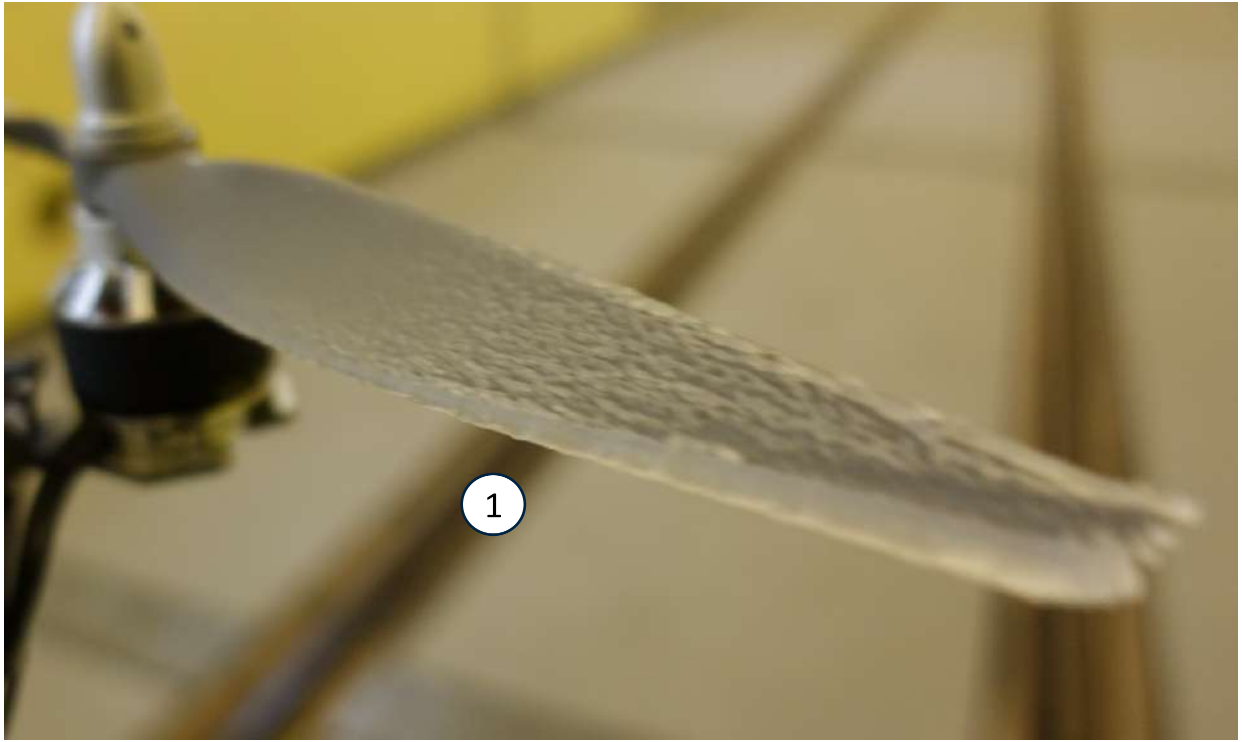


1 – after 30 sec lower less distinct ice growth than before

Results Setup 3.1 No. 11: Cumuliform Cloud

Propeller Type 2 (yellow)

- Heavy icing at the blade edges with a clean round edge
- The ice layer on the propeller is less distinct than at the edges
- Under these conditions a drone's flight capabilities will be strongly reduced; its endurance is reduced by about 50% after an exposure of 90 seconds



1 – after additional 1 min exposure time the ice layer grows steadily

Results Setup 3.2: Impact on Operational Drone

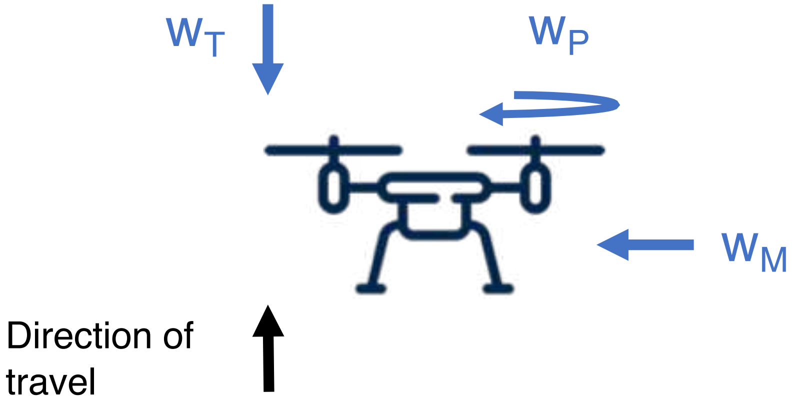
- Several tilt angles were measured for the drone, simulating different orientations towards the wind direction from the icing tunnel

- As can be seen from the image on the left, the results show that although, depending on the angle, icing occurs less heavily on the propeller blades, the rotor edges are still the bottle neck when it comes to icing conditions

- In conclusions this means that the air flow due to the movement of the drone is of minor importance for the formation of ice on the propellers

- The hull experiences more icing when turned directly towards the air stream as would be expected, since its area of exposure increases

Results Setup 3.2: Impact on Operational Drone



- The results show, that icing is the heaviest where wind hits the aircraft the strongest

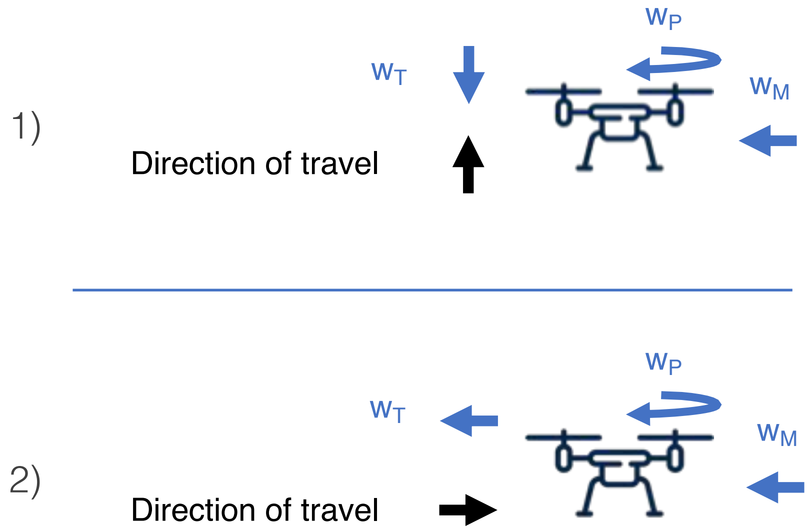
- Typically there are three different contributions for wind stream hitting the UAV: wind flow as response to moving towards the direction of travel (**w_T**), the meteorological wind (**w_M**), and a wind exposure of the propeller blades due to their movement (**w_P**)

- Typical wind speeds are:
  - w_T = speed of travel e.g. 4-10 m/s
  - w_M = anywhere between 0-20 m/s; typically 5 m/s
  - $w_P = 2\pi r \ * RPM$ with Propeller 1 and about 5000 RPMs that means approximately 70 m/s at the propeller tip

- The contribution from w_P is significantly higher than from the two others, which means **icing will accumulate the fastest on the leading edges of the propellers, independent of UAV movement or wind**

- In consequence, icing hits exactly the most important part of the UAV for maneuverability, which makes it very dangerous

Results Setup 3.2: Impact on Operational Drone



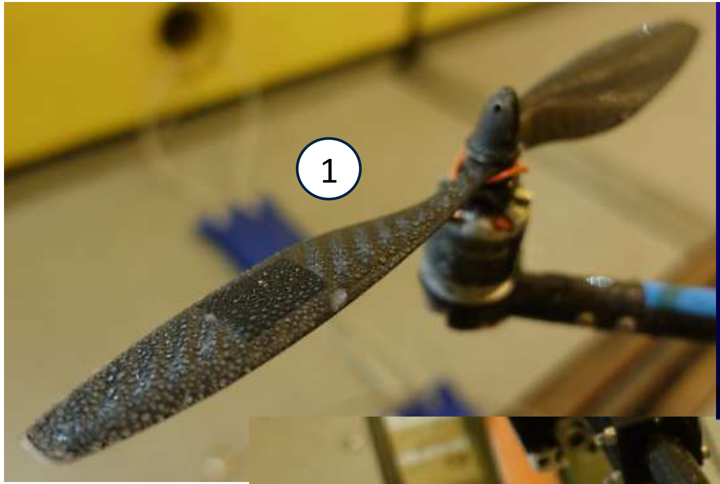
- Although the propeller exposure is the strongest contribution towards flight performance degradation, different types of operations may contribute towards a faster icing built-up and in consequence to a faster degradation of flight performance

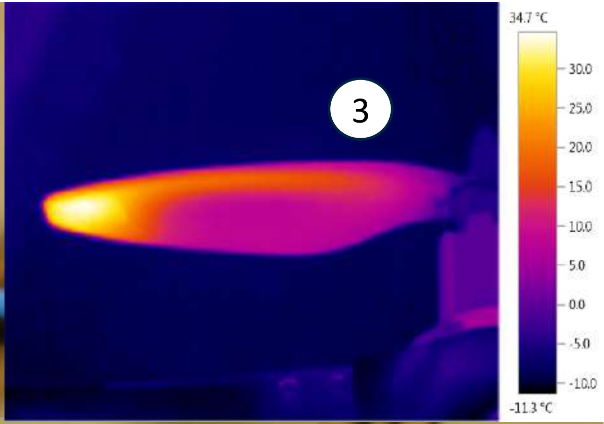
- Mode 1 shows a typical Meteodrone operation, where the direction of travel is straight up, wind may come from the side leading to a slightly enhanced icing on the propellers; a light ice formation on the main body due to the inflow of w_T is to be expected. Over time this will lead to increase of weight, however, it is negligible compared to icing of the propellers

- Mode 2 shows a typical scenario of other drone uses, where the UAV moves sideways; here w_M and w_T come from the side, enhance propeller icing lightly, and do not effect the body, but icing affects the propeller as significantly as in Mode 2

- Icing conditions without anti-icing measures on a drone should be avoided independent of the mode of operation

Results Setup 3.3: Anti-Icing Measures

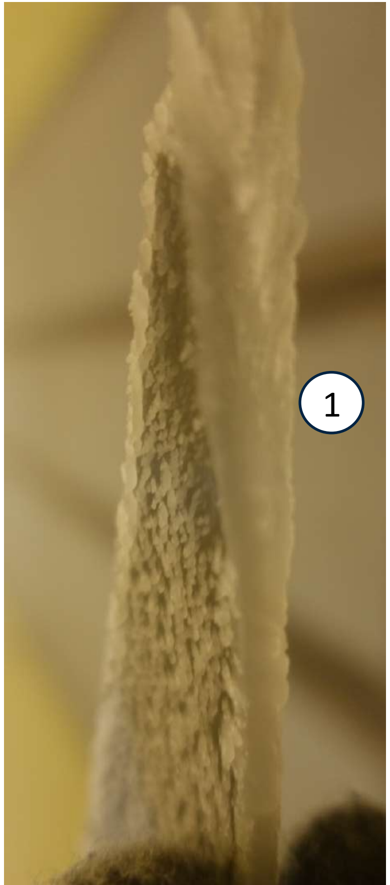




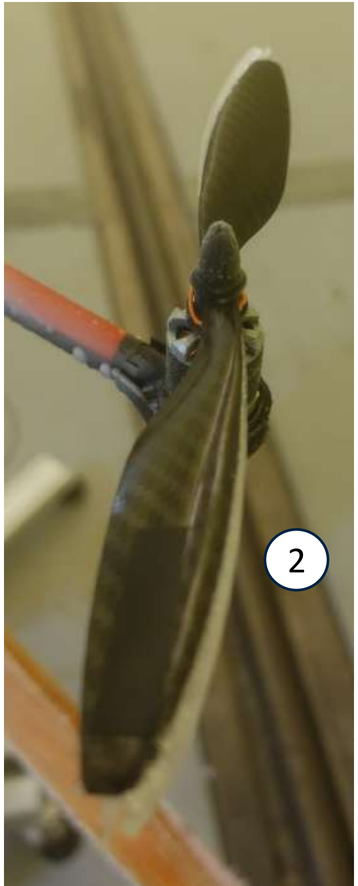
(1) – Icing without anti-icing heating
(2) – Propeller with active Meteomatics anti-icing propeller heating
(3) – IR image of operational anti-icing heating

- As seen before, while under stratiform cloud conditions and -5 °C icing is less severe, the propeller without anti-icing heating is completely and evenly covered with ice **(1)** and flight performance is expected to be impacted severely
- The propeller with our anti-icing heating system in place **(2)** is completely ice free, although small ice crystals may form at the propeller tip under these conditions, where the liquid water run-off freezes immediately again
- While this run-off frozen ice often breaks off from the tip, further improvements of the heating system are in order

Results Setup 3.3: Anti-Icing Measures



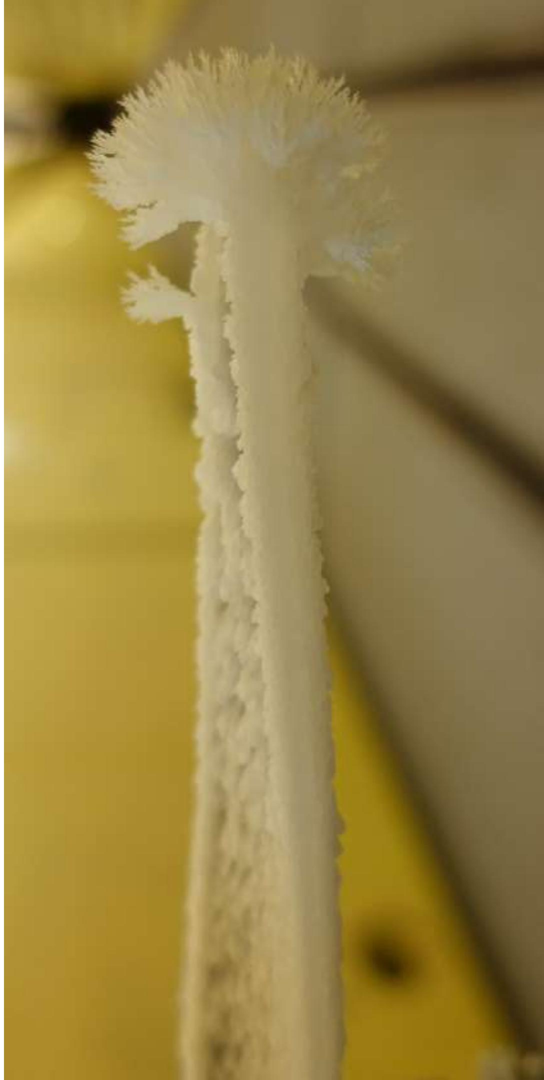
Two propellers exposed exactly to the same conditions; left **(1)** without propeller heating, right side **(2)** with propeller heating



- Under much harsher conditions (cumuliform cloud, LWC 2.5, -10 °C) the icing is extremely severe as can be seen in **(1)**
- With our anti-icing propeller heating device the whole propeller blade is completely ice free, while at the edges icing still occurs mostly due to liquid water run-off and immediate freezing over at -10 °C
- These results show clearly how important a well performing anti-icing heating is, especially at the propeller front edges
- It is expected that with propeller heating the drone will stay operational and maneuverable much longer than without, where the limitation is only the capacity of the battery

Conclusions: Icing Results (1)

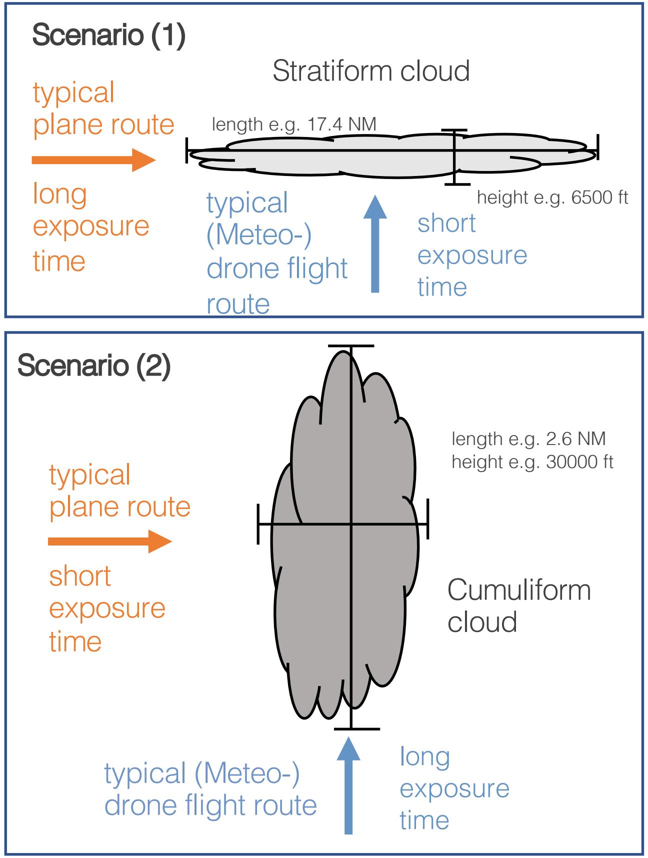
- Under all conditions with temperatures below freezing temperature, ice starts to accumulate on the propellers with a layer forming on the propeller blade and strong accumulation at the edges, where a smaller pitch leads to slightly heavier icing on the propeller blade
- Depending on the conditions (LWC, MVD, Temperature) icing hits slower or faster and deteriorates flight performance partially significantly up to a very likely loss of control of the aircraft
- Stratiform cloud conditions are generally less severe than cumuliform conditions that can contain large amounts of LWC
- Exposure times, without any anti-icing heating measures, before flight parameters are severely reduced, lie between 30 and 90 seconds
- The operational drone shows strong icing especially at the propeller blade edges independent of its orientation towards the airstream, which means conditions simulated in the CWT can be regarded as highly representative – although certainly posing “worst case” scenarios – with respect to real-world operational flight
- Propeller heating shows a significant step towards mitigating ice growth on propellers and will be a safety requirement for flying in given conditions



Conclusions: Icing Results (2)

- Contrary to a typical flight route of a plane, a UAV will fly through a cloud vertically, which leads to very different exposure scenarios for the two aircrafts in different cloud conditions (illustrated in right figures)
- The results show that icing in stratiform cloud conditions is much less severe than in typical cumuliform cloud conditions, depending on the LWC, which together with the exposure scenarios on the right, dictates the flight envelope for UAVs
- We expect a vertical flight through stratiform clouds, where exposure time is often shorter than for cumuliform clouds, to be feasible especially with suitable anti-icing (e.g. heating) measures; considering a 2 km cloud and a ascend rate of 10 m/s the total exposure time is limited to 200 seconds
- Flying through cumuliform clouds and hitting the right conditions can lead to severe icing; once icing is encountered a UAV pilot is advised to turn the aircraft around since pulling-through is unfeasible and anti-icing mitigations are expected to hold only for a certain time, rather ensuring a safe return than making it possible to fly through
- For defining a final flight envelope for UAVs in icing-conditions the next step is to analyze the maneuverability of the aircraft when ice is accumulated on the propellers; this however is far beyond the scope of this investigation and demands further studies

Typical exposure scenario UAVs vs. planes



Conclusions and Outlook

- Icing poses a severe thread for high altitude drone flights and mitigations need to be instated

- Anti-icing measures are effective but increase electrical power consumption; they will allow for a safe return flight and might even enable flights through icing conditions, however, icing and mitigation strategies will always depend on exposure time

- Stratiform clouds pose lower thread than cumuliform cloud, not only because of typical water droplet sizes and water content but also because of the typical flight routes and with that the exposure time

- The next step further for defining exact envelopes for UAV flights in icing conditions is the maneuverability with and without anti-icing mitigation strategies and mock-ice build up on the drone propellers

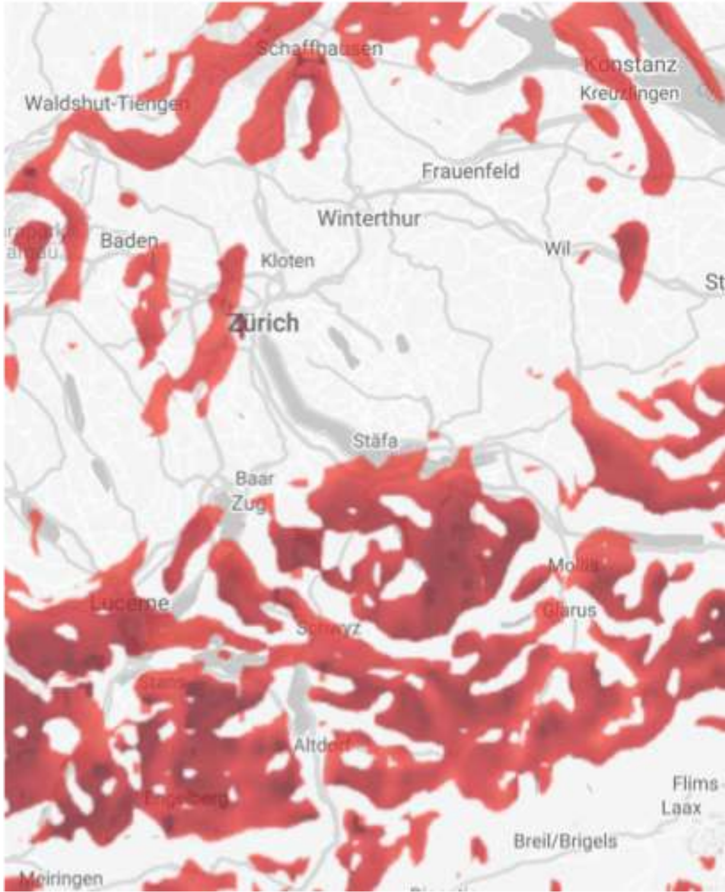
- The following strategies can be implemented in UAV operation:
  1. Avoid icing conditions (do not start or emergency descent)
     - Recognize icing conditions → see next slide for our implementation of our world wide icing forecast model, which can be used for strategic flight planning
     - Detect icing during flight and start icing mitigation
     - Descend when encountering heavy rain cumulus clouds
  2. Remove ice accumulation in flight
     - Remove or avoid ice accumulation by applying propeller anti-icing heating
     - Implement smart anti-icing strategy to adjust flight duration and flight height dynamically

Icing Forecasting Model: Icing Index

1. Avoiding icing or assessing icing mitigation strategies requires a icing forecast model

2. The icing index allows for an objective assessment and forecast of severity and occurrence of icing

3. A world wide icing model, based on state-of-the-art research, was implemented by Meteomatics allowing for real live icing information around the globe



Icing Index Method & Description

Current Icing Potential: Algorithm Description and Comparison with Aircraft Observations

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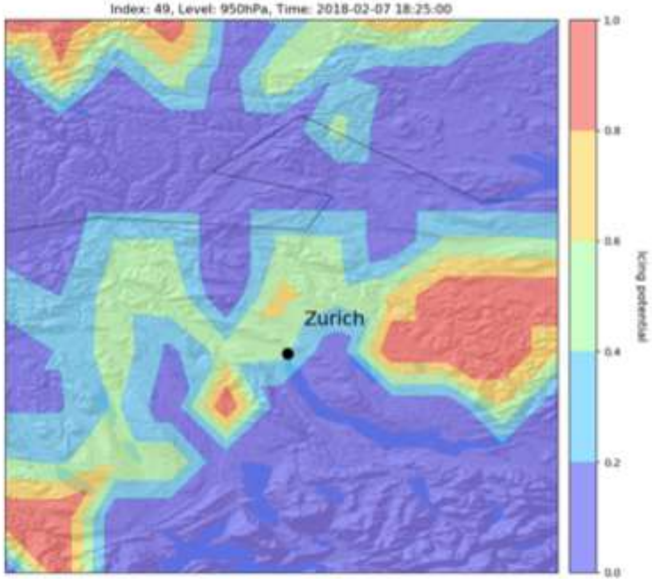
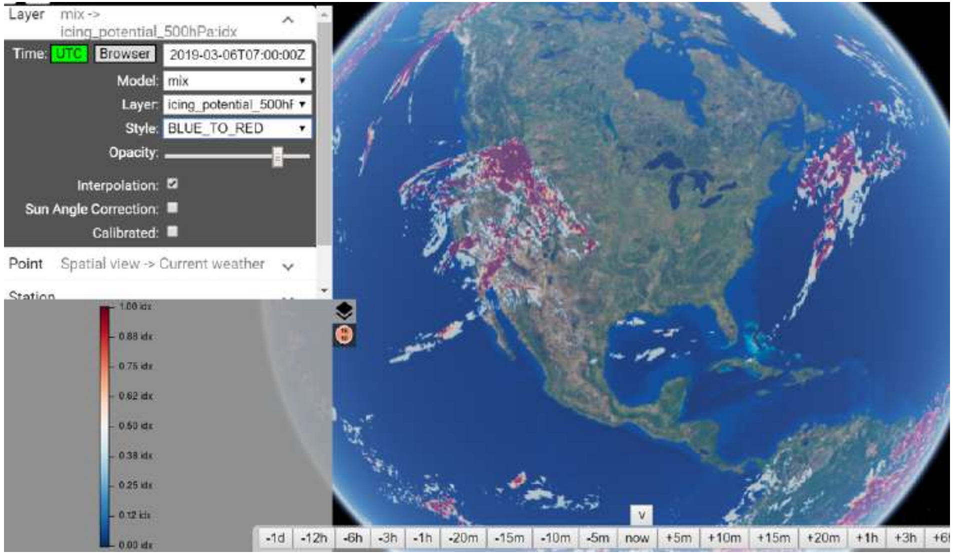
NASA Glenn Research Center, Cleveland, Ohio
CORY A. WOLFF AND GARY CUNNING
Research Applications Program, National Center for Atmospheric Research, Boulder, Colorado*

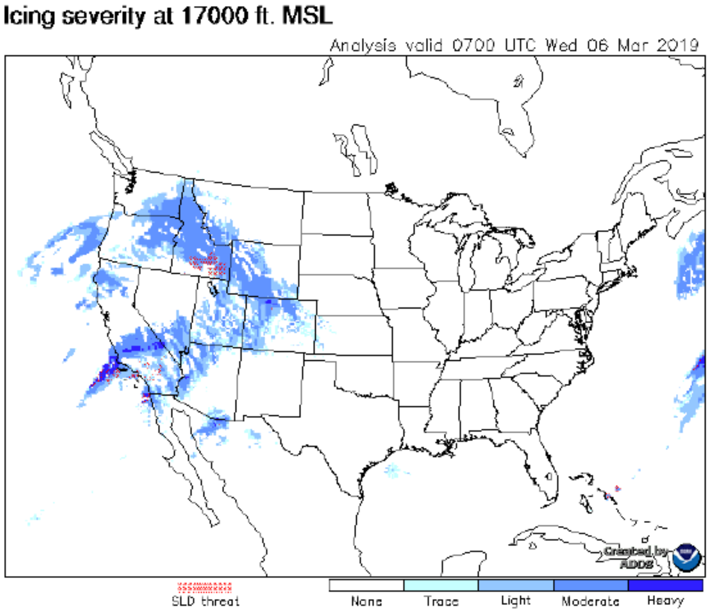
Index	Description
0.0-0.2	No icing
0.2-0.4	Traces
0.4-0.6	Light
0.6-0.8	Moderate
0.8-1.0	Heavy



A Comparison with AWC: **500 hPa / 18'000ft**

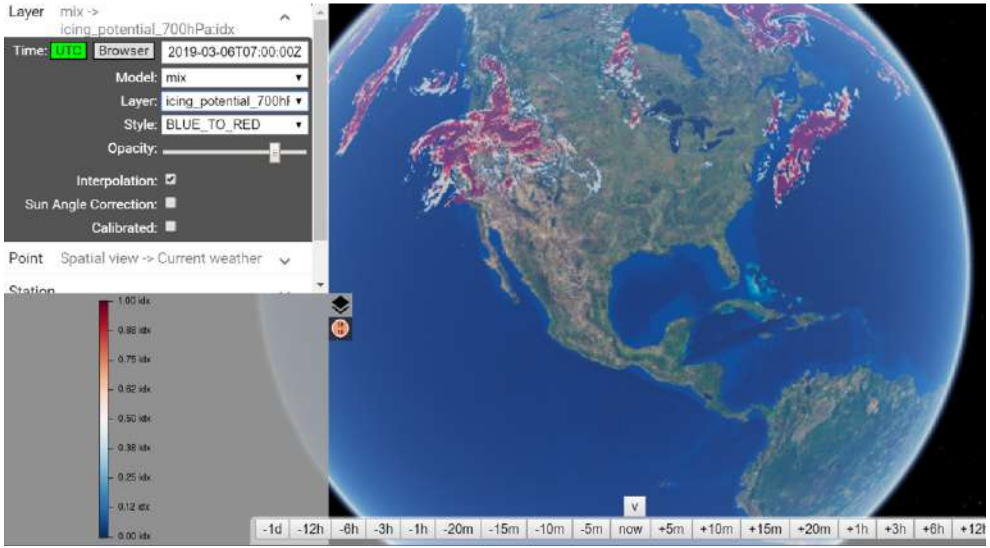
Icing potential index over North America, 06 Mar 2019, 07:00 (nowcast) from Meteomatics (left) and NOAA (right). 500hPa respectively 17000ft.

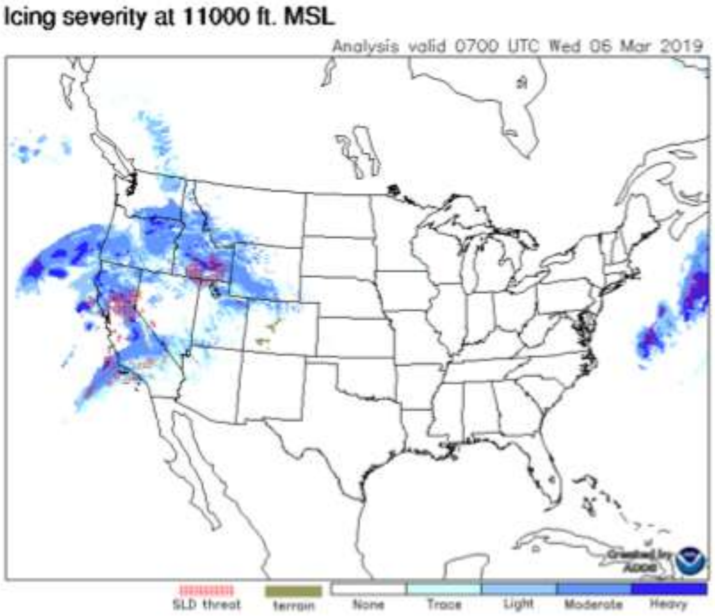




A Comparison with AWC: 700 hPa / 10’000ft

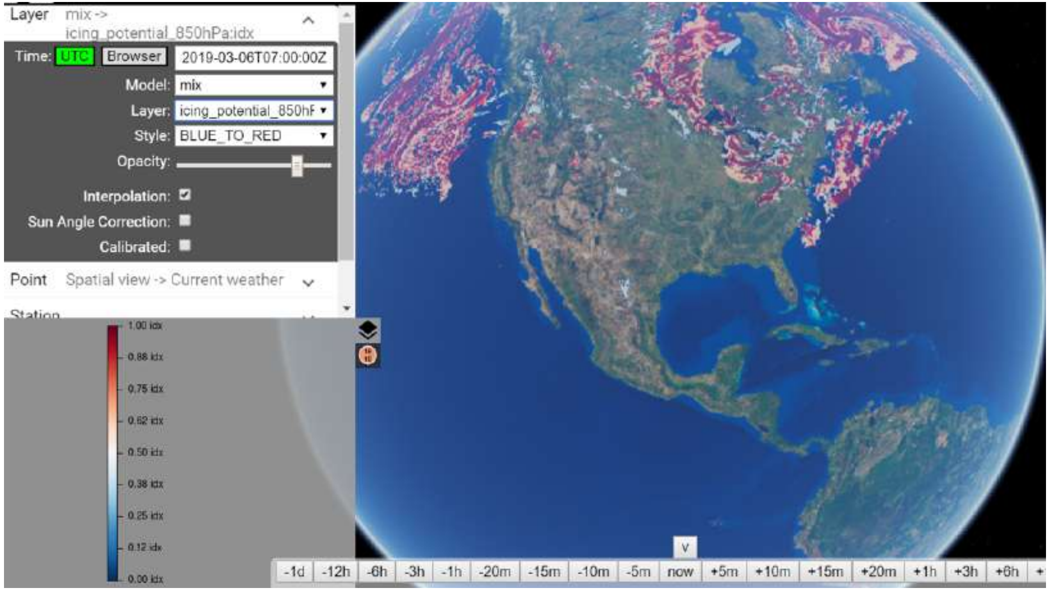
Icing potential index over North America, 06 Mar 2019, 07:00 (nowcast) from Meteomatics (left) and NOAA (right). 700hPa respectively 11000ft.

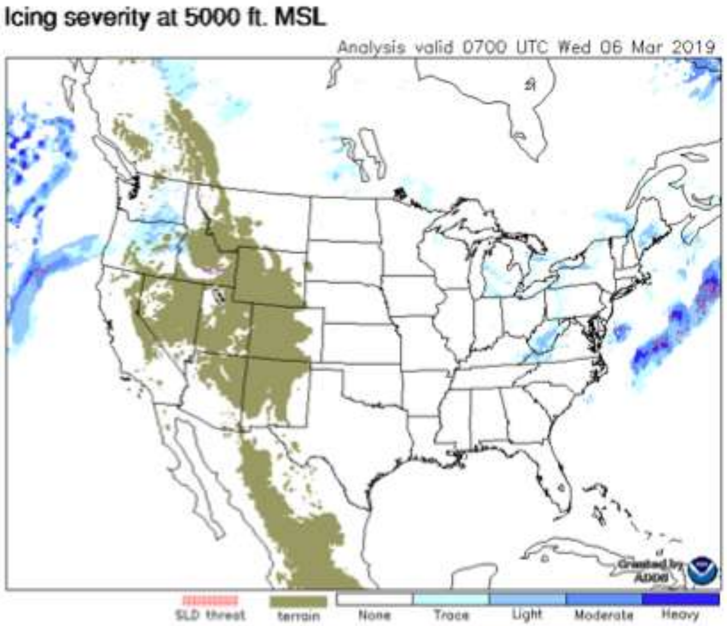




A Comparison with AWC: 850 hPa / 5’000ft

Icing potential index over North America, 06 Mar 2019, 07:00 (nowcast) from Meteomatics (left) and NOAA (right). 850hPa respectively 5000ft.





Icing Events: Summary

- 95% of all inflight icing events described in this study could be reproduced: Most icing events the model predicts moderate to heavy icing potential in the region of interest. This is a promising result for further predictions.
- For some icing events the location is not specified well enough, this makes validation more difficult.
- Icing might be underestimated due to a lack of supercooled liquid water content in the model
- An operational round of automatic predictions and a subsequent validation can significantly improve on the level of confidence for the icing forecast performance.
- Our model could be further improved by incorporating METAR reports and PIREPS
- **A combination of the aforementioned mitigation strategy and icing analysis combined with the aforementioned icing forecast model allows an operator an informed strategy management of icing conditions**

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