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FFI-RAPPORT

Icing and wind

– implications and mitigations in high-intensity, safety-critical drone operations in Norway

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Summary

The background of this project is a desire at the Oslo University Hospital (OUS) to explore the feasibility of using drones to transport blood samples between two major hospitals in Oslo. The motivation is to achieve improvements in patient care, and possibly consolidate laboratory services to a single location.

We start by discussing the user requirements, based on a thorough study performed at OUS. We conclude that there is a need for frequent drone flights (possibly 15 minutes apart), carrying relatively light loads – under 3.5 kg. Safety is paramount. We continue by describing how current commercial or professional small drones are affected by icing and wind. Relevant weather statistics are summarized, and analyzed in the context of the use case. We discuss possible mitigations, and attempt to outline essential elements in the path towards making the vision of drone-based transport a reality.

We especially underline the importance of developing new solutions for planning and control, leveraging a high level of automation. This is necessary e.g. to make good use of meteorological services in route planning and decision-making. We also emphasize strongly the requirement for ice protection systems (IPS) on board the drones. Furthermore, we identify the need to study the responses of drones to icing and strong wind in greater depth.

A comprehensive and holistic approach should be taken. Solutions should be gradually matured based on what is learned in low-intensity, risk-controlled exploratory operations.

We finally conclude that transporting blood samples with drones between Rikshospitalet University Hospital and Ullevål University Hospital is realistic within 5–10 years, provided emerging IPS and new planning and control technology are used.

A residual risk of serious incidents and accidents will remain, however, even if the suggested approach is followed. This risk stems from rare weather events, as well as from other threats to safe operations such as collisions and technical malfunctions. Risk acceptance and mitigation should be studied further.

Sammendrag

Bakgrunnen for dette arbeidet er et ønske ved Oslo Universitetssykehus (OUS) om å utforske mulighetene for å bruke droner til å transportere blodprøver m.m. mellom to sykehus i Oslo – Rikshospitalet og Ullevål sykehus. Hensikten er å oppnå forbedringer i pasientbehandlingen og å oppnå høyere effektivitet ved å konsolidere to av de store laboratoriene.

Vi innleder med å diskutere brukerbehovene. Vi baserer oss på en omfattende studie utført av OUS. Vi konkluderer med at det er behov for hyppige droneflygninger hele døgnet (muligens 15 minutter mellom hver flygning), med lette nyttelaster – alltid under 3,5 kg. Sikkerhet er et særdeles strengt krav.

Vi beskriver videre hvordan operasjoner med nåværende kommersielle og profesjonelle droner blir påvirket av ising og vind. Vi oppsummerer relevant værstatistikk og sammenstiller dette med brukerbehovene. Vi identifiserer så aktuelle tiltak og skisserer viktige elementer for veien videre mot å realisere visjonen om dronebasert transport av blodprøver.

Vi understreker spesielt betydningen av å utvikle nye løsninger for planlegging og kontroll, der nyere utvikling innen automatisering og autonomi utnyttes. Dette er nødvendig for å være i stand til å utnytte meteorologitjenester og målinger fra droner og eksterne sensorer effektivt. Isbeskyttelsessystemer bør bli standardutrustning på alle droner i profesjonell bruk i Norge. Vi understreker også betydningen av å undersøke oppførselen til aktuelle dronesystemer i større grad enn i dag.

En helhetlig tilnærming blir viktig, med en gradvis, risikostyrt modning basert på læring gjennom begrensede operasjoner.

Vi konkluderer med at det spesielle tilfellet med transport av blodprøver mellom Rikshospitalet og Ullevål sykehus er realistisk i et 5–10-årsperspektiv. En viss begrenset risiko for alvorlige hendelser og ulykker vil gjenstå selv om den foreslåtte tilnærmingen følges. Denne risikoen er forbundet med sjeldne værsituasjoner så vel som med en rekke andre forhold, eksempelvis kollisjonsfare og teknisk svikt. Helhetlig risikohåndtering og risikoaksept bør studeres videre før intensive operasjoner med transport av blodprøver kan tillates i urbane strøk.

Contents

1 Introduction

Will the weather be an important obstacle to safe and efficient drone based logistics in Oslo? This is the driving question behind this study.

Icing and certain wind phenomena are well-known dangers in manned aviation. After more than 100 years of aviation, the risks and costs incurred by weather are still significant. The strong growth in the drone market has taken place largely without addressing the issue of challenging weather.

We now stand at the threshold of an era in which unmanned systems will enter service in an ever-widening spectrum of professional applications – civilian and military, commercial, ideal and governmental. To unleash the full positive potential of drones, we must be able to operate them safely, efficiently and effectively in (nearly) any weather conditions.

This report describes how current drone technology is affected by icing, wind and turbulence. We summarize and analyze relevant weather statistics in the context of regular, safety critical and intensive drone operations in Norway, focusing on Oslo primarily. We discuss mitigations, and attempt to describe what it would take to operate a drone-based service with an acceptable level of safety.

This report is financed by the research Council of Norway, grant no. 282207/2018, under the HELSEVEL program.

We have used practical testing, simple calculations and qualitative assessments based on open sources and published studies to build an understanding of the subject matter, including the behavior of drones when iced down or subjected to wind and turbulence.

With this report, we hope to support efforts to bring drones into beneficial use in healthcare (including logistics and emergency response).

Even though our focus is on hospital logistics in Oslo, the study is hopefully also of relevance in other professional applications of unmanned systems. Such applications include law enforcement and defense.

Many potential drone applications have in common that they seek to leverage the potential advantages that drones provide in terms of low cost, high availability etc., and at the same time satisfy strict requirements regarding safety, availability, reliability and efficiency.

2 Scope

This study focuses on civilian drone use in the Oslo area, and especially the point-to-point hospital/laboratory logistics problem, transporting blood samples between Rikshospitalet and Ullevål Sykehus. We are limiting our discussion somewhat to small commercial or professional rotary wing drones, up to around 15kg. We are also limiting the discussion to low-level flight, defining this informally as below 500m above ground level (AGL). We also focus on the in-flight mission phase and the landing phase, postulating that the take-off phase and ground handling are more “easily solvable” challenges.

Figure 2.1 Norwegian company Aviant have performed a number of long distance winter flights as part of a push to realize medical logistics with drones. The aircraft and systems supporting them are not yet equipped for operations in icing or strong winds [13].

3 User requirements

The realism of a drone based transport service depends strongly on the user requirements. Payload size and weight, flight distance, number of flights per day, punctuality etc., are among the variables of importance. User requirements stem from the user “business model”, regulations, existing infrastructure, personnel plan, finances etc.

Requirements differ among the different use cases in health care. They may vary greatly for a given type of application in different locations. The Rikshospitalet-to-Ullevål use case is a special case, with a very large number of blood samples each day and a very short distance between the two locations.

Several projects in Norway have been, or are currently exploring the use of drones in hospital logistics (Airlift [14, 15], Aviant [13], Senseloop and Dronebud Solutions [16]). It has been shown that drone flights carrying blood samples (or other medical payloads) over some distance are feasible, and that the effects on the blood sample quality are probably not significant, provided certain precautions are taken [17]. The question of a full-scale operational service in an urban context, and in challenging Nordic weather is another altogether.

Figure 3.1 Zipline, perhaps the most well-known drone logistics operator [18].

Zipline [18] is possibly the best-known operator of medical logistics drones. They started in Rwanda, Africa, and have since diversified and spread their business to other countries.

Technical solutions and operations have come far, and have contributed to the growing interest in the use of drones to improve the reach and response times of medical services and logistics. User requirements must be expected to be quite different in a Norwegian hospital context, and thus the solutions should be expected to be different as well.

The HELSEVEL project was established in 2018, in order to lay the foundation for drone logistics for Oslo University Hospital (OUS) – based on a vision. The project was set up to study hospital logistics and internal processes, the weather related issues of icing and wind, as well as the possible effects of drone transport (vibrations and turbulence) on blood sample quality. The HELSEVEL project started out with an ambition of “99% drone availability, 24/7/365”, without having based that ambition on any stringent analysis. An ambition to guarantee test results within an hour from sampling time emerged early on, although this was at the time not based on any specific need for a 60 minute limit.

Irrespective of formal requirements, a strategy or a plan, several industry initiatives have emerged in Norway, following similar efforts abroad. Fixed wing drones (FW), rotary wing drones (RW) and hybrid FW/RW drones have been tested, and put forth as candidate solutions. Demo flights have been performed, and this has helped spark interest in the idea. These efforts may prove useful on the way forward, gaining further insight into requirements and possible solutions – which must co-evolve.

Figure 3.2 Swedish company Everdrone has developed a solution to deliver a heart starter using a DJI Matrice 600 drone. It was recently used to save a life. This type of application requires the ability to “fly anywhere, any time, on short notice”[8].

OUS have performed an in-depth study of the blood sampling process and sample logistical flow. This study gives us a basis to define user requirements. Johannessen et al (2021) [19] presented a model for drone transport of the complete annual analytic volume of 6.5 million analyses during a given year (2018). The transport of both routine and emergency samples between the two inner-city laboratories was simulated. The laboratories are located 1.8 km apart. A 60-minute time restriction from sampling to analysis result was imposed.

The blood sampling activity at OUS was found to display a characteristic pattern, with the most intensive traffic between 8 a.m. and 12 a.m. on weekdays. There is considerably less traffic the rest of the day, at night and on weekends (Figure 3.3). Drone schedules with departures 15–60 min apart were simulated. A maximum of 15 min between flights was required to meet the emergency demand for the analyses being completed within 60 min. The required drone payload weight capacity was below 3.5 kg at all times, given this 15-minute schedule. In these simulations, the variations in the clinic- and laboratory-related time intervals caused violations of the allowed total time in 50% of the cases.

The above study concludes that drone transport could enable reduced time to provide blood results, as well as enable consolidation of laboratory resources. The main question raised, is whether it is practically feasible.

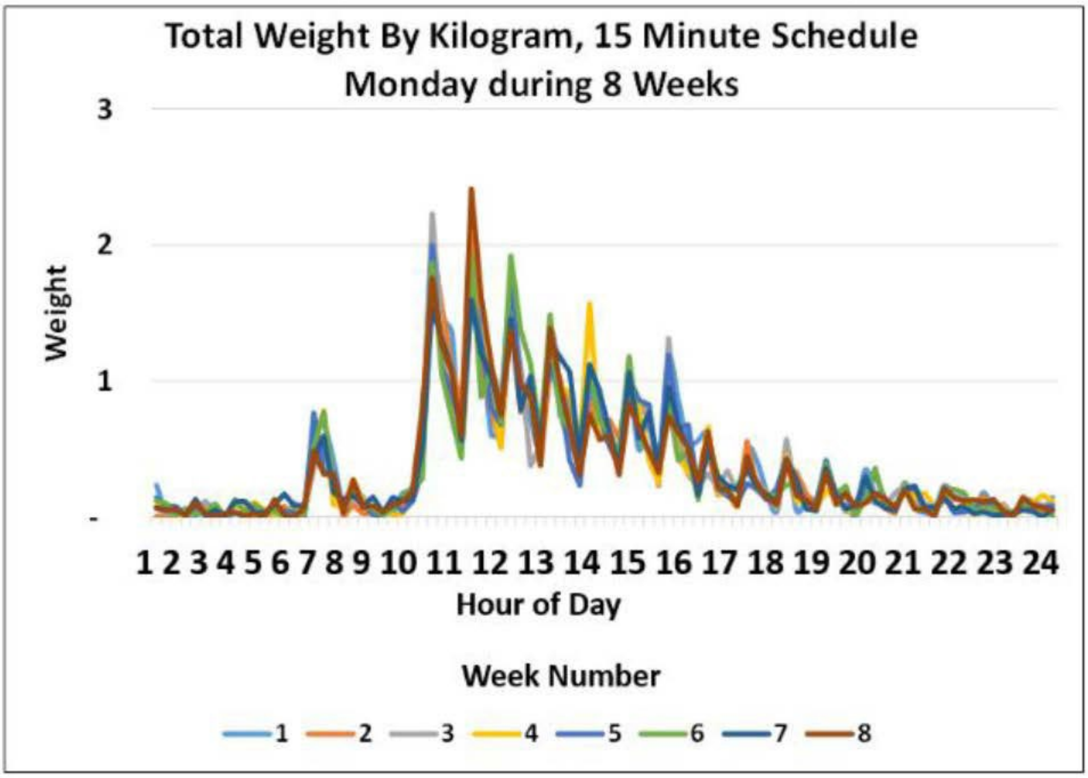

Figure 3.3 From the study conducted by Oslo University Hospital (OUS), which analyzed the complete blood sampling volume and process [19].

Based on the study at OUS, we may list the direct and inferred requirements to the drone transport service:

- 15 minutes between flights
- Payload weight below 3,5kg
- A very short flight distance of under 2km (In a straight line. We may assume that a straight line will not be appropriate, so we may stipulate a flight distance up to 4km)
- Much less demand (lower payload weights per flight) during the night
- The loss of an aircraft with payload would be critical in some patient cases (emergency samples), and less critical in others. Flight safety outweighs flight regularity and flight time in this particular use case. We cannot read any acceptance of loss or delay tolerance from the study, however

Certainly even more critical than the loss of blood samples, would be the loss of life or serious injury due to a drone crash in a populated area. Intuitively, and not in any way scientifically based, this could mean that not even one loss per year would be acceptable. I.e. a loss rate of one in every 70 000 flights, when stipulating one flight in each direction every 15 minutes, all year round.

We may conclude that in the particular hospital logistics applications we focus on, we want the mission to be completed safely, first of all, and secondly with a high frequency of flights, with small payloads. Some slack in regularity etc is acceptable.

What loss rate would be acceptable? In manned aviation, there is an established limit to failure rates of “one in a million”. This would equate to one catastrophic loss every 14 years or so, in the OUS case. We suspect that realistic loss acceptance could be higher than this, but still not on the level of one loss per year. This should be studied further.

Having this rather incomplete and tentative understanding of the user requirements in mind, we will dive into the subjects of icing and wind in the following chapters. We will assess the effects of icing and wind, weather statistics, how drone systems handle this today, the operational consequences and finally possible mitigations which may help us satisfy the requirements.

Figure 3.4 *(Left) Senseloop with their drone developed by Globe, during testing from Rikshospitalet to Ullevål Sykehus in 2021 [16]. (Right) Sabrinus 4-20. Airlift Solutions tasked Sea Technology and Easy Form with developing this drone for use in their efforts in medical drone logistics. The drone has a 4kg internal payload capacity, 20 kg total weight and 20 km range [14, 15].*

4 Icing

Icing is an ever present risk in aviation. The risk is mitigated through good airmanship, meteorology, in-flight ice protection systems (IPS) and de-icing on the ground before take-off.

Figure 4.1 De-icing passenger aircraft is a costly and time-consuming activity, and critical to flight safety. The effect is temporary, so aircraft also depend on in-flight ice protection systems (IPS) to operate safely [20].

There is often a residual risk, even after the very best of precautions are taken. This residual risk varies greatly according to aircraft type, operation type, time and location. The importance of the problem is visible to all air passengers in the Nordic region, frequently needing to wait for aircraft de-icing (Figure 4.1).

The risk of icing is also increasingly being addressed in the energy sector, with wind turbines and power lines occasionally icing heavily (Figure 4.3).

The general guidelines related to manned aircraft icing are well-known (Dannevig,1969 [21]).

Figure 4.2 In flight icing on the leading edge of a NASA research aircraft (left) and an air speed sensor (right)[3].

Icing occurs when a structure is exposed to the combination of below-zero temperatures and liquid water – either precipitation or cloud droplets. Water droplets freeze on the surface if the temperature of the surface is below zero or the droplets are supercooled. The ice that builds up, may have the following effect:

A. Changes the airflow around the aircraft, altering the wing lift-to-drag ratio and force moments

B. Increases the weight of the aircraft

C. Reduces propeller efficiency significantly

D. Introduces an imbalance in propellers, causing vibration (as ice sheds off)

E. Reduces the reliability of airspeed sensors (pitot tube icing)

The severity of the icing will depend on the amount of liquid water available as well as on droplet size, temperature of the air, flight velocity, airfoil shape etc. The icing process on a given structure is complex. Different aircraft may have very different response to the same icing conditions. Freezing rain is generally associated with severe icing, whereas freezing drizzle or fog causes moderate icing [21]. Flying in snow or ice clouds will generally not result in icing.

A number of meteorological parameters may be used to assess icing risk and intensity, including:

1. Temperature (air temp below zero, or aircraft surface temp below zero): Temperature far below zero gives reduced risk of icing, as more water will be in ice form

2. Relative humidity (>95%)

3. LWC – Liquid Water Content (liquid fog/cloud water droplets)

4. SLD presence: Supercooled Liquid Droplets

5. MVD – Median Volume Diameter

6. Dewpoint (the temperature at which water in the air mass starts to condense and form droplets)

7. Vertical air mass velocity (indicates condensation)

Figure 4.3 Icing on power lines and wind turbines is the subject of extensive research. The statistics and prediction tools are somewhat relevant to drones. (Left) The ICEBOX project has been working to increase knowledge about the icing process, ice shedding, and icing conditions statistics [22, 23]. (Right) De-icing wind turbine blades is a costly activity, but important, as ice shedding from wind turbines is a serious threat to safety (Image by Alpine Helicopter).

4.1 Icing and small drones

Most drone operators have never encountered icing. This has a lot to do with the way drones are used today. As we shall present and argue later, the weather statistics also support the impression that icing is not very common, even in Norway. Yet, in the context of this study, the chances of drones in service all year round encountering icing is far from negligible. Some accounts of drone icing among hobbyists can be found [24], and scientific studies thoroughly establish that icing poses a significant threat to small drones [25].

Figure 4.4 A hobbyists account of a drone crash due to icing [24].

Drones in professional use will need to pass through or operate within stratus clouds in sub-zero temperatures, heavy cumulous, freezing fog and drizzle. These are conditions which are avoided for the most part today when operating small drones. Hobbyists and many professionals have the opportunity to wait for better weather, or they operate locally, where they observe local conditions and take precautions.

The sum of the icing effects must be expected to be different for different drone systems, under any given weather condition. Generally, stability, controllability and performance may suffer severely sometimes, even with a small amount of ice. The type and amount of ice is of great importance.

For drones – especially small drones – the problem of icing is less studied and understood than it is for manned aircraft. Studies suggest that the vulnerability of drones is different, possibly higher and certainly more unknown than for manned aircraft [26-28]. The effect of small differences in icing conditions, ice amount and ice structure is not precisely predictable using available simulation tools. This being said, the simulation tools (such as FENSAP ICE, [29]) now often seem to be able to get fairly close to observed icing in controlled experiments [27].

Manned aircraft may rely on power demanding and heavy ice protection systems (IPS) to operate safely for a limited time, despite icing. They also have the advantage of having operators who may be able to detect icing onset or clouds, and thus react appropriately. A drone pilot today has very little to go on to assess whether the aircraft is beginning to ice over, and whether it is in a high risk air mass.

Indications may sometimes be seen in the behavior of the drone – an uncommanded loss of altitude, loss of airspeed or erratic airspeed measurements. Some systems now give the operator a warning when there is a mismatch between power draw and thrust (e.g modern DJI drones will provide a warning of this).

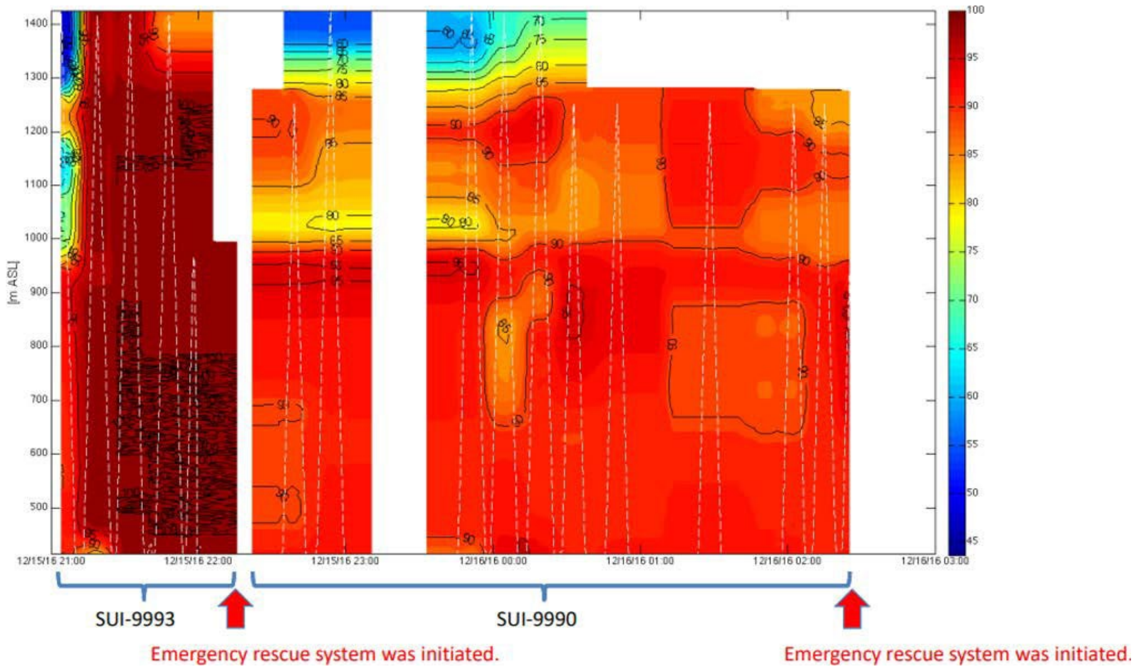

Figure 4.5 Small, low flying drones operate in a regime with significant local and temporal variations in icing conditions. Here, relative humidity was measured by Meteomatics, using a MeteoDrone [25]. Three test flights are included in this figure. In two of them, an emergency parachute system was activated because the drone became unstable/uncontrollable due to icing.

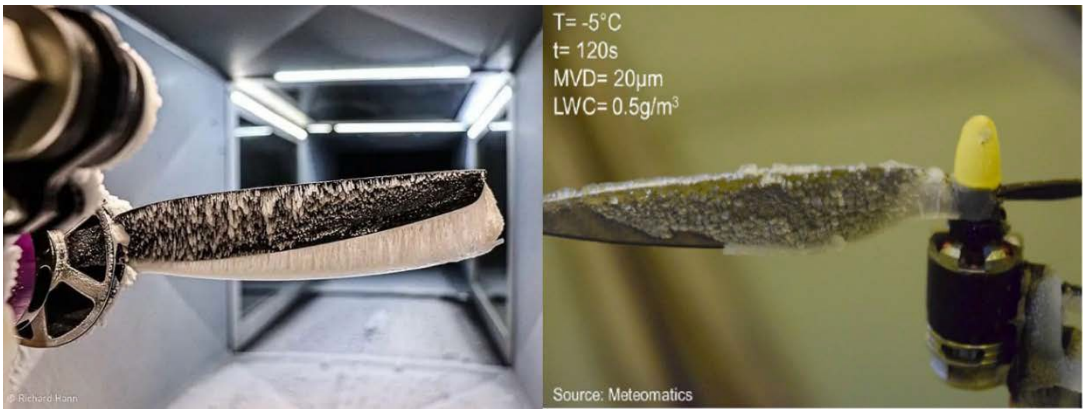

Figure 4.6 Propeller icing experiments by Ubiq Aerospace [30] (left) and Meteomatics [25] (right), among many others, have established that icing will seriously affect the efficiency of propellers.

Small, low flying drones operate in a difficult icing regime, with high water content (LWC – Liquid Water Content) and temperatures often close to zero during winter. There are very large local variations in icing conditions, with rivers, lakes, bogs, rising air due to terrain etc affecting the local meteorology strongly. Drones also have a long flight time in risk areas close to the ground. As drone use expands, more and more flights will be “beyond line of sight” (BLOS).

Observations in icing wind tunnels [30] as well as anecdotal evidence shows that, given the right conditions, icing sets in and develops very quickly – building to dangerous levels within minutes ([25]). Data on actual, real world in-flight icing is very sparse.

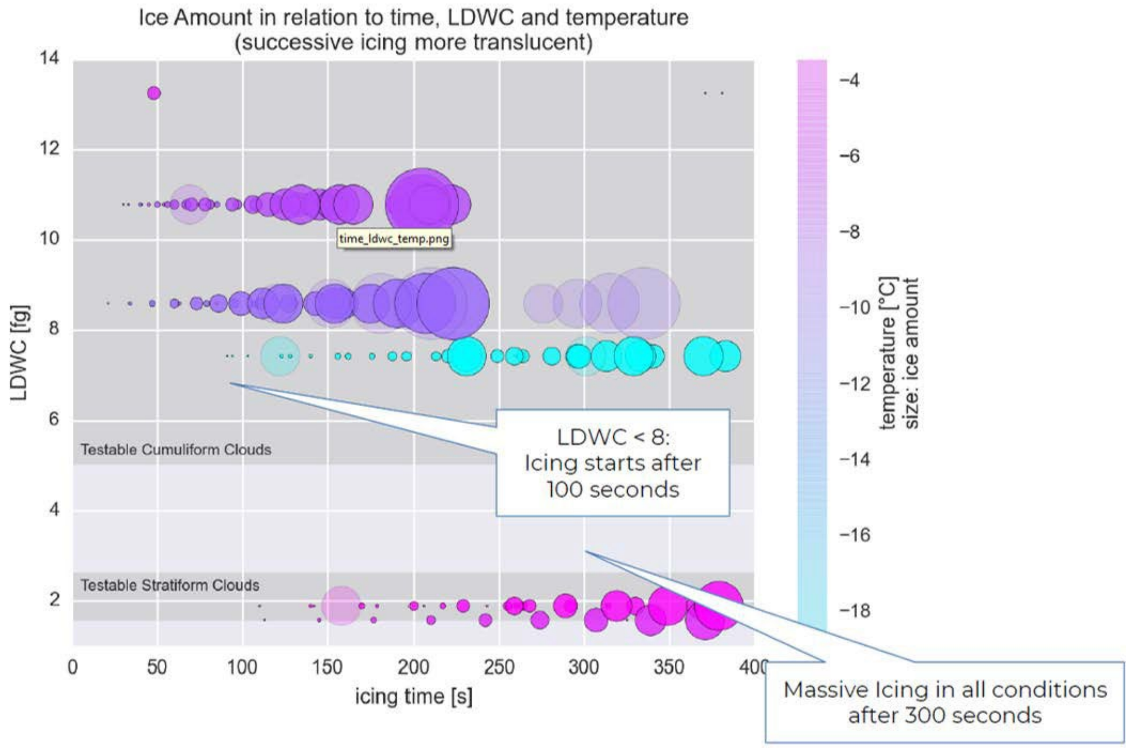

Figure 4.7 This illustration of results from Meteomatics [25] tells us that heavy icing may set in quickly, given the right conditions. Icing sets in faster in higher liquid water content (LDWC) and in temperatures close to zero. A high LDWC is characteristic of cumulous clouds, whereas stratiform clouds have a lower liquid water content.

There are no mature solutions in place for drones, specifically aimed at the icing problem. There is no quality control or regulation regarding icing tolerance and mitigations. It is recognized that knowledge from manned aviation is of only partial relevance and that prediction and ice protection solutions used in manned aviation are not necessarily applicable to small drones flying at low level.

Both basic research and technology development are needed to increase understanding of drone icing. Work is underway, for instance at the NTNU UAS Icing Lab [31] and Ubiq Aerospace [30]. The Andøya Space “IceSafari” project [4] is also aimed at gaining more knowledge into the basic atmospheric science related to drone icing.

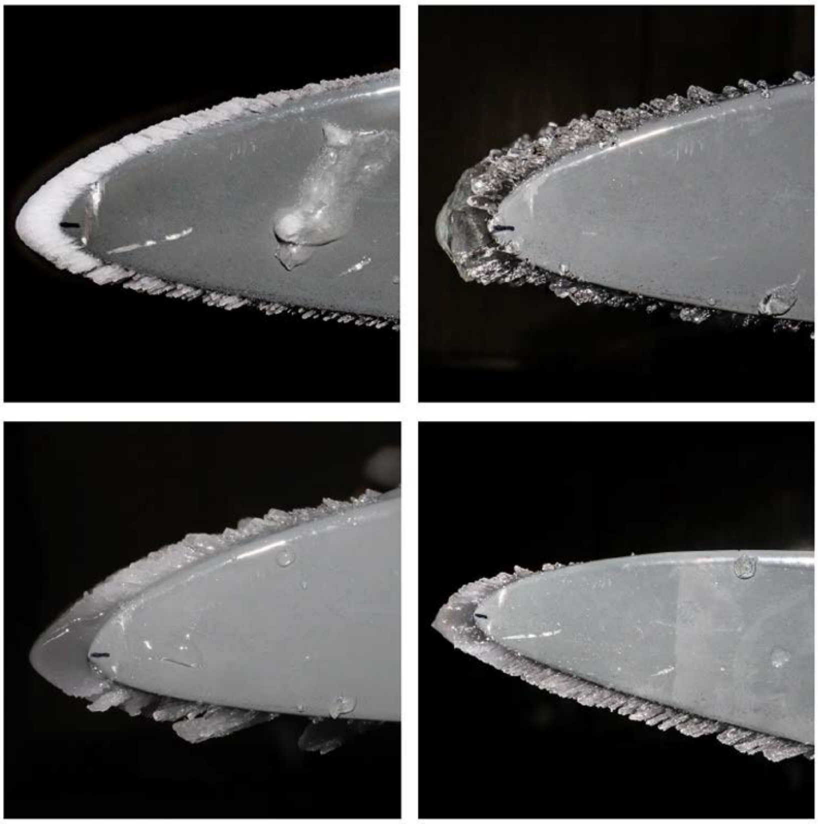

Figure 4.8 Rime ice (top left), glaze ice (top right), mixed ice (bottom left) and mixed ice at a high angle of attack (bottom right) [27].

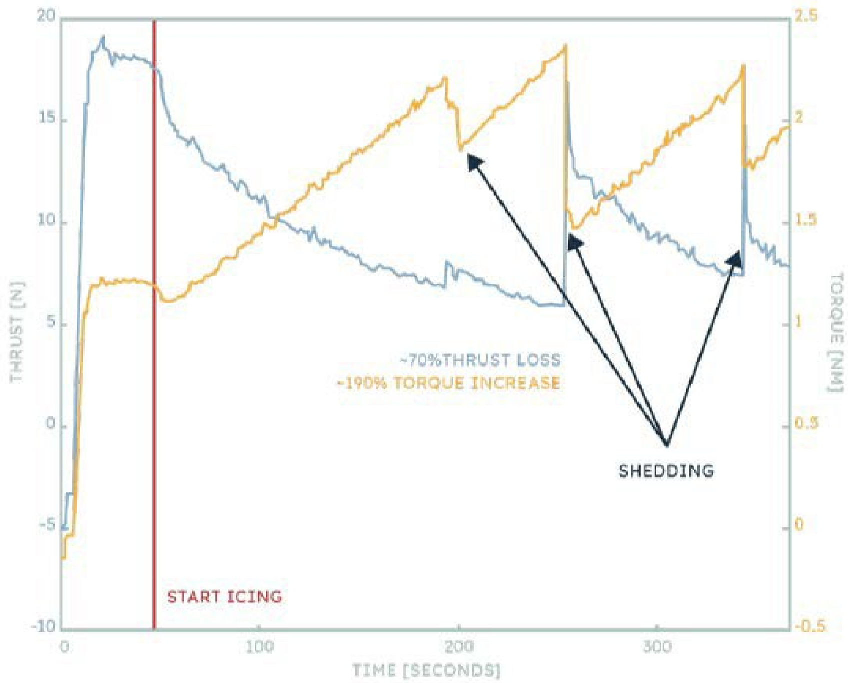

Figure 4.9 Propeller performance degradation and the effect of multiple ice shedding events.

When ice builds up, thrust is dramatically reduced and torque increases (as a consequence of increased propeller drag), until ice sheds, restoring thrust [7]

4.2 Practical tests

We have performed a limited series of propeller bench tests and live flight tests. The practical tests focus on what we consider a representative rotory wing drone type – the DJI Matrice 600 [32]. For a quick comparison, a commonly used "non-DJI" propeller type was also tested in the bench test setup. We have used two different types of coating to emulate ice on the propellers – a velcro band and an "anti-slip tape". Only the anti-slip tape was used during the live flights.

4.2.1 Live flight test

To assess the real-world response of a drone to propeller icing, we performed a small series of flights with and without an emulated ice coating. To ensure a low risk approach, we chose to use an anti-slip tape (Figure 4.10), emulating a moderate ice layer on the propeller blades.

This simple experiment provided interesting results. The roll- and pitch dynamics and the power draw are plotted in figure 4.11 and 4.12, respectively. The most immediate observation was that the sound of the drone with emulated ice was noticeably different, compared with the "clean" state. More importantly, we readily observed that the dynamic behavior was slightly different. At each abrupt commanded stop, the drone veered slightly more to one side (left) than it does without icing. During rapid descent, the drone clearly and consistently looked a little less stable.

The behavioral changes were, however, not dramatic. Studying the logged data, however, we see that the effects of the emulated ice were significant. Looking at the pitch and roll angles during the rapid vertical descent and ascent, there is clearly much more deviation from zero.

The increase in power required to hover increased dramatically, even with such a moderate coating. The increase is roughly 80% (178W to 321W for each motor). Time did not allow for tests with a slightly more aggressive propeller coating.

Figure 4.10 The DJI Matrice 600 during practical testing with emulated ice coating on propellers, January 2022. (Bottom left) Clean DJI propellers and (bottom right) propeller with emulated ice coating using an anti-slip tape. This ice emulation could roughly correspond to a moderate mixed ice buildup (FFI).

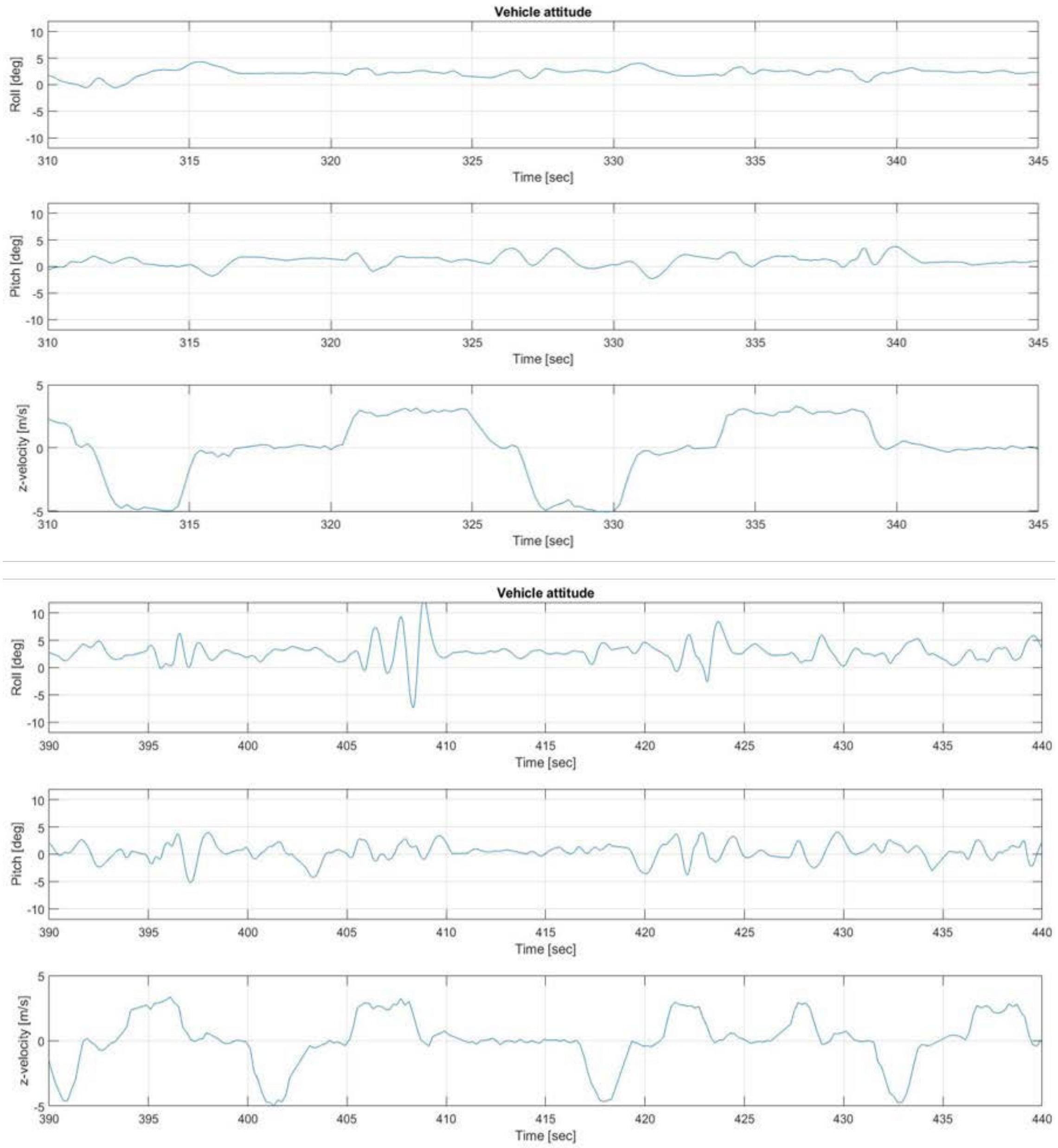

Figure 4.11 Roll and pitch measured during the test. Top three panels: without icing, and (bottom three panels) with icing, emulated using an anti-slip tape on the propellers.

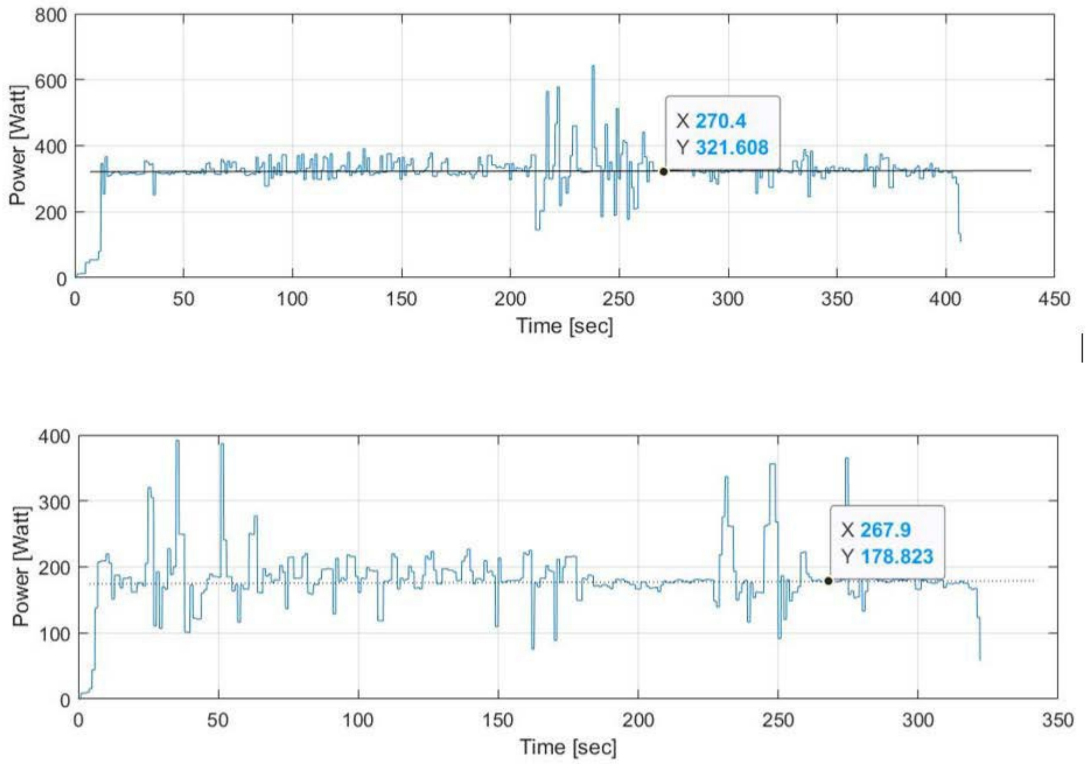

Figure 4.12 Logged power draw during a test flight with an emulated ice coating (top) and without ice (bottom).

4.2.2 Static testing

Static testing in a semi-enclosed box was performed for the DJI 2170 propeller, paired with a DJI 6010 motor, as well as for a smaller 17 inch T-motor Carbon propeller, using the T-motor U7 electric motor. The RC Benchmark (RCBM) 1580 test apparatus was used in both test series, with an added element of a Jeti speed controller and RC controller for the case of the DJI setup. This was needed in order to work around the limitations in the particular RCBM test stand model, which cannot handle the high voltage required to run the DJI motor/propeller combination

The results from the static tests very clearly show the significant effects of the two different types of emulated ice. For the case of the anti-slip tape, the power required to hover increases from approximately 155W to 285W, giving us an increase in power requirement of 84%, corresponding quite well with the live flight tests. The propeller RPM (revolutions per minute) required for hovering flight increased from 2700 to 3300.

Using the more aggressive coating (the velcro tape), the effect is even greater. At any given

RPM, the thrust is significantly lower than in the case of the moderate ice emulation. The maximum achievable thrust was not determined in our tests, but there is reason to postulate that stable flight is not possible with such a performance degradation. Tests performed with a common high performance propeller other than the DJI model, confirm the very dramatic effect

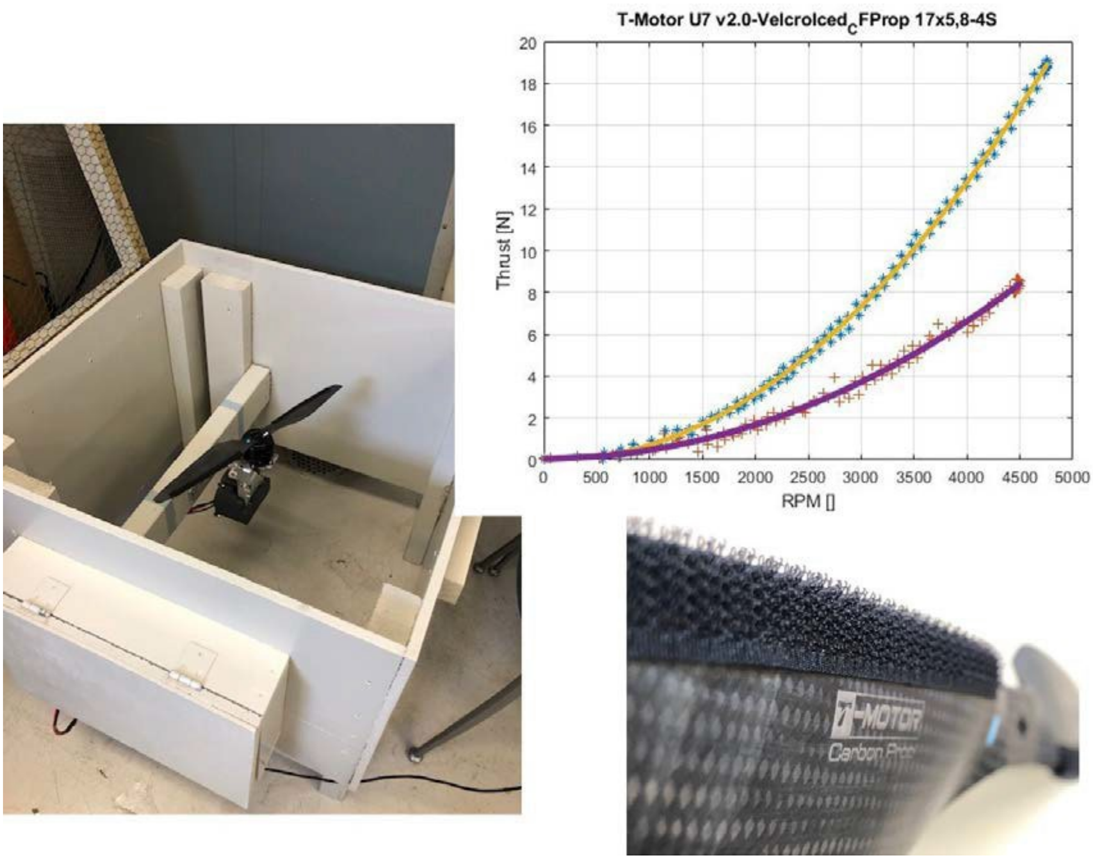

Figure 4.13 Propeller testing using the RCBenchmark 1580 test apparatus, and a T-motor CF Prop. The bottom (purple) curve is thrust for the "iced" propeller, using a very ough velcro tape to emulate icing (FFI)

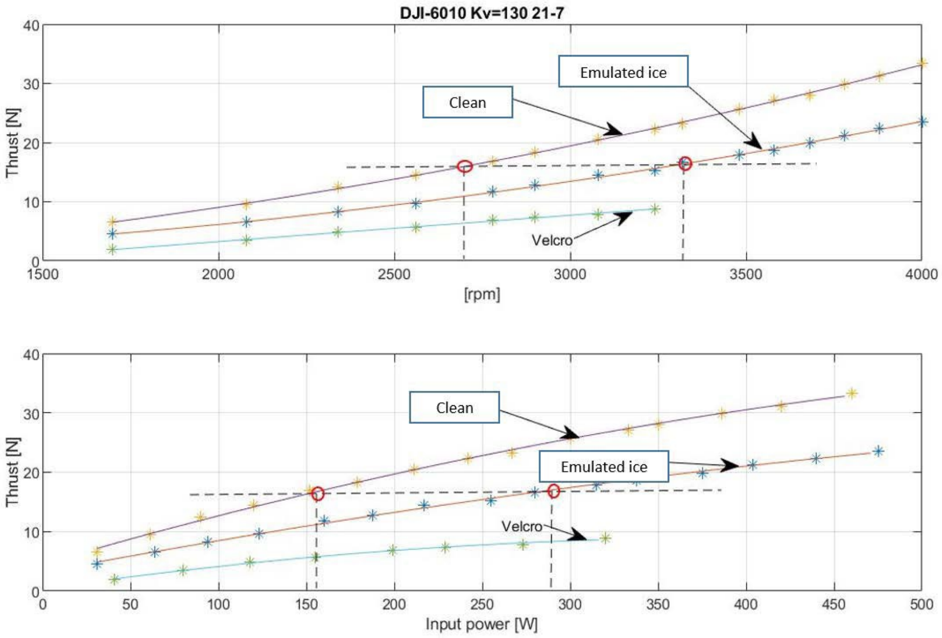

Figure 4.14 Propeller test results for the DJI Matrice 600 propeller and motor (FFI). The dashed horizontal line indicates required thrust from one motor and propeller in static hover mode.

Figure 4.15 The two types of emulated ice used in the static bench tests. (Top) An anti-slip tape and (bottom) a velcro tape, both from BILTEMA (FFI).

4.3 Icing conditions statistics

Ubiq Aerospace, FFI, met.no and others have published studies which indicate how often icing might occur [1, 2, 7]. Kjeller Vindteknikk have produced an icing risk map which may be relevant for drones [33]. The met.no study was based on surface observations, whereas the Ubiq Aerospace study included model data, and aggregated the results in altitude bands and full-height columns. The lowest altitude band covers 1-3kft AGL (Above Ground Level) for several locations, including Rygge, which is the closest one to Oslo.

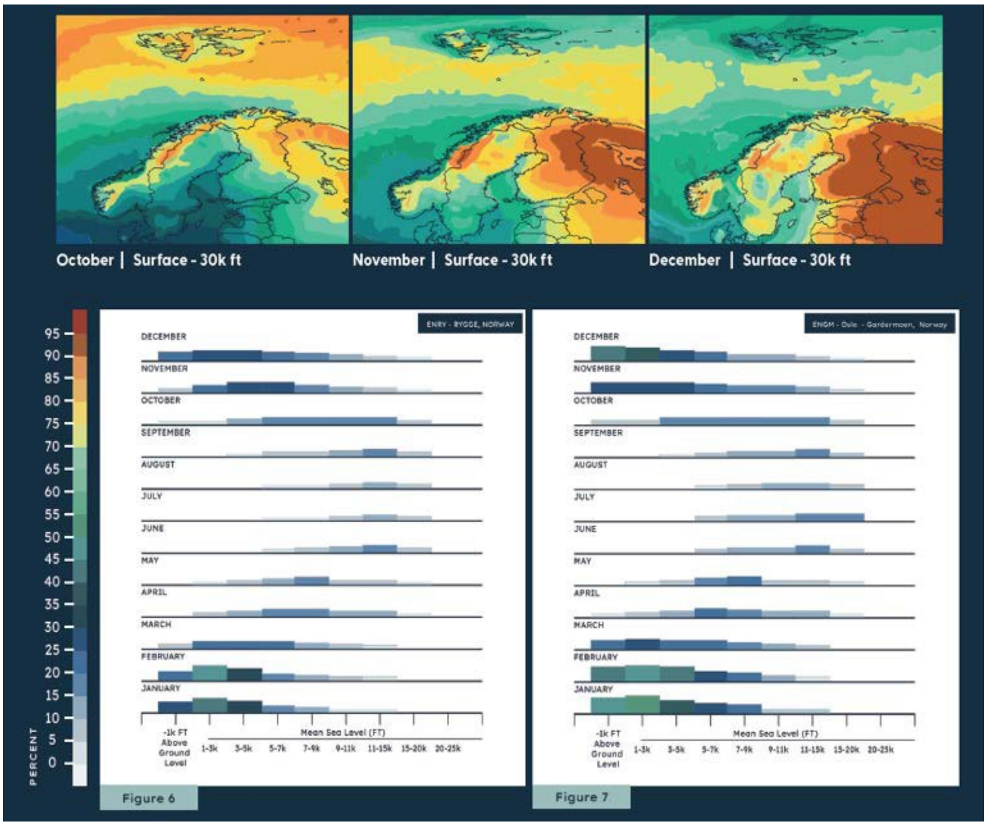

Figure 4.16 (Top) Aggregated full column icing probability from the surface to 30000 feet (k ft). (Bottom) Icing probability in altitude bands for the Nordic region [7]. (Bottom left) Rygge and (bottom right) Gardermoen. This study produced much higher icing probabilities than the met.no Helsevel study, exceeding 50% during winter months in the lower altitude bands

Based on a general review of the studies mentioned, the majority of low altitude drone flights in the Oslo area will probably not encounter a high risk of icing. Low altitude UAS missions in Oslo would be exposed to a risk of icing perhaps 5-10 % of the time during the winter months. The risk increases rapidly with increasing altitude, referring to Figure 4.20, displaying the increasing likelihood of entering clouds with increased flight altitude. The Ubiq study indicates a higher risk, due to the inclusion of higher altitudes in the lowest band, which would cover flight in clouds more often than the case for VLL-flights (Very Low Level), which were the focus of the met.no study.

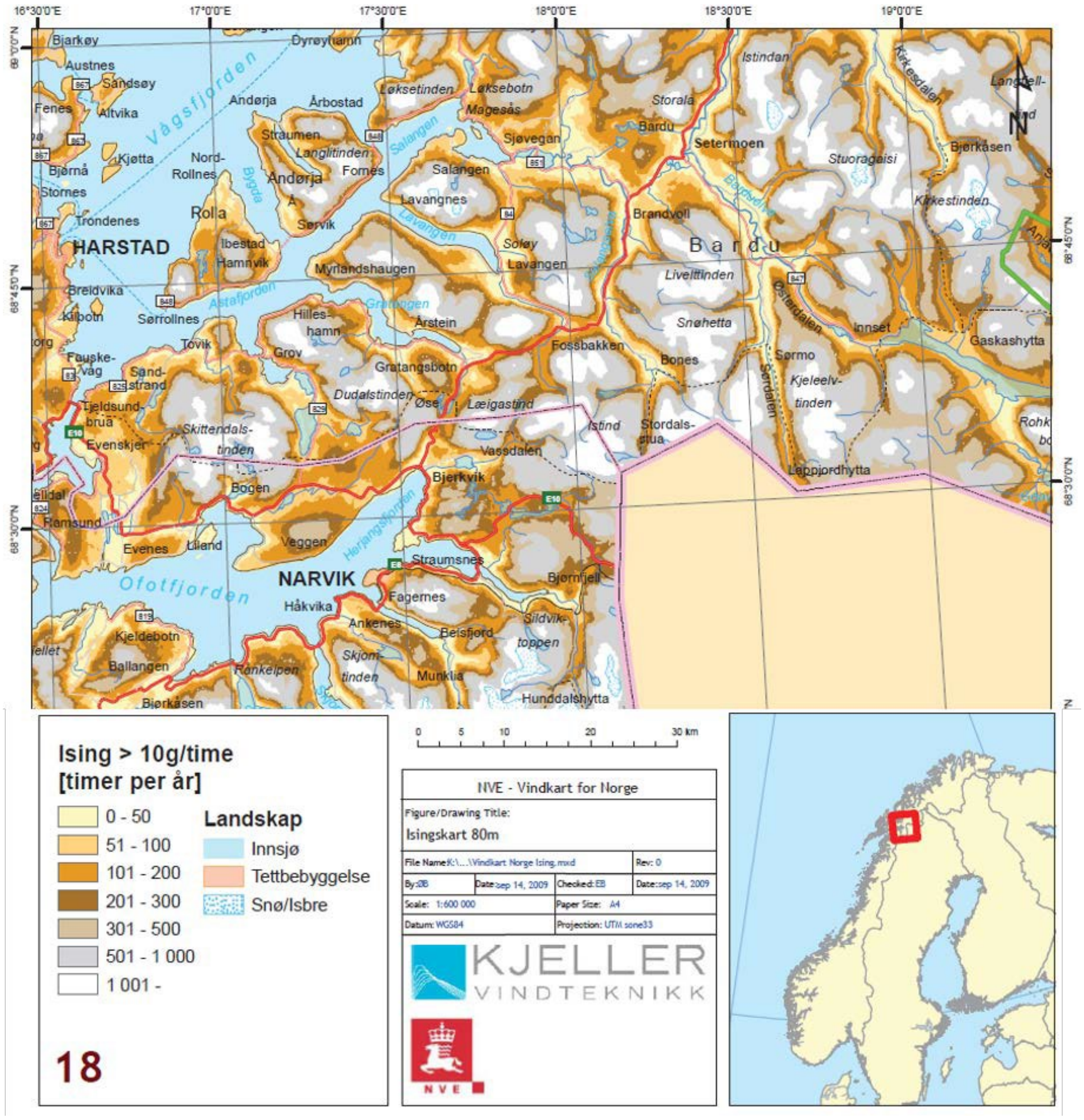

Figure 4.17 Icing intensity frequency map generated by Kjeller Vindteknikk [34, 35].

It should be noted that in operations with small drones, it is relevant to plan for flight altitudes up to at least 500m AGL. The altitude band of interest will depend on the use case. This implies that an aggregated “full column” icing risk is somewhat relevant, and thus that we must plan for a much higher risk than 5%.

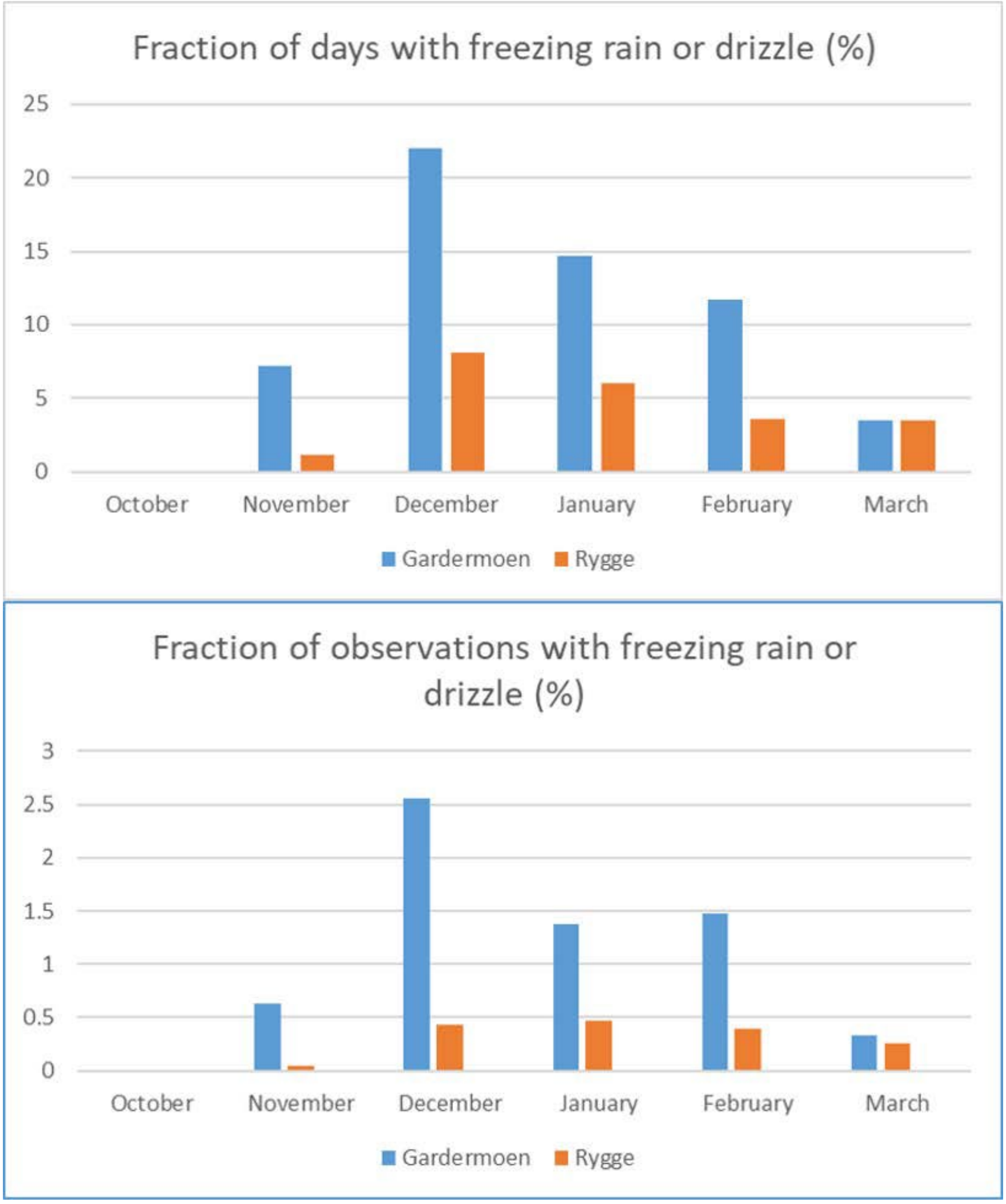

Figure 4.18 Statistics of observed instances of freezing rain or drizzle at surface level at Gardermoen and Rygge between 1 jan 2013 and 1 april 2019 [1]. This study was part of the Helsevel project.

There will be days and weeks in Norway (specifically the greater Oslo area) when icing will occur frequently, and throughout certain missions. The majority of winter drone missions will however not encounter icing. We do not have any statistics for severe convective activity, which could increase the risk, although most such events take place during the warmer months.

Given the available studies, planning for an icing risk up to 30% of the time between autumn and spring seems pertinent. This would allow the developed systems and operational concepts to be applicable in other parts of Norway with a higher risk of icing than Oslo.

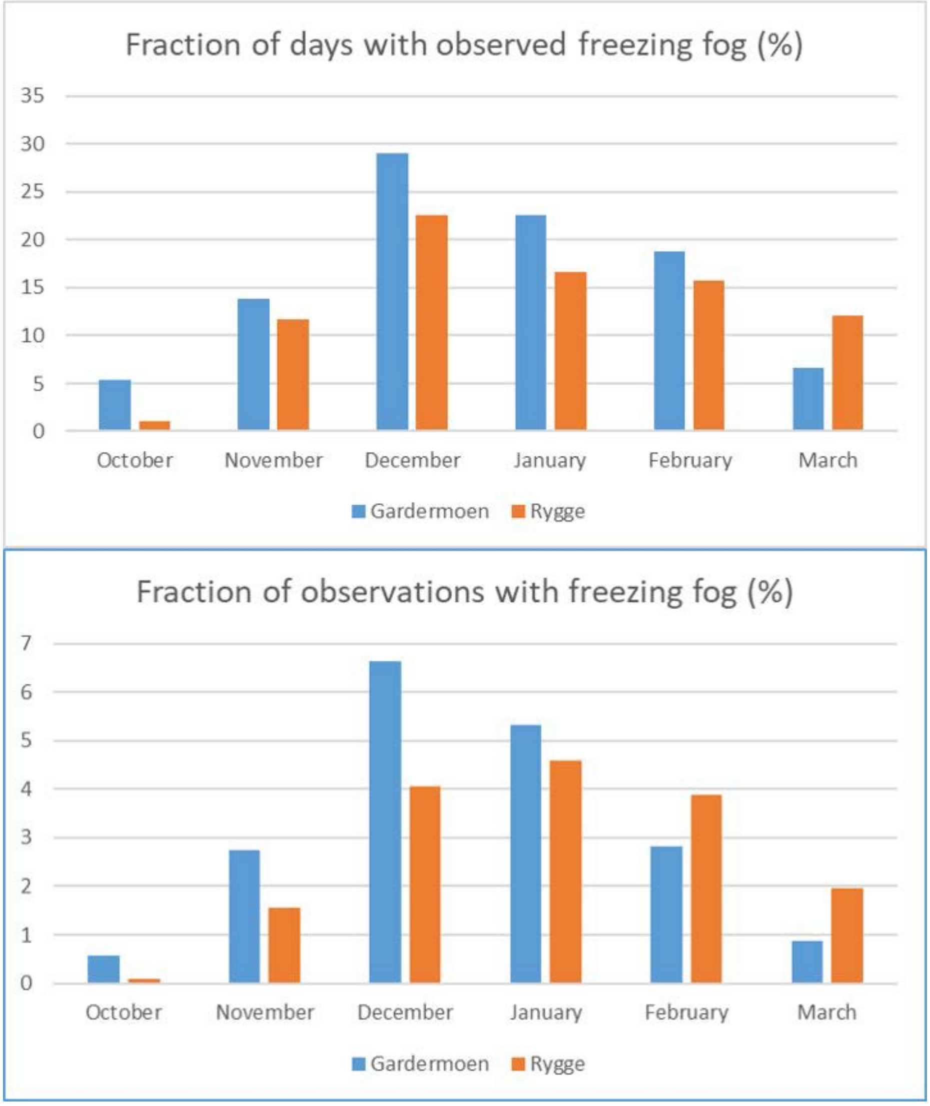

Figure 4.19 Surface level observations of freezing fog at Gardermoen and Rygge [1]

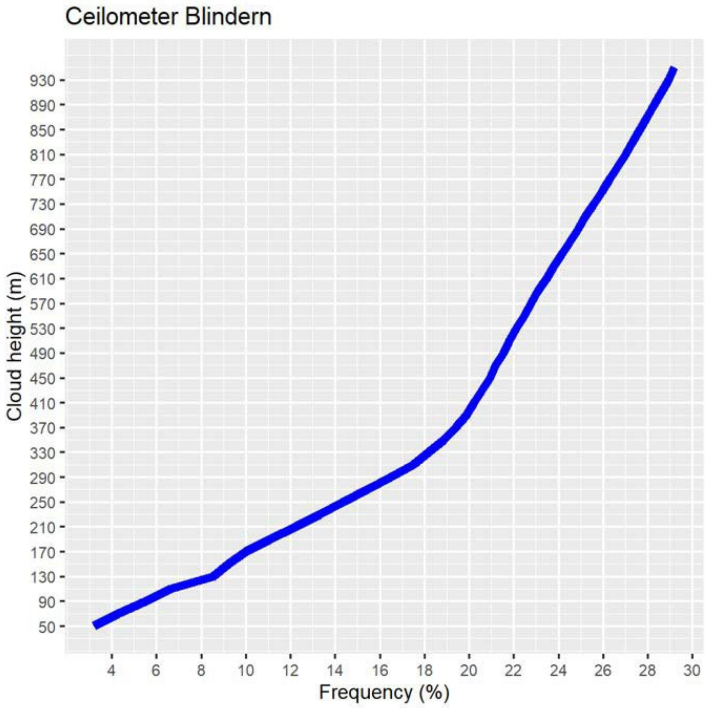

Figure 4.20 Measured cloud base using the cielometer at Blindern, Oslo [1].

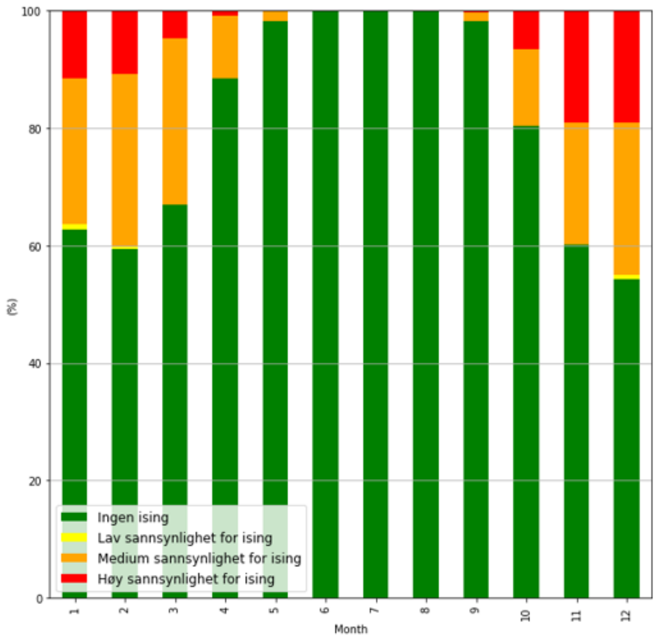

Figure 4.21 Estimated risk of icing at Bardufoss in Norther Norway [2]. Green=no risk, yellow=low risk, orange=medium risk, red=high risk.

4.4 Icing mitigation

There are several ways to mitigate the problem of in-flight icing on small drones. We will briefly introduce and discuss some of them.

4.4.1 "Brute force" icing mitigation

The idea of ensuring a large enough thrust margin may work up to a certain point, when icing becomes excessive. We have seen in our practical tests that the power required to fly is easily doubled, even with moderate icing. Power delivery saturation or propeller stall will set in at some point, which is system specific. We may assume that it is unlikely that we may use "brute force" – i.e. a large available power surplus to withstand icing beyond a certain system specific limit, which must be determined.

4.4.2 Icing forecasting

Icing forecasts for aviation have been available for decades. Some icing forecasts specifically intended for the drone community are also now available ([9] is an example). Aviation icing forecasts are available through a number of different web sites (such as the IPPC [36]), the METAR and TAF routine briefings etc. The forecasts cover a spectrum of formats. The available data covers forecasts several days ahead as well as what we may call "nowcasting" – which is either a forecast for a very short time ahead (e.g. 1 hour) or actual reporting of the current situation at a given location.

The AROME models run by the Norwegian Meteorological Service run a 2,5km horizontal grid. In addition to the issue of spatial resolution, the fidelity of the models is known to be generally less than desired, with different models having different strengths and weaknesses.

There is a noteworthy lack of high resolution forecasts for icing. The products are also not extensively validated, especially not with respect to validity for drones. Areas outside of established air routes and aerodromes are generally not covered by observations. The common icing met products are clearly adapted to use in support of manned aviation.

The quality of existing ice hazard forecast services should be studied more closely. The representation of liquid water droplets seems to be an area of needed improvement, although the added value is uncertain. Also, improved understanding and quantification of the situation dependent uncertainty in the icing index services may be important. These issues are being addressed by the meteorological community ([37]). The drone community could and should work to influence the developments in the forecasts, and contribute to validation and assimilation by providing insitu measurement data.

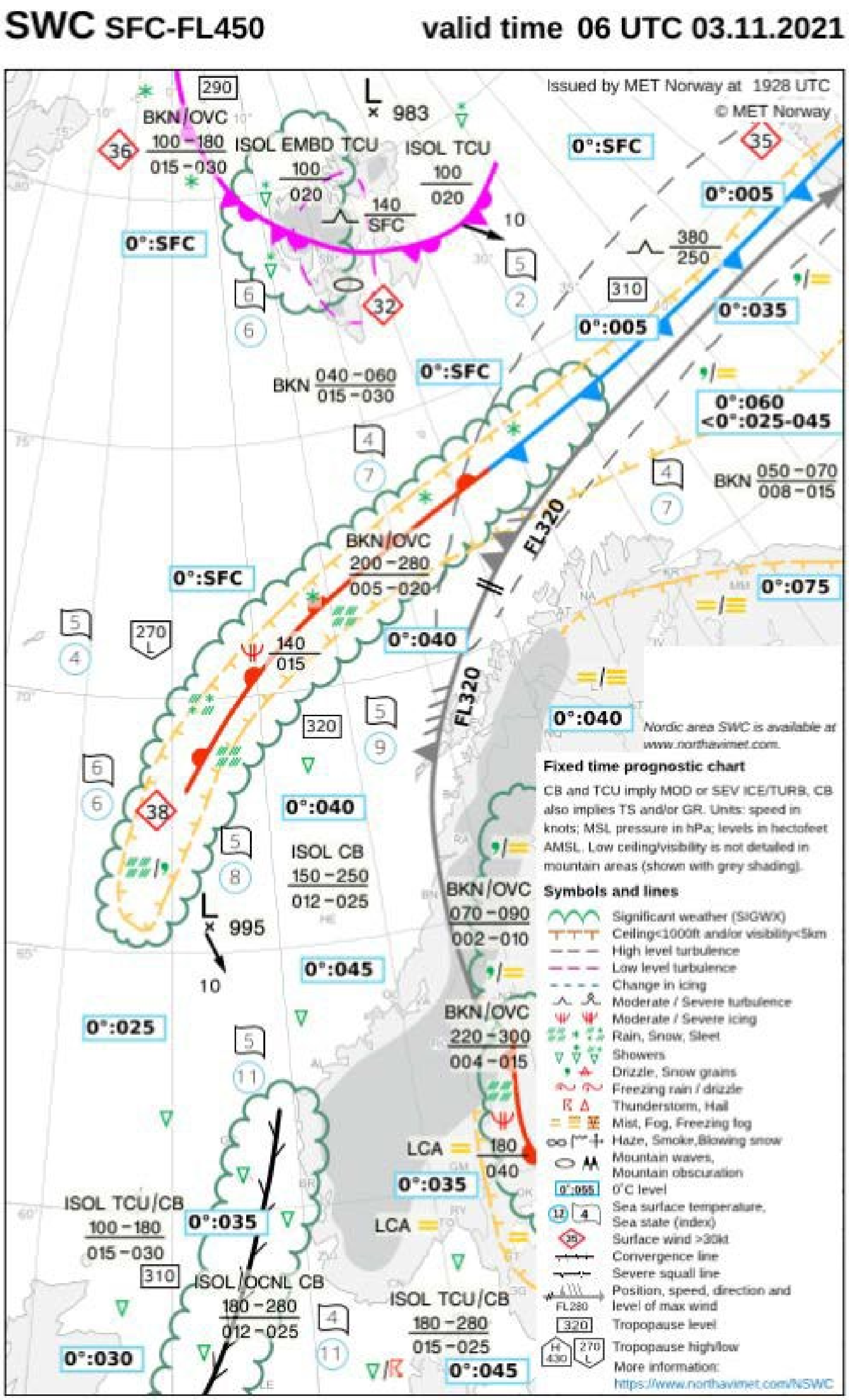

Figure 4.22 A typical chart showing the significant weather features, including icing, on a very course scale [36].

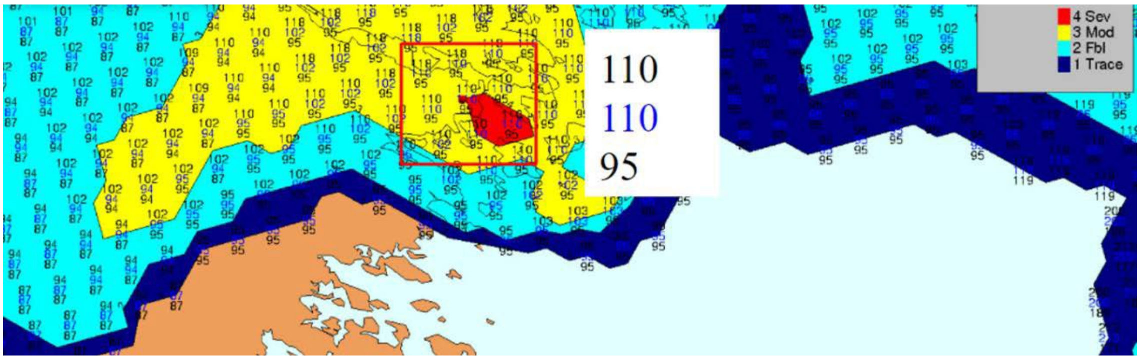

Figure 4.23 An exerpt from an operational icing forecast for general aviation, generated by met.no, and available on the IPPC site. This product displays the top and bottom of the icing layer, as well as the flight level for the most intense icing [36].

Improving the quality of the met services relies on more knowledge about the drone icing process, and the atmospheric processes which give rise to icing conditions. The "IceaSafari» project ([4]) will provide further insight into icing and atmospheric physics. Other important work is ongoing globally, ensuring future improvements, which may be leveraged by the drone industry.

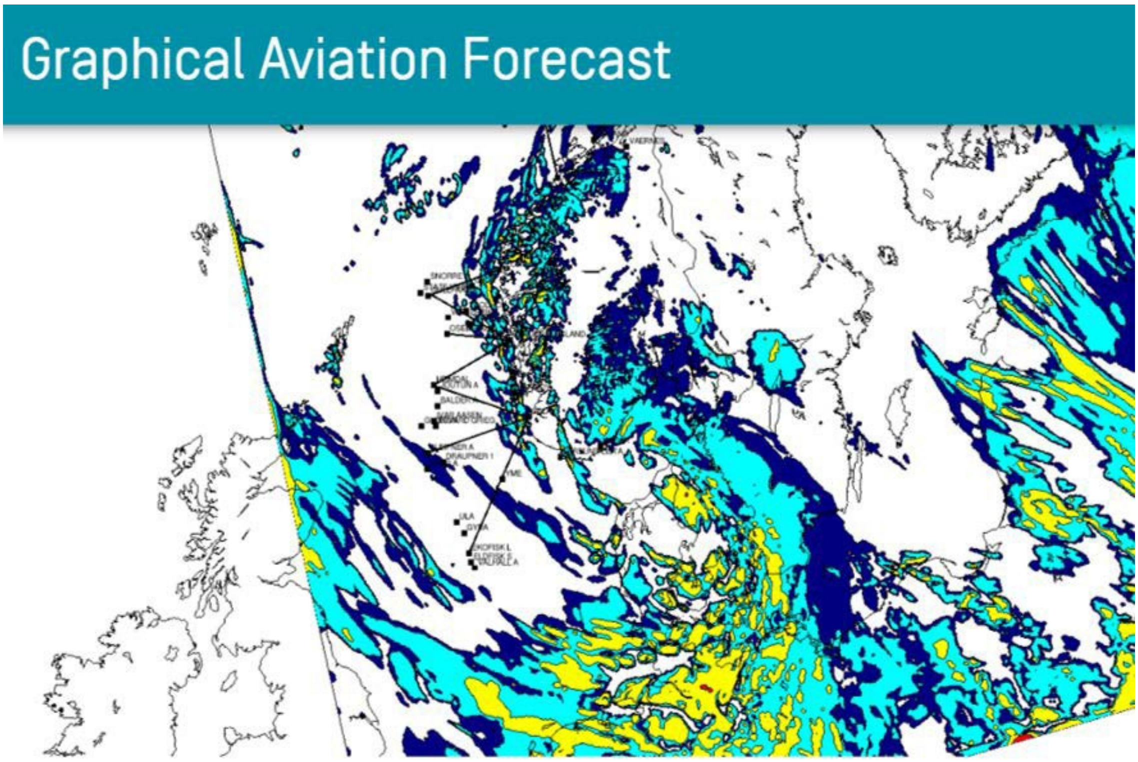

Figure 4.24 Another typical icing chart that may be accessed on the IPPC site.

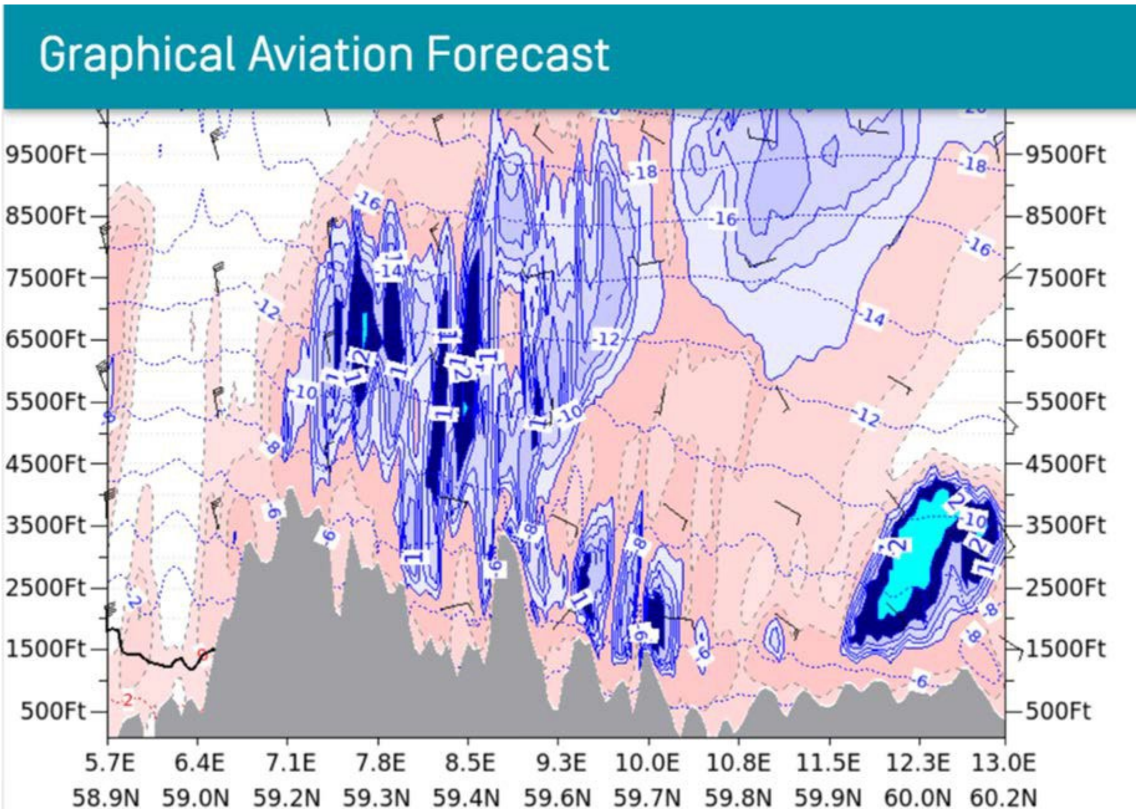

Figure 4.25 An icing forecast for a given route gives you an impression of the large scale icing probability and its variation with altitude. Light blue (cyan) indicates a high risk. This figure depicts the direct route Bergen (Flesland) –Gardermoen (OSL).

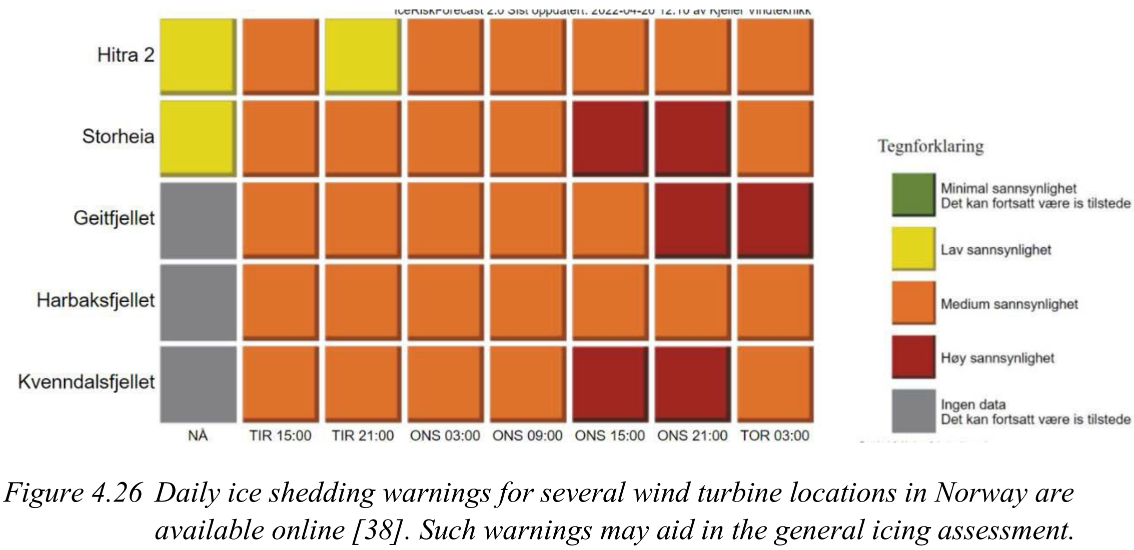

Figure 4.26 Daily ice shedding warnings for several wind turbine locations in Norway are available online [38]. Such warnings may aid in the general icing assessment.

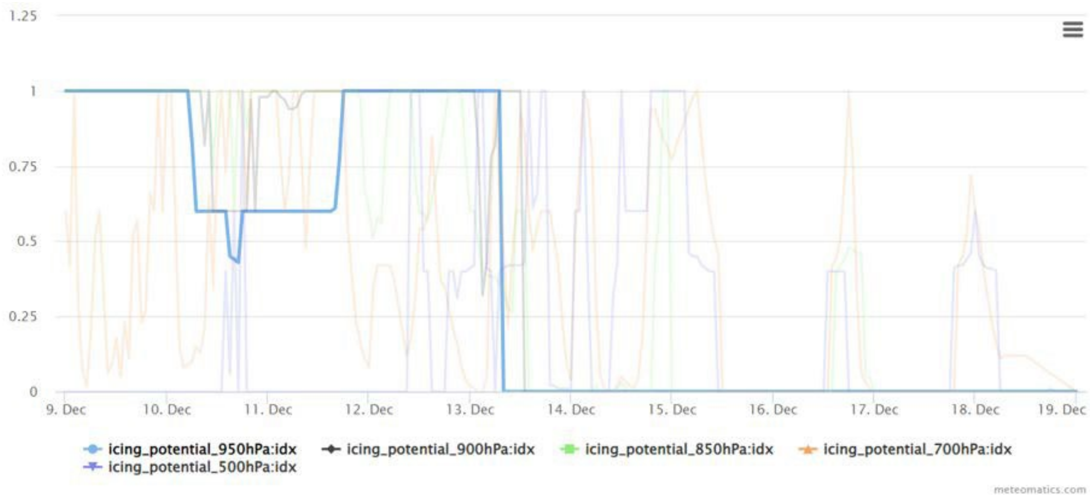

Figure 4.27 Meteomatics Weather API icing index forecast for December 9-19 2021. Highlighted is the 950hPa icing forecast for Nordbergveien in Oslo, showing a value of "1" a great portion of the time. 950hPa corresponds to ca 500m ASL, or about 360m AGL at this location [10].

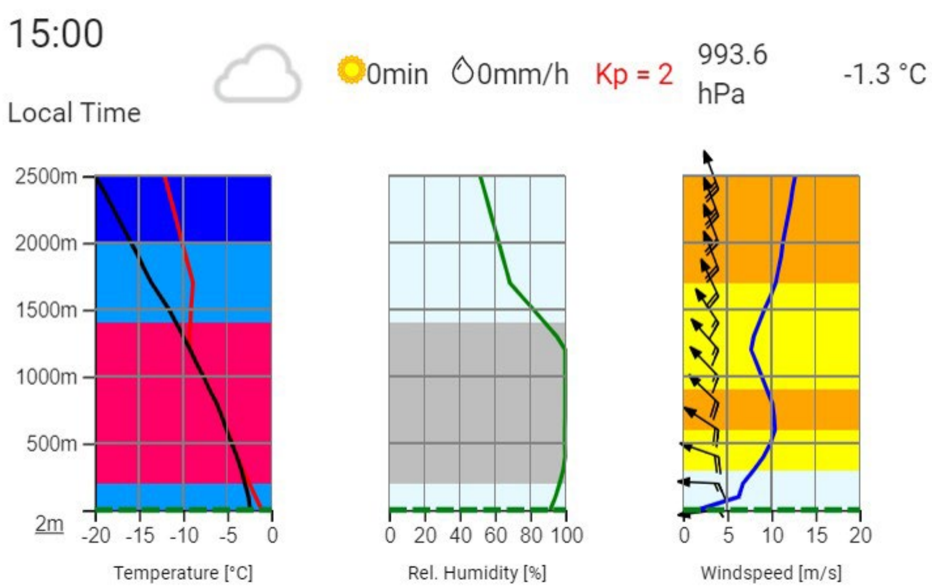

Figure 4.28 The Meteomatics Drone Weather open online service. This screen shot corresponds in time and location to the API results above from Nordbergveien in Oslo. This product is based on temperature and relative humidity. The red region indicates icing. Black line: dewpoint, red line: T. Hight is AGL (above Ground Level) [9]

4.4.3 Mission planning

Given an icing forecast, it is possible to plan a route that minimizes the likelihood of icing, and to choose when to fly. There are some prerequisites:

1. The resolution of the icing forecast is sufficiently high, resolving meaningful variations in the icing risk

2. There are provisions in the airspace management scheme, which allow different routes to be chosen, instead of following e.g. a strictly defined, narrow three-dimensional corridor.

3. Airspace management must allow some flexibility in take-off time

4. The user community must allow for variations in mission timing

The merit of a route plan based on meteorological icing predictions will be limited by the uncertainty in the models, which we must assume is large today. Small-scale variability is poorly represented in the available services. Replanning “on the fly”, in reaction to what we encounter, will be essential in some missions.

The term “route planning” could in the very local domain possibly be replaced by the term “path planning” or “motion planning”. The details in the way an air vehicle maneuvers and moves to follow its general route plan, adds complexity to the problem. All air vehicles have limitations in the way they fly, and the behavior is altered when icing sets in. The route/path planning software must account for this. Special behaviors for different drones, adapted to icing events, will need to be defined and implemented in the control system.

There is directly relevant work underway at NTNU, Ubiq Aerospace [30] and Maritime Robotics [39]. We may expect that at least one route planner will become available within the next 2-3 years, based on the state of the art, as found e.g. in several recent published Masters Thesis (an example is found in [40]).

4.4.4 Insitu sensing

We have discussed some of the limitations of aircraft weather robustness, ice forecasting and ensuing limited expectations to flight planning to avoid icing. The next step is to build awareness of the flying conditions where the drone is at any given time and of the actual state of the drone (ice buildup).

It seems probable that measuring cloud properties in situ, and then using a good model for the icing process for the actual aircraft type in question, will enable a quicker response than relying on ice buildup detection –after the fact. This should be studied further. In any case, cloud property data and/or aircraft icing detection from onboard sensors, or from other aircraft nearby, will help:

- guide the use of IPS (Ice Protection Systems)
- inform decisions (emergency (auto)pilot action)
- inform other aircraft on their way into the same air mass
- development of better icing forecasts

The standard meteorological measurements of temperature, humidity and pressure may be part of a low cost sensor suite on any drone today. These measurements will be useful in estimating the risk and intensity of icing, using a rule-of-thumb like the "Appelman Line" (as used in [2]). Measuring the size and density distribution of supercooled liquid droplets (SLD), could allow a much improved early warning capability. Such cloud insitu sensing is currently not possible onboard small drones. Several development efforts are underway, e.g. at Spec Inc in Colorado [11], USA.

The Icesafari project [4] is a collaboration between Andøya Space and Romanian universities, and has set out to develop an "early warning system" - the IceWarn sensor suite. To support the development of IceWarn, the IceSafari team will work to advance the understanding of mixed-phase clouds. These clouds consist of both super cooled liquid droplets and ice particles. An aircraft-certified holographic cloud probe called HoloScene will measure the concentration and size distribution of cloud droplets and ice crystals in order to develop the numerical models that IceWarn needs.

It is uncertain when suitable sensors that will allow more "ambitious" onboard icing condition sensing will be available, and whether sensor units will be mostly suitable for scientific research or regular operational use on board a large number of (small) drones. It does however seem fairly safe to assume that cloud particle imagers, cloud lidars etc will continue to mature and become more readily available for use onboard drones.

Figure 4.29 The Icesafari project is developing the IceWarn sensor suite, an early warning systems for use onboard drones [4].

Figure 4.30 The IceMeister icing sensor is one example of available solutions [5].

There are several technologies that may be used to detect or observe ice buildup [41-43]. Sensors based on probe electrical properties (capacitance and resistance), optical path blocking or optical imaging etc exist, and are used in a wide array of industrial and scientific applications. It is also possible to detect icing indirectly by estimating anomalous drone performance, e.g. thrust to power (or RPM) ratio for a propeller. Detecting the aerodynamic effects of icing is a workable solution, one method for which has been patented by Ubiq Aerospace. Image based ice detection may be supported by automated image processing. Photographing icing on propellers in motion (also at night), rotating at e.g 4000 rpm, has to our knowledge not been attempted on an airborne drone.

Ice detectors for manned aircraft have been used for decades. Many of these are too large and/or too heavy for small drones. Some may however be usable on the size of drone we are focused on. A few different ice detectors that are suited for use on drones are now available (e.g. [5]), but we are not in a position to comment on the usability or quality at this time.

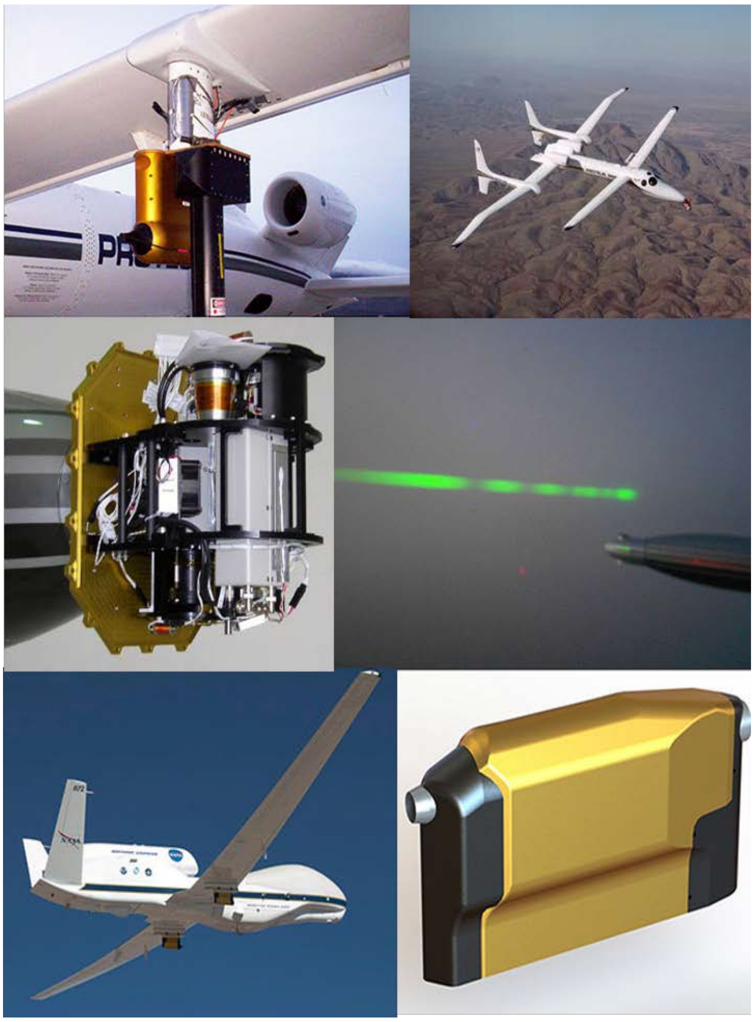

Figure 4.31 *Sensors from Spec Inc, USA, cover a spectrum of measurement techniques. Sensors which are usable onboard small drones may become available in the relatively near future. (Top) The cloud particle imager (CPI) mounted on the Scaled Composites Proteus, records high-resolution (2.3 micron pixel size) digital images of particles (see examples) that pass through the sample volume at speeds up to 200 m/s. (Middle) In situ cloud lidar, measuring Liquid Water Content (LWC) and droplet radius at distances of 25-1000m from the aircraft. Learjet wingtip pod. 532nm (green) laser. (Bottom) Hawkeye Combination Cloud Particle Probe mounted on the NASA Global Hawk [11].*

4.4.5 IPS – Ice Protection Systems

When efforts to avoid icing conditions fail, ice buildup must be actively counteracted. This may be done preventively or after ice has begun to accumulate. The options fall into the following categories:

- Hydrophobic coating
- Using an anti-freeze liquid
- Heating
- Physical expulsion using e.g. piezoelectric shock or rubber boots

For small drones, thermoelectric heating is currently the most promising method. However, there remains some development work and testing. We must assume that the first working solutions may be implemented within 1-2 years (e.g. from Ubiq Aerospace [30]).

Winter drone operations in Norway must use IPS covering propellers in the case of rotary wing (RW) drones. When using fixed wing (FW) drones, or hybrid RW/FW drones, IPS solutions must also cover lifting surfaces (wings), airspeed sensors and possibly also the control surfaces. Protecting imaging sensor apertures may also be relevant for any type of drone, as these may be iced over, inflicting performance loss in critical functions such as "see-and-avoid" sensors. Protecting the aircraft body from ice buildup is probably not practical or economical, although not impossible. The potential added weight of ice must be taken into account when designing the system.

The performance, optimal use strategy, energy and weight penalties of the different IPS solutions are currently rather uncertain. We may however assume that the energy needed to counteract icing will at times be comparable to the energy used to fly [26]. In the case of small drones, the IPS will probably at times draw more power than the propulsion system. This means that the endurance of ice-protected drones may be severely reduced, if the IPS is used during significant parts of the mission. This is an important motivation for developing good forecasts and route planners for longer distance/duration missions. Different aircraft and different missions will require or allow different ways to employ IPS.

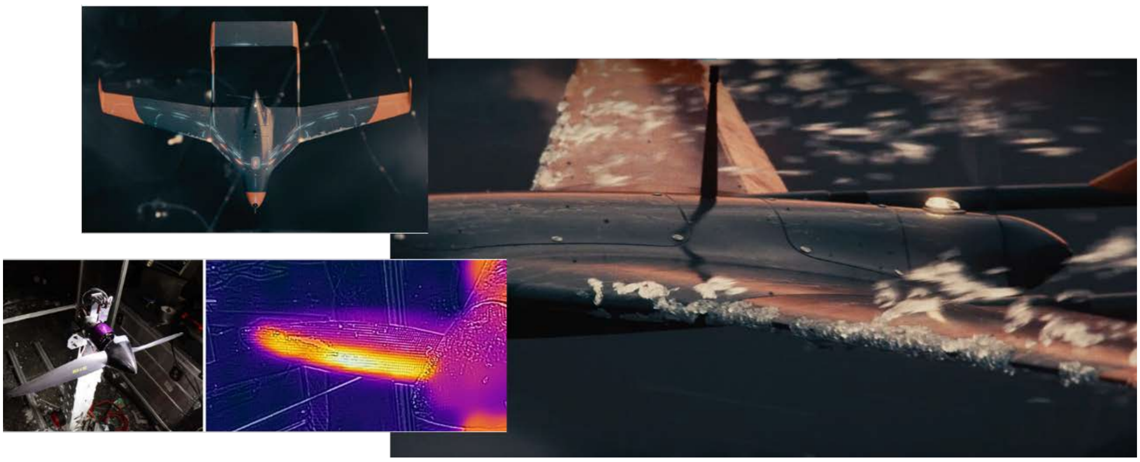

Figure 4.32 Ubiq aerospace D-ICE, is a complete ice protection system (IPS) which is being tested on the Maritime Robotics Falk UAV [30, 44] .

5 Wind

Wind is a major factor in aviation, affecting flight times and safety. In general, two different aspects of wind are of importance:

- Magnitude and direction of steady (laminar) horizontal wind
- Special local phenomena like updraft or downdraft, turbulence induced by buildings, terrain, other aircraft etc, microbursts, tornados, wind shear and more

A number of serious incidents and accidents involving wind have occurred in manned aviation in Norway (accidents at Mehamn 1982, Værøy 1990, Gildeskål 2018, Meråker 2018 [45-50].

The large-scale laminar horizontal wind is of great importance in relation to flight time from A to B, whereas the smaller scale phenomena are more often threats to safety. For example, supercells (large thunderstorms) produce powerful winds, in part powerful downdraft and in part powerful updraft, as well as possibly large hail, microburst (powerful down- and outflow), and lightning. Aircraft of any size and design may be in serious trouble in super cells, wake turbulence, rotor wind associated with mountain lee waves, and other special wind phenomena.

Drones will often experience highly variable conditions. Phenomena at smaller scales will be more important when travelling low and at low speed. We will explore some of the effects of wind on small drones in the following sections.

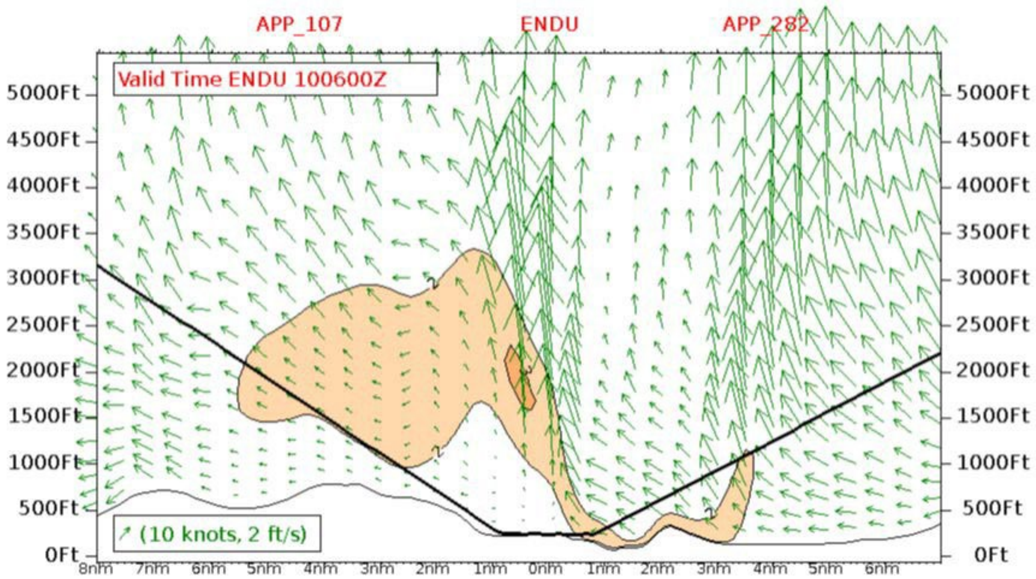

Figure 5.1 An example of a local wind forecast for Bardufoss (ENDU), displaying severe turbulence (orange regions) directly above the airstrip. The threshold levels are adapted to manned aviation [36].

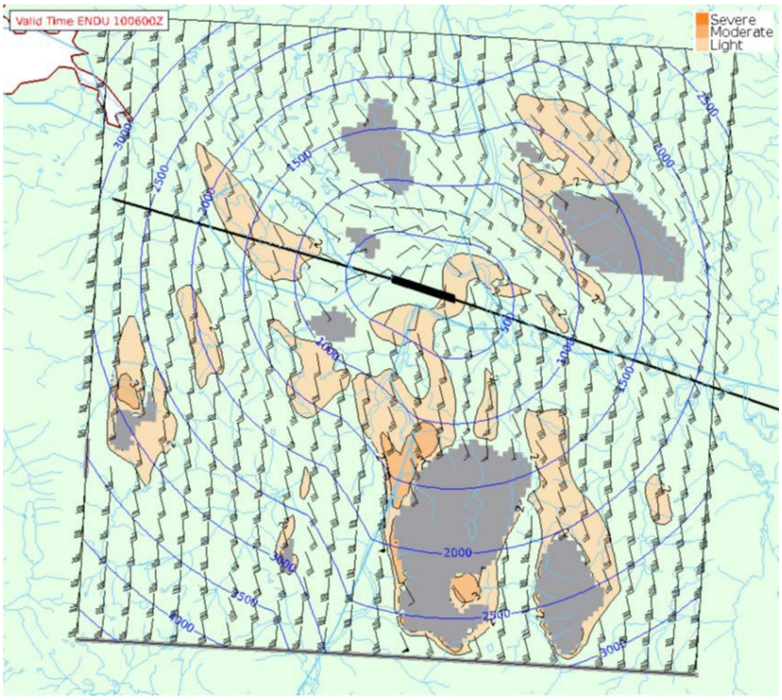

Figure 5.2 The horizontal view corresponding to Figure 5.1 above, with significant turbulence in the lee of the mountains clearly depicted.

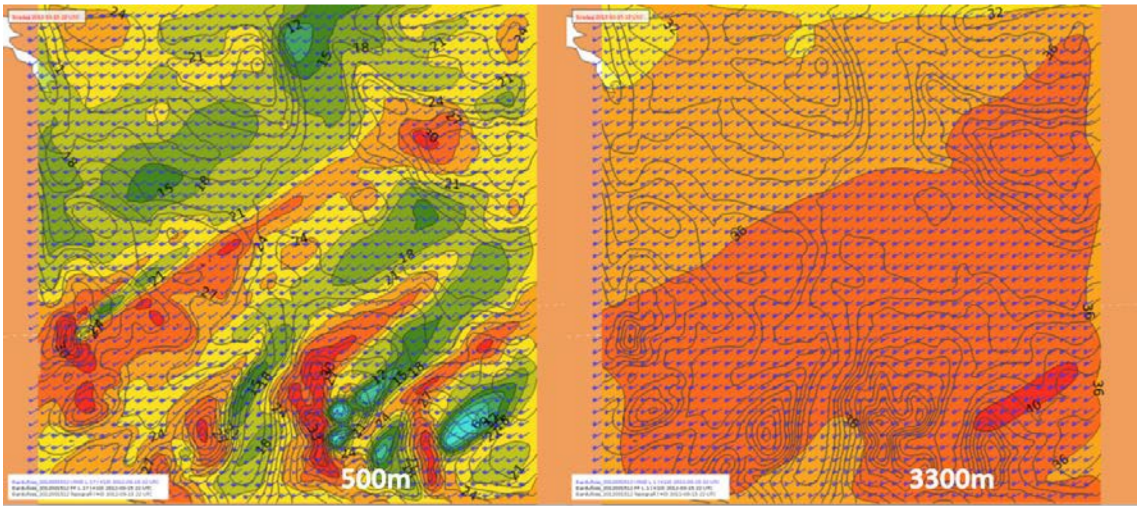

Figure 5.3 The fine scale wind model SIMRA has been used for many years, providing useful forecasts for a number of Norwegian aerodromes. On the left we have a highly variable wind field at 500m, and on the right a much less variable wind for the same time at 3300m [36].

5.1 Drone response to wind and turbulence

Many drone systems come "out of the box" with a specified wind tolerance, in addition to temperature and precipitation tolerances. Commonly, the given wind limit is 8-10 m/s or so. The reason for the given limit is probably to ensure a reasonable ability to maintain ground speed in headwinds. There is usually no information on tolerance to vertical wind or turbulence.

5.1.1 Horizontal wind effect on flight time

The most commonly encountered effect of wind on small drones is the occasional – and sometimes unexpected – very slow progress over ground against the wind, causing concerns about the ability to get back to the home point and land safely. Outlandings – landing short of the intended target or home point – are quite common with drone operations among hobbyists.

Rotary wing (RW) drones have flight control systems that will usually seek to maintain a desired/commanded ground speed. When encountering a headwind, a RW drone will detect a reduced ground speed (usually based on GPS), and consequently increase its tilt angle and increase thrust in order to achieve the desired ground speed. This will take place at the cost of increased power consumption, and thus result in reduced endurance. At a certain wind velocity, a (system specific) limit to thrust or allowed tilt angle may be reached, and the drone will no longer be able to compensate. Ground speed will then suffer, coinciding with a reduction in endurance.

It is common to assume incorrectly that, for a mission as a whole, the time lost (if unable to maintain planned ground speed) going out against the wind is made up for going back. A typical mission with a flight distance of 10km from start to the turnaround point, drone airspeed 60km/h (17m/s) and wind 36km/h (10m/s) along the direct route, will take 33 minutes if the drone does not compensate for the wind, whereas the same mission will take 20 minutes without wind.

The effects of wind on the practical out-and-back range may be large, but is expected to be highly system specific. In the case of the DJI Matrice 600, if set up to maintain an airspeed of 16m/s, a wind speed of 8m/s along track (which we for simplicity assume is not compensated for by the aircraft), and stipulated 25 minutes endurance at this airspeed, the out-and-back range of the M600 is about 9km. Without wind it is about 12km. Faster drones will be less affected, relatively. In "real life", ground speed will in this case probably not be reduced by 8 m/s when going against the wind, or increased by this amount when in a tailwind, due to the control system compensation. Rather, ground speed may often be held at the nominal (in this case) 16 m/s, but at a significant cost in the form of reduced endurance in a headwind (see chapter 5.1.2 for explanation).

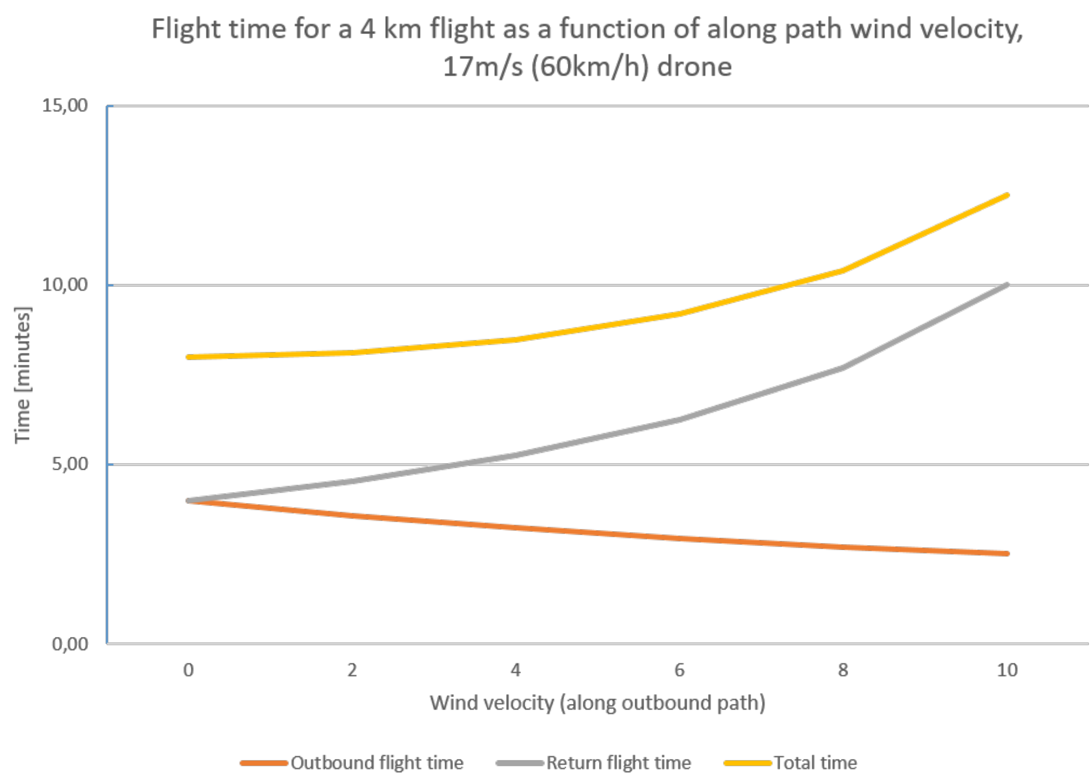

Figure 5.4 Flight time for a distance of 4 km, which is about twice as far as the straight-line distance between Rikshospitalet and Ullevål, for a typical drone in the category which we are using in this study. For the sake of simplicity, we are here assuming that the drone does not compensate for wind (i.e aiming for constant air speed)

The use case of flying blood samples from Ullevål Sykehus to Rikshospitalet may be considered a special case, with a very short flight distance (1,8km minimum and a more likely and less direct flight distance of 4km). The effects of horizontal wind are mostly negligible, except for rare cases with severe wind. A headwind of 10m/s increases flight time to 10 minutes, if uncompensated, as compared to four minutes without wind (see Figure 5.4).

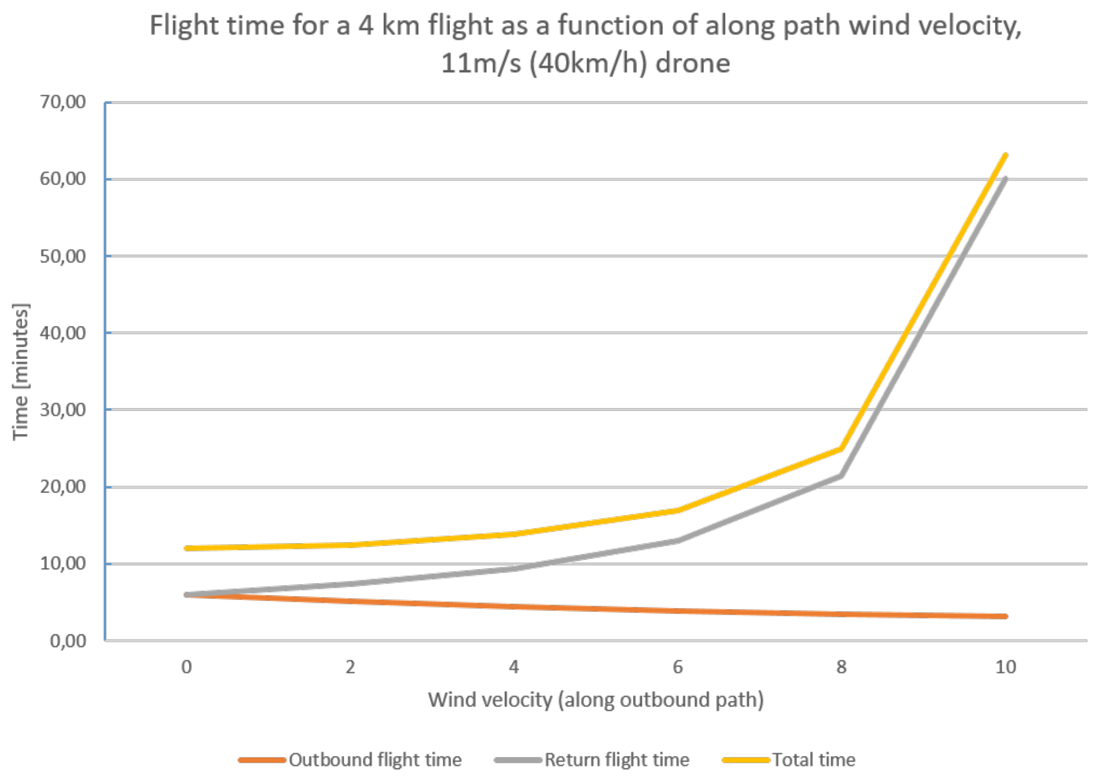

Figure 5.5 *In the case of a somewhat reduced ground speed potential, either due to the payload weight, icing or moderate downdraft, even a very short flight of 4km may at times be at the limit of what a common commercial drone may handle.*

5.1.2 Drones in vertical wind

Strong vertical wind will from time to time be encountered when operating drones regularly. As we shall discuss later on, forecasting will not allow us to avoid certain local phenomena. The behavior of small drones in e.g. thunderstorms, slope wind or mountain lee waves is for the most part unexplored or undocumented.

After entering a rising or sinking air mass, we postulate that RW drones will mostly be able to compensate and maintain altitude, with little impact on the mission. Still, we must expect that the limits for such compensation may be exceeded on rare occasions.

Different designs have varying maximum climb and descent rates. They may have greatly differing ability to counteract rapidly rising or sinking air. For both rotory and fixed wing drones, we must expect situations in which undesired altitude deviations will occur, increasing the likelihood of collisions with the ground, buildings or other air traffic.

There are important differences in the way fixed wing (FW) and rotary wing (RW) drones are affected by vertical wind components and changes in these vertical components. We will focus on RW drones.

Wind with an upward component will cause the aerodynamic drag force acting on the drone to have a component acting upwards (see *Figure 5.6*). The drag force acts in the opposite direction of the apparent wind, which is determined by the motion of the aircraft through the air, and the local ambient wind. This vertical component of the aerodynamic drag force will allow the drone to apply more of its available thrust to the horizontal component, or save energy at any given speed. The effect of the wind on propeller efficiency is potentially an important unknown. This is expected to be highly design dependent.

If the upwards wind velocity causes a vertical drag force component that approaches the magnitude of $mm \cdot gg$ (see Figure 5.6), the drone could be in a situation somewhat equivalent to "free falling" at terminal velocity. The drone will need very little or eventually (in principle) no thrust to maintain altitude. The free fall velocity of drones should be expected to vary greatly. There are important differences in the drone drag as a function of wind direction relative to the drone body. Also, weight varies greatly among similarly sized and shaped drones. Theoretically, the drone may become unable to avoid rising upwards, unless it is able to produce a downward thrust component. We may assume that a situation in which a RW drone will rise due to upwards vertical wind, will be extremely rare. If it occurs, it will be in a local wind phenomenon, such as e.g. in rotor wind associated with mountain lee waves, or in a very strong updraft in slope wind. It is unknown to us how current flight control solutions would handle this situation.

When a rotary wing drone encounters a downward vertical wind, an aerodynamic drag force component directed downwards will add to the force required to maintain altitude. Referring to figure 5.*6*, we see that this will detract from the available horizontal thrust component. With an increasing downward vertical wind component, ground speed may eventually be halte altogether, unless the drone has sufficient thrust surplus to compensate, or it sacrifices altitude for horizontal progress. In extreme cases of sinking air, such as in a microburst, a drone may lose altitude quickly. One possible, though unconfirmed, account of this is found online [51].

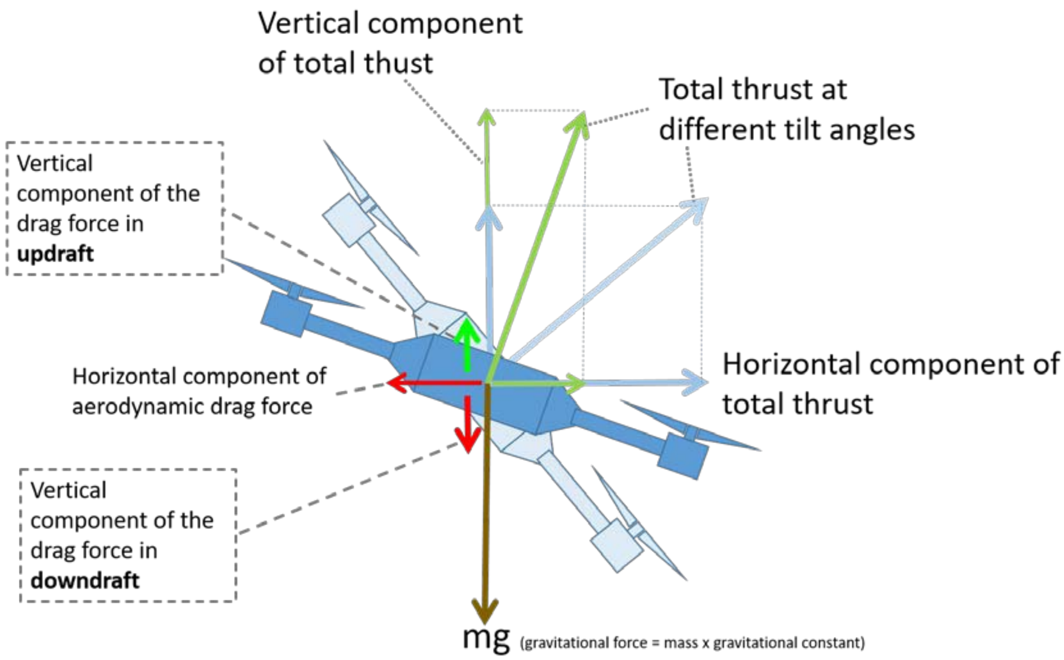

Figure 5.6 *Force components for a rotory wing (RW) drone (for illustration purposes – the arrow lengths are not necessarily correct). Greater tilt provides more thrust in the horizontal direction, and less vertical (lift) force. A vertical wind component will add to or subtract from the force needed to maintain altitude, affecting the power available for forward motion.*

The maximum achievable climb and descent rate should be determined for a specific candidate system. As should the effect of wind on thrust. As an example, the Meteomatics Meteodrone is rated at 20 m/s climb [52]. The Matrice 600 could be expected to have a far lower climb rate. The DJI Matrice 600 is specified to have a maximum operator commanded rate of climb of 5 m/s, and a maximum commanded descent rate of 3 m/s. We can reasonably expect that it can suppress the effect of vertical winds in excess of this

Ascertaining the actual response of a specific type of drone in strong sinking or rising air, will require time-consuming testing. There are significant challenges in creating artificial, controlled vertical flow fields in an environment where free flight, full dynamics testing may be performed. Alternatively, chasing after naturally occurring strong up- or downdraft is somewhat comparable to "tornado chasing".

Studying this topic further, using a combined approach with simulation and live flight testing, natural and "artificial" wind, is a task which is possible, but beyond our current scope. For now, we conclude that strong up- or downward wind is an unknown with the potential to cause several incidents every year. We further postulate that strong downdraft is the most serious threat to safe flight at low altitude, based on common drone performance figures. Downdraft may cause an increased risk of colliding with terrain or structures following uncontrolled descent.

Figure 5.7 Developing Cumulonimbus over Oslo (left), thunderstorm with lightning over Oslo (center) and a plot of the lightning frequency in Norway (far right)(Met.no)

5.1.3 Drones in turbulence

Drones occasionally experience turbulence – from mild to severe. We will focus on the landing phase for rotary wing drones. We will not cover the subject of fixed wing drones in turbulence, beyond postulating that the aircraft will experience higher accelerations than rotary wing drones, with occasional shock of magnitudes that could be relevant when assessing payload tolerance levels [17]. The accelerations will depend greatly on air vehicle design and airspeed.

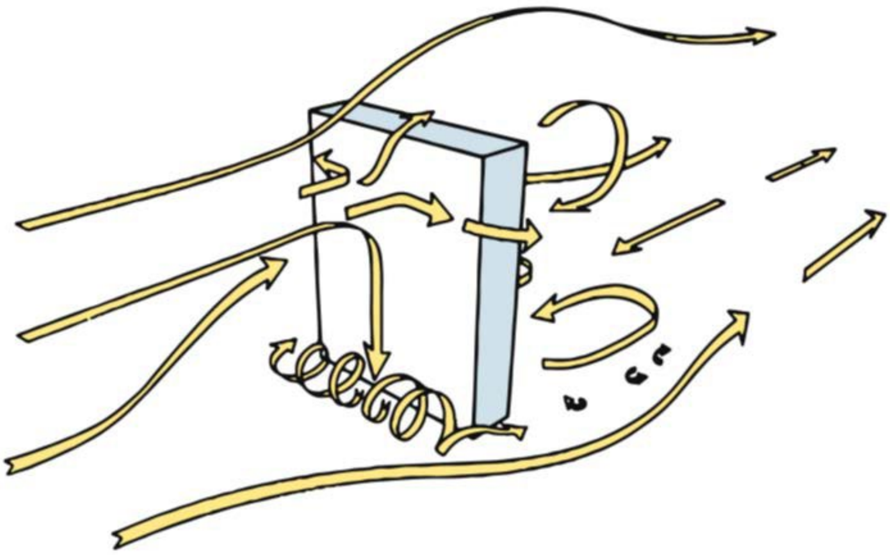

Figure 5.8 Building-induced turbulence may at times prove challenging for small drones [6].

During the final stages of landing a rotary wing drone, turbulent wind will result in rapid changes in the horizontal wind speed (velocity and direction), and not significant vertical wind. Wind gusting during landing may thus cause horizontal displacement of the drone, as well as tilting as the drone counteracts the wind. We may question whether current arrangements of unsheltered, unaided landing on e.g. a flight deck will work in strong gusting. The importance of the size of the landing deck, and of the potentially significant tilting of the drone just as it is touching down, will vary from system to system. We may intuitively expect that sheltering of the landing site, and possibly a mechanical “capture” method may be needed in some drone applications, e.g. in an offshore context.

The difficulties of performing practical tests, as discussed briefly in the previous section, apply equally to the case of turbulence. To find relevant conditions which occur naturally, measure these sufficiently and perform a number of test flights, or alternatively generate artificially varied wind fields is a demanding task, worthy of its own project.

There are several ways to generate local strong wind, but it is important to investigate the fine scale variability in this wind field, and the impact it has on testing. Microturbulence and flowback regions are to be expected with any fan system, and these phenomena must be addressed.

Qualitatively, we expect rotary wing drones, especially those which are rather heavy in relation to their physical size, to display a much greater “sink through” tendency (i.e. dampened response to wind disturbances) than light drones or fixed wing drones. For drones such as the Matrice 600, the aerodynamic drag forces will be moderate in relation to the aircraft mass.

Especially when the weight approaches the MTOW of 15 kg (depending on payload configuration). Most multirotor drones are much heavier, compared to their size, than fixed wing drones. This effect dampens out accelerations in any direction.

To study this subject, a simulation model was set up, using MATLAB SIMULINK [53]. The response to abrupt changes in horizontal wind component (gusting wind) was simulated. The results from a simulated response to a sinusoidally varying wind (0-20m/s) is shown in Figure 5.9. Step changes were also simulated. The study generated interesting insight into the responses to different frequencies and amplitudes of wind changes. We must note that the results rely on a set of important assumptions. Therefore, the study results should be regarded as a qualitative guide. The uncertainties are associated with drag estimation, propeller thrust in general, and especially as a function of relative wind speed and drone pitch angle and finally tuning of the control system.

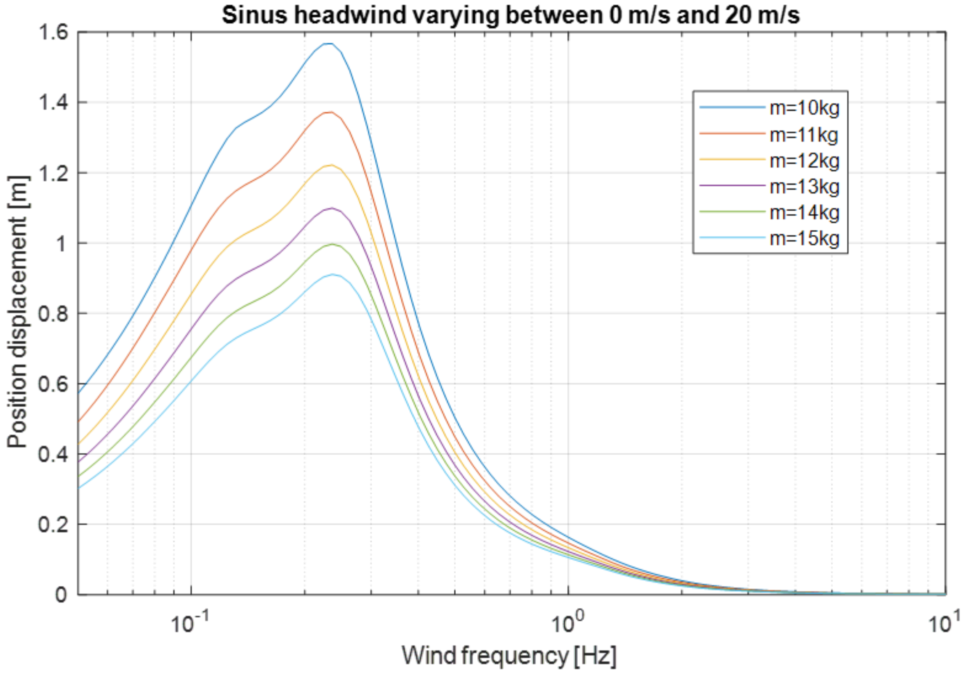

Figure 5.9 Results from a simulation, showing the horizontal position displacement of a drone exposed to a headwind with sinusoidal variation.

The study shows, as experienced in practice, that a multirotor drone has a very good suppression of gusting wind. An increase in drone mass is beneficial to the gust suppression, both due to the low pass filtering effects and the fact that a heavy drone needs to be tilted less to counter the wind-generated forces. However, our simulation shows that if the increased mass also contributes to a significantly increased moment of inertia, the pitch angle response will suffer and so will the wind suppression performance. An increase in the weight of center-mounted batteries or an internal payload will have a lesser effect than increasing the weight of e.g. an underslung payload (such as in Figure 5.2).

In general, if a drone is loaded with a heavy underslung payload, it will behave more sluggishly, especially if the control system is not auto-adaptive or retuned to the new working conditions. Also, if the increased mass leads to saturation of the motors, controllability and stability of the drone will suffer. This means that drones which are not designed to carry heavy payloads internally, and instead rely on external payload containers, will probably suffer in terms of stability and suppression of gusts/turbulence.

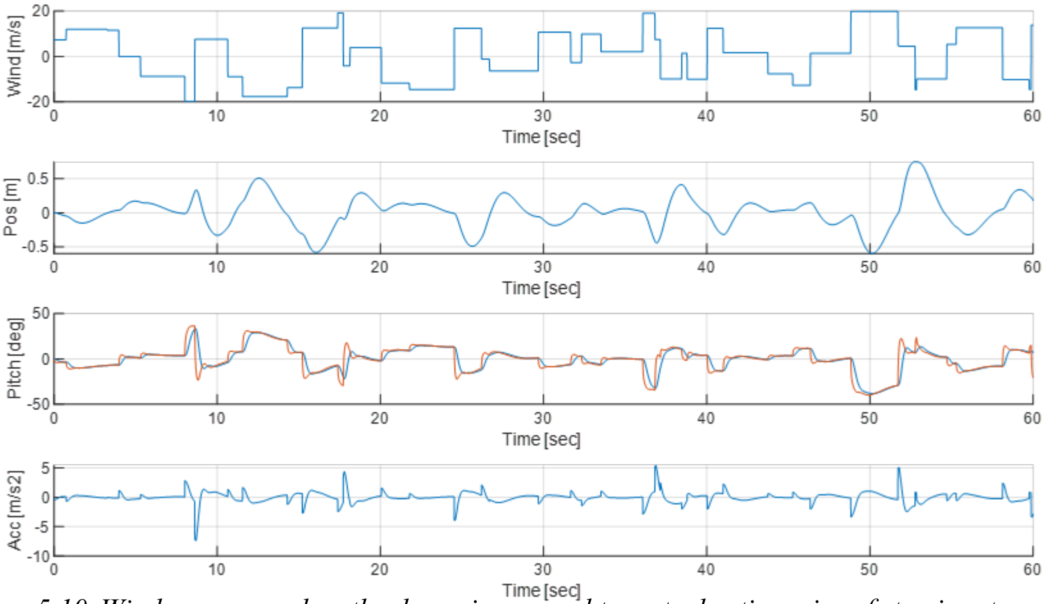

Figure 5.10 Wind response when the drone is exposed to a stochastic series of step inputs, representing gusts or turbulence (drone mass is 12 kg). The pitch reference (red) is shown together with true pitch angle (blue). Position deviations are small, generally below 0,5m, even with such strong wind variations. It is important to note the significant tilting of the drone, as it counters the wind.

Our analysis shows that a drone similar to the Matrice 600 has very little position response to wind disturbances at frequencies above 1-2 Hz. Generally, the drag of the drone with payload should be minimized in order to reduce the influence of wind.

Our impression is that only the most extreme turbulence/ horizontal gusting will cause a rotary wing drone in the relevant size range to become significantly affected. We may conclude that destabilization may occur in rare cases, especially if the thrust is reduced by icing and/or if the drone is carrying a heavy underslung payload. The conventional landing method will work in the majority of cases, but shielding from wind and a capture mechanism may be required in some applications.

Figure 5.11 The DJI Matrice 600 is a typical professional drone, which we have used for practical tests. In this image, we have attached a payload section for testing purposes, which adds significantly to the drag and the moment of intertia of the aircraft. This is an example of "how not to do it"(FFI).

5.1.4 Drones in wind shear

Abrupt spatial changes in horizontal wind direction or wind velocity is well known to cause problems for fixed wing aircraft. When wind relative to the aircraft direction of motion suddenly decreases, and "stays that way" for a meaningful amount of time (e.g. several seconds), a dramatic loss of lift may occur, until the aircraft has accelerated sufficiently to regain lift. Loss of lift causes dangerous situations, especially when the wind shear occurs close to the ground. A sudden "headwind" increase will be less dramatic, causing a lift increase, occasionally disrupting e.g. a landing approach.

Rotary wing drones are not as vulnerable as fixed wing drones in horizontal wind shear. The situations that cause a dramatic loss of lift for a fixed wing drone (change to a "tailwind" situation), will cause a sudden increase in ground speed for a rotary wing drone. The effect on thrust as the propellers suddenly are subjected to a different airflow angle and velocity, is uncertain and system specific.

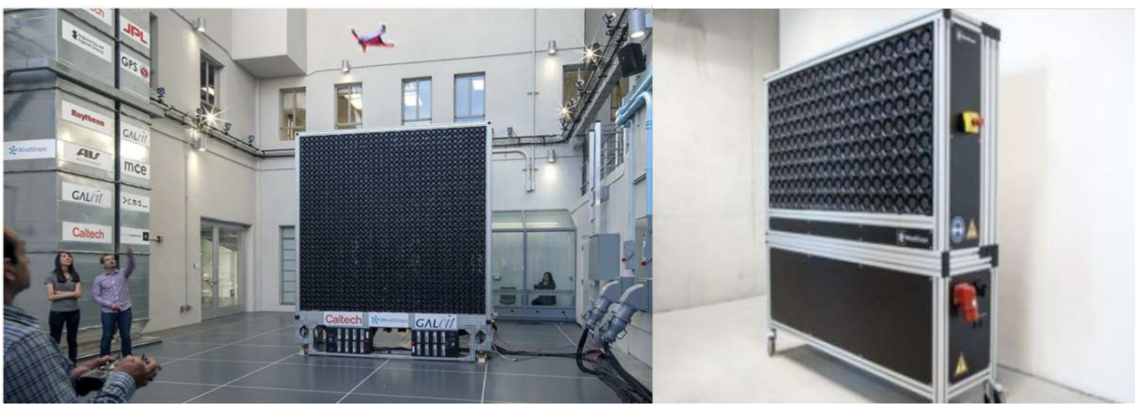

Figure 5.12 The Tyto Robotics (formerly RCBenchmark) windshaper allows you to create a custom wind field in the lab, including abrupt changes in wind field. This could prove useful when testing landing methods, responses to vertical wind and horizontal wind shear. The microturbulence in the flow field, as well as available wind velocities that the many 10x10 inch fan blocks would give, must be determined [54].

5.2 Wind statistics

A wind study was performed by the Norwegian Met office, as part of the HELSEVEL-project [1]. Data were collected for five sites in sentral southern Norway:

- Blindern (the met office location)
- Rikshospitalet at Gaustad
- Kjeller
- Gardermoen
- Rygge.

For Blindern and Kjeller, data for the periode 1 January 2014 to 1 July 2021 were analyzed, whereas for Rikshospitalet, data were available for the period 1 February 2020 to 1 July 2021. Mean wind and gusts were analyzed for magnitude, direction and frequency of occurrence (wind roses). The strength (turbulent kinetic energy) and finer structures of turbulence was not studied.

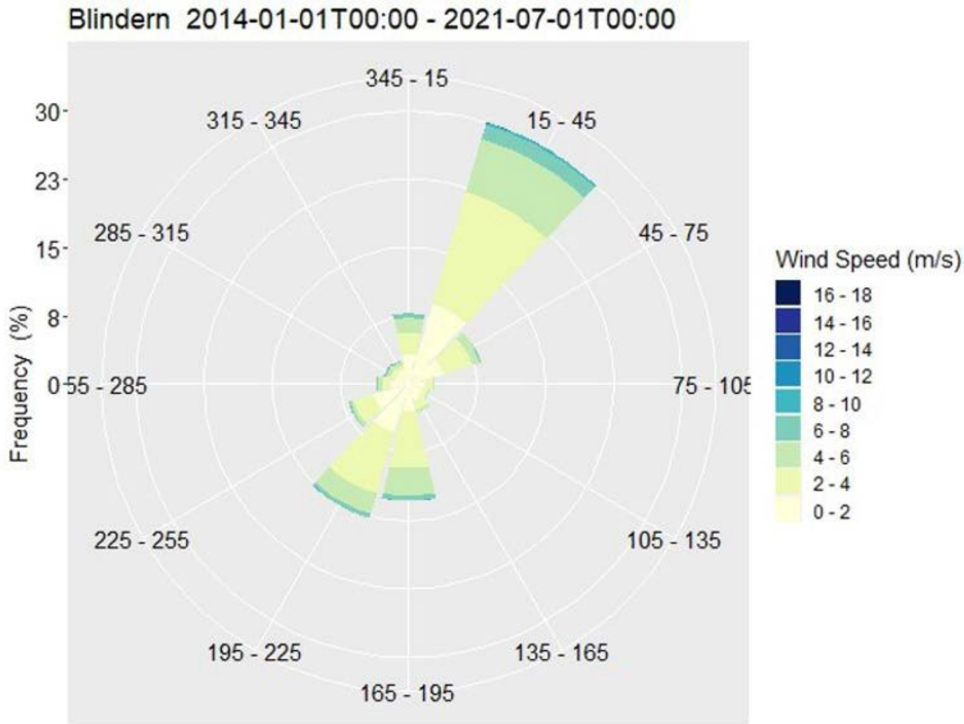

Figure 5.13 Wind rose for Blindern, which is near the Oslo University Hospital, showing that strong winds are not common there [1].

The study showed that the prevailing wind direction at Blindern is north-northeast, and that the mean wind speed rarely exceeds 12 m/s. The main wind directions at Rikshospitalet are from the north and from the south, and steady wind speeds above 10 m/s were not observed during the period the instruments were in place (15 months). Between january 2014 and july 2021, the observed gust at Blindern exceeded 20 m/s only 15 times, and during the period wind was monitored from Rikshospitalet, gusts exceeding 20 m/s were not observed. Wind data from Kjeller indicate that wind conditions here are similar, except for the lack of one dominant wind direction.

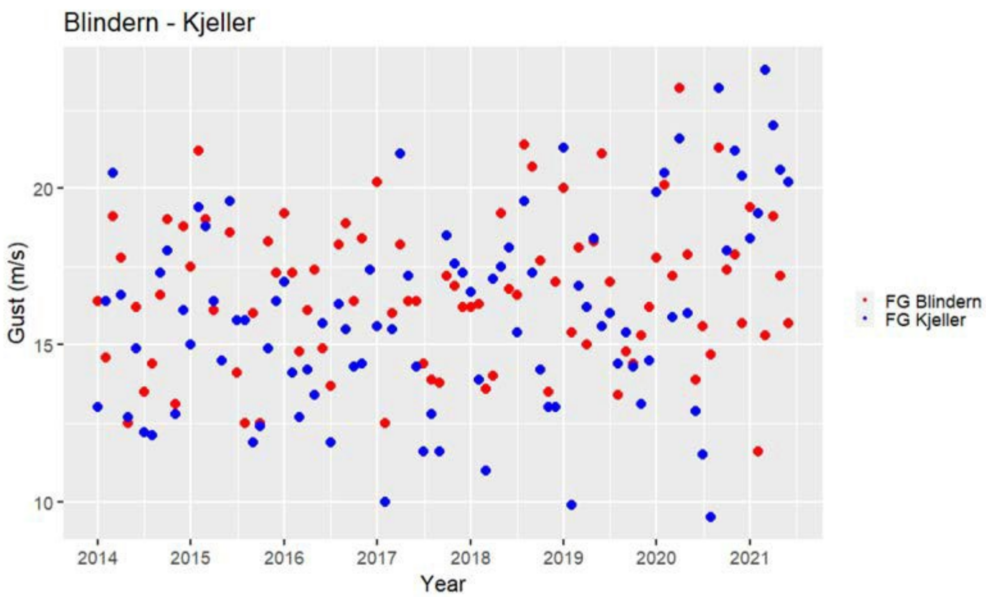

Figure 5.14 Gusting wind at Blindern (Oslo) and Kjeller[1].

In conclusion, the greater Oslo area is rarely exposed to severe winds. However, the gusts at Rikshospitalet indicate that turbulence induced by the hospital buildings should be expected.

Wind charts from Kjeller Vindteknikk and NVE [34, 35] (Figure 5.15) support the assumption that Oslo is much less exposed to strong wind than many other parts of the country. The above study for Oslo did not gather data on special wind phenomena (e.g. thunderstorms).

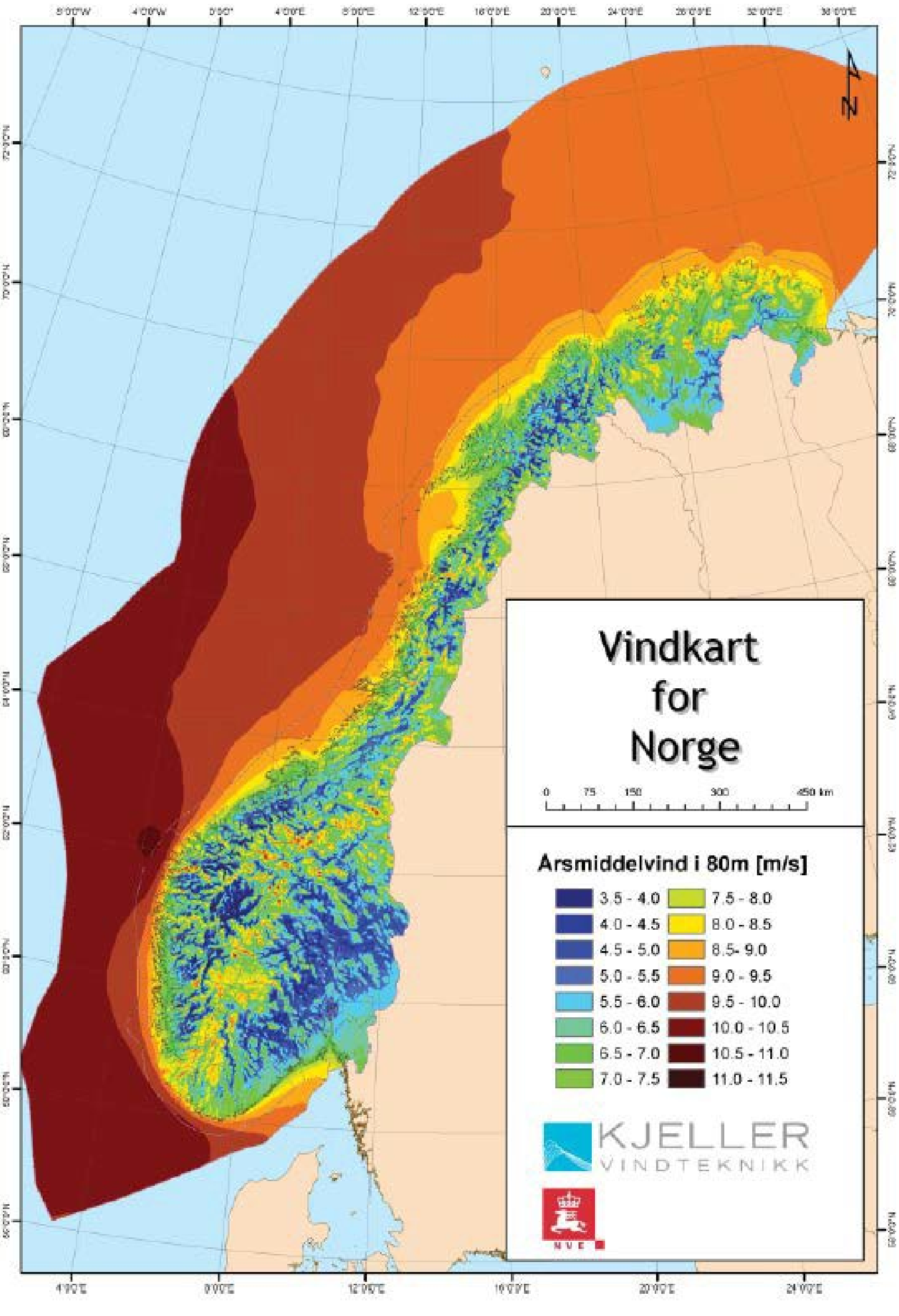

Figure 5.15 A wind chart showing the yearly mean wind at 80m above ground [34].

5.3 Wind Mitigation

The potential adverse effects of wind may be mitigated in a number of ways. As for icing, we discuss some of the alternatives below.

5.3.1 "Brute force" wind mitigation

We may consider ensuring that drones on critical missions have a somewhat higher tolerance for strong winds, both horizontal and vertical, than current commercial drones. Even more importantly, the behavior and limits must be well documented, which is not the case today.

The balance between air speed, vertical speed capability and cost must be found in an analysis which is supported by practical exploratory operations. Commercial drone designs tend to lean towards low cost and long endurance, to cater to the hobbyist and aerial photography market. Racing drones are built to be fast, sacrificing endurance. Professional drones are headed in the direction of robustness, payload capacity, and higher quality control standards. Being able to fly against headwinds in excess of e.g. 15m/s, making mission adequate headway, is fully possible. As is designing drones that may handle strong vertical winds much better than current drones would. Higher airspeed and thrust surplus, will most certainly translate to increased cost.

Whether it would be more sensible to use different types of drones for "normal operation" and "extreme conditions", is unclear. Especially since we cannot always predict when we will encounter very challenging winds locally, and thus not know when we need the more robust drones.

5.3.2 Wind forecasting

Wind is a well established element of forecasting aimed at manned aviation and other user communities. After decades of development – in effect covering at least 80 years – the quality of meteorological support to aviation has increased greatly. The reliability of weather forecasts (and lack thereof in certain contexts) is quite well understood. In general, the reliability decreases as the resolution increases and as we go further ahead in time.

There is a great number of available sources of wind forecasts, which cover the globe. Examples are MET Norway, Meteomatics and Storm Weather Center. All of these providers are constantly working to develop and adapt new services. The needs of drone operators is increasingly influencing this development.

Following serious accidents and incidents in the 80'ies and 90' ies (Mehamn [45, 46], Værøy [47, 48]), the focus on improving our understanding and the predictability of certain smaller scale wind conditions increased [45]. These efforts contributed to the turbulence warnings which are provided routinely for many local aerodromes in Norway [36]. The vertical and horizontal view that can be accesses by users on the IPPC web site, give an operator an impression of the risk of strong turbulence, and vertical wind components. Atmospheric mountain lee waves are often visible in the wind fields. High resolution wind models are an important field of research globally.

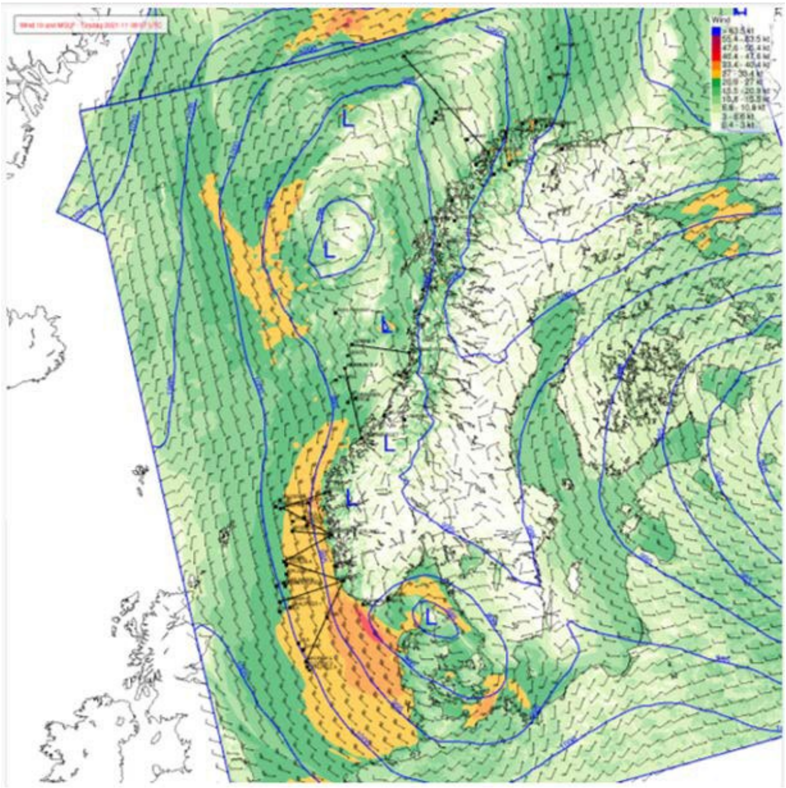

Figure 5.16 A typical wind forecast from yr.no. You can zoom in quite a bit, but local details are not available or reliable.

Drone operators are likely to become increasingly important customers for meteorology service, requiring somewhat different services compared to manned aviation – regarding both icing and finer scale, low-level wind.

"Drone Weather" forecast services are available today, and these are already helpful when assessing the wind conditions locally, although they are seldom experienced to be "correct".

Some weather products use interpolation to increase the "apparent" resolution. This in part only increases the perceived resolution, aiding interpretation.

A drone operator may obtain a general understanding of the wind conditions in the required area, using the SIGMET (see Figure 4.22) and a host of other products. During days with strong winds or risk of certain conditions, and especially when conducting long range mission, there are serious deficiencies in the met services and in the way operators may exploit them:

- Finer scale wind structure close to terrain and buildings is not well resolved for large areas

- The update rate is usually once an hour or once every few hours, leaving the forecast more and more uncertain before the update is available

- Special phenomena such as tornados, microbursts, lee wind/turbulence etc are not (well) represented in the operational forecasts, although general area warnings and live tracking of large features may be available

The visual presentation (online or in user-specific applications) of the weather products also leaves something to be desired. A 3D, "immersive" user experience would perhaps be a desired improvement.

Wind models at a very fine scale exist (e.g. less than 1m or "100m"), but are not yet used for operational weather services, in part due to the computational resources and time involved. These models have the capability to resolve the effects of wind flow around buildings and local scale terrain. Such fluid dynamics models have been developed at FFI [6], Sintef [55] and elsewhere.

A Sintef study under the HELSEVEL project explored the value in coupling models of progressively fine resolution to obtain a very fine scale fluid dynamics computation. The "multi-scale methodology" described by Helsevel project partners in [55] involves coupling three models operating on different scales. An operational meso-scale numerical weather prediction model (HARMONIE, 2,5km) feeds into a micro-scale model that captures terrain-induced wind influence (SIMRA, run at 112m resolution). Using this data, a super-micro scale Computational Fluid Dynamics (CFD) code is run to capture building-induced wind (run with 0,15m resolution at the finest). The fine scale "correctness" of the model setup has not been validated. This would ideally require a 3D grid of measurements.

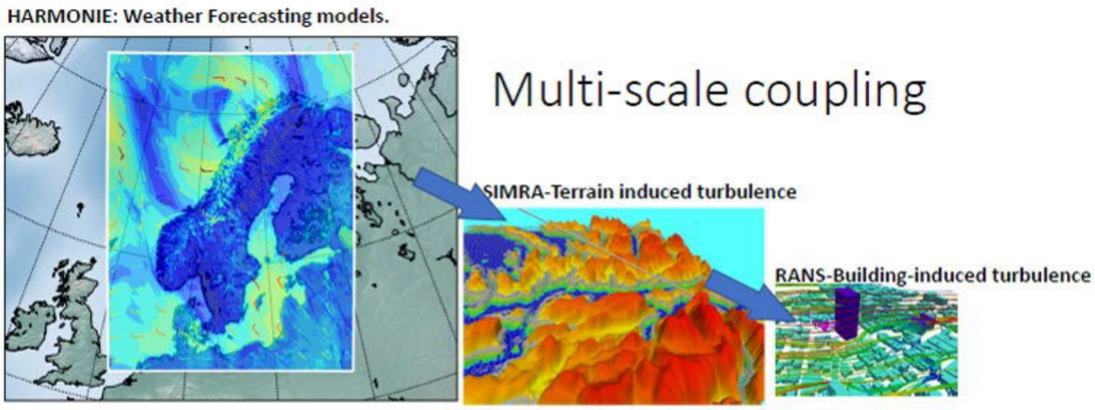

Figure 5.17 A study by Helsevel partners demonstrated the potential in coupling models of progressively fine resolution. Validation is necessary [55].

In another report prepared by FFI under the HELSEVEL project [6], a simulation methodology for estimating urban wind fields under given meteorological conditions was demonstrated. An example simulation for Rikshospitalet was carried out, and the resulting data was analyzed using both "traditional" metrics (such as mean wind speeds and turbulence levels) and more experimental methods.

The simulations show that the urban wind field is complex and turbulent. The results give a qualitative overview of the flow field as well as selected examples of more quantitative analyses. The results indicate that the methodology is well-suited to support drone system design and certain aspects of operation. The results confirm the intuitive expectation that UAV handling may become more difficult closer to buildings, particularly in regions of several large structures close to each other. However, validation against experimental data is not yet available.

Depending on specific UAV tolerance levels, simulations may contribute to quantifying the risk and related safety distances to urban structures, as well as aid in determining suitable take-off and landing locations. Estimation of realistic worst-case flight conditions, may be essential if 24/7/365 service is required. Remaining work includes validation against field data and investigations of both real-life and virtual specific flight paths.

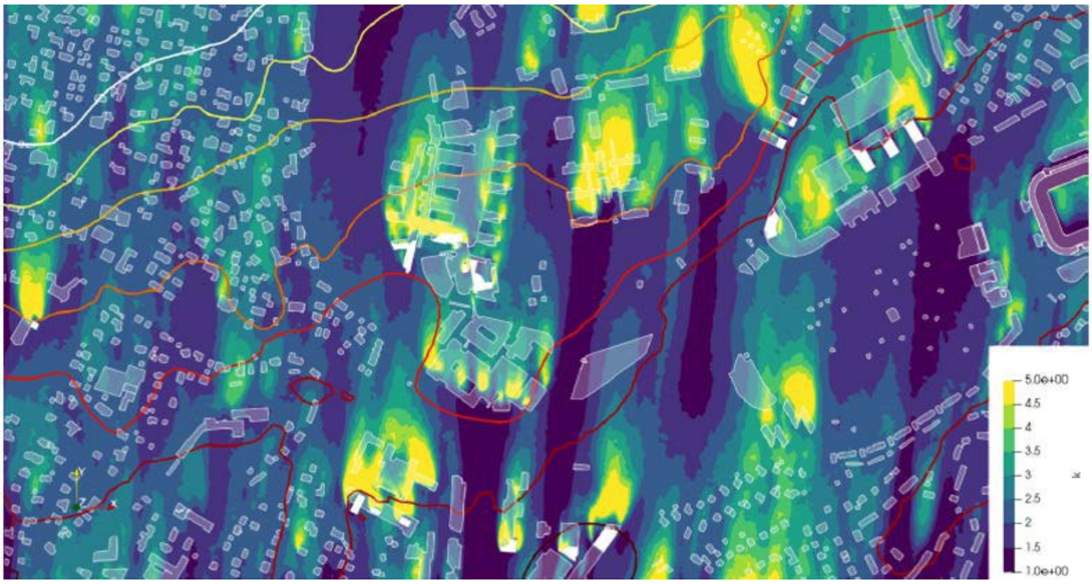

Figure 5.18 Contours of turbulence kinetic energy 20 m above ground level. Isolines of terrain elevation are shown in color every 10th elevation meter. Buildings below the contour surface are shown in transparent white. Rikshospitalet's main building is the large structure in the center [6].

Fine scale models are not currently a "real time tool". They cannot yet be used in support of ad hoc drone operations in a large area. The time it takes to configure and run such models for an area of meaningful size, means that the main uses are currently to:

- generate a "library", "wind atlas" or "risk map" that may be used to guide both system design and operation. The location and characteristics of landing sites may be guided by the use of such a CFD model. It may also be used in local path planning, or in defining alternate flight corridors, avoiding areas with a statistical risk above a system specific threshold

- provide operational forecasts for very small areas routinely (such as the case with SIMRA and the turbulence forecasts)

Advanced flight-path optimization based on CFD data may represent a long-term research goal. A number of improvements could be considered, and these would depend on reliable UAV specifications, including tolerances related to wind speed and turbulence.

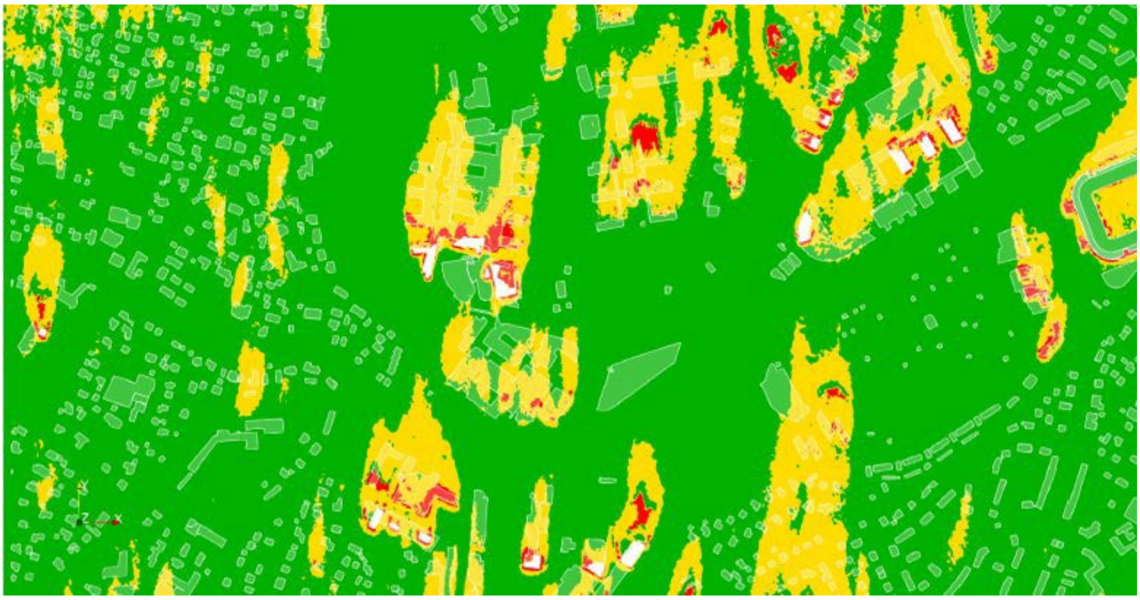

Figure 5.19 An example of a proposed risk map, i.e. contours of the total risk field, at an altitude of 20 m above ground, centered on Rikshospitalet in Oslo. The three risk levels are colored by green (no/low risk), yellow (medium risk), and red (high risk). Buildings below the contour surface are shown in transparent white [6].

5.3.3 Wind nowcasting and remote sensing

Using available forecasts as actively as possible, we must still expect that a great deal of uncertainty will remain as to the present wind field.

A "nowcast" may be based on very recent forecasts or on measurements of current conditions. Sparse measurements in (near) real time are available today. The METAR and TAF give you the current measured wind at aerodromes. The tracking of precipitating clouds, is an example of a nowcast which may be used by drone systems. Such features indicate, but do not describe the wind field in any detailed way.

The available nowcast resources leave a great deal to be desired regarding the details of the actual current 3D wind field. Using lidar or radar wind profilers, the local wind field could be remotely measured. Greatly expanded networks of airborne and ground based insitu sensors are feasible, and could be used to improve the quality of near term forecasts. This could be a useful option when operating regularly in the same area. Stationary, unattended sensors are employed by the Norwegian Air Ambulance [56], with their network of weather cameras, improving their awareness of current local conditions.

5.3.4 Mission planning

Improvements to mission planning, including how and when to fly, is an obvious mitigating action. Route planning software that makes use of wind forecasts are being developed, among others by NTNU ([31]). The new route planning software will also use icing forecasts.

In our special use case, route planning is quite constrained, compared with long range flights. Factors other than the wind will limit operational freedom to corridors (e.g. other air traffic (ambulance helicopters), risk to the population or noise regulations). We also have little room for waiting for better conditions, as the concept relies on very frequent flights. For our specific use case, we must therefore rely strongly on local sensors, local forecasts as well as risk maps (as discussed in chapter 5.3.2), allowing us to:

- time flights within a narrow time range
- choose between alternate, predefined flight corridors
- define fixed, alternate flight corridors and landing sites for the best possible statistical merit

5.3.5 Insitu wind sensing using drones

It is possible to measure wind using the drones themselves. In our concept, there will be very frequent drone flights in a constrained area. This will allow a much improved local situation awareness compared with many other drone applications. It will also support model improvements over time.

Most drones will alert the operator when the horizontal wind exceeds a threshold. The horizontal airspeed may be deduced from the known commanded speed (thrust and tilt), as compared to the GPS-based ground speed. The instantaneous local 3D wind is normally not measured or reported by drones. But the technology to do so does exist. 3D wind may be calculated and reported by drones, based on system specific calibration of air vehicle behavior related to a measured wind field.

Meteomatics provide drones that measure local 3D wind [52], based on onboard accelerometers and careful calibration work for the specific drones. Such capability is relevant when validating fine scale wind models, such as those discussed in chapter 5.3.

5.3.6 Ground infrastructure – drone docks

There is a clear trend towards using automated or remote controlled drone bases, or drone docks. Some security, science, agricultural and industry drones may now be delivered as "all-up" complete systems, with significantly reduced need for handling. This will reduce the personnel and competency requirements, and open up for many new applications. Drones will be protected from icing and wind when not in use and during charging/automated battery swap between mission. It is possible to protect the landing point from strong wind, and to assist landing with diverse sensor systems and mechatronics (e.g. capture mechanisms). As we will discuss in chapter 6.3, we consider automation to be essential in high intensity operations. Automated drone bases/docks will enable safe landings, take-off and efficient turn-around in challenging weather conditions.

Figure 5.20 DJI has recently come up with a drone dock solution, which will allow remote controlled and automated operations [57].

Figure 5.21 The meteomatics MeteoBase [52].

6 Discussion

We have discussed the way multirotor drone systems handle icing and wind, and some ways to mitigate adverse effects. We have also presented some statistics that allow us to conclude roughly how often we may expect icing conditions and significant wind in the Oslo area. This forms the basis for a discussion on the feasibility of a drone based medical logistics service, as described in chapter 3 on user requirements. Our goal is to develop a foundation for specific recommendations concerning system requirements and the general way forward.

6.1 Mission impact of icing and wind

Based on our exploration of the subjects of icing and wind, we may operate on the assumption that drones are generally more vulnerable to weather than manned aircraft. The vulnerability is system specific and largely unknown. We do not need “extreme weather” to run into serious problems with drones as they are today. The impact is often not highly safety critical, but rather mission critical, with excessive flight times or insufficient aircraft range. In general, rotary wing (RW) drones are not very susceptible to turbulence, compared to fixed wing (FW) aircraft.

Hybrid fixed wing/rotary wing drones (FW/RW, see Figure 2.1) are advancing as tools of choice in many applications. We must expect these to be significantly more vulnerable to the effects of wind phenomena like strong vertical wind and turbulence – the latter especially during landing and take-off. They may, however, be somewhat less vulnerable to mission failure due to flight time increase or endurance loss, because they usually have a large endurance surplus. That being said, such FW/RW hybrids are often intended for long distance missions, covering more than 100km. The effects of icing/IPS power drain and detrimental wind may be significant.

The Oslo area is generally a quite benign flying environment. Even so, statistics show that a regular 24/7/365 service, flying drones perhaps four times an hour, will not be advisable without mitigations, which are not in place today. We may roughly estimate that hundreds of the 70 000 flights per year between Ullevål and Rikshospitalet may be affected by adverse weather. These weather events will be distributed unevenly and somewhat unpredictably. If we postulate that weather statistics indicate a mission failure rate of about 1-5% for current drones, and that 1% of these mission failures may result in a crash, then we would statistically have roughly 7-35 crashes every year. This would clearly be unacceptable.

We postulate that icing is more often going to be a problem than wind. Icing, if unmitigated, will quite often during winter reduce the performance to dangerous levels within minutes. Even the short flight from Ullevål Sykehus to Rikshospitalet will be perilous a number of times every year without IPS (Ice Protection Systems) in place. Wind will most likely cause unsatisfactory mission performance from time to time, but this will be extremely rare in the case of the very short flight from Ullevål to Riksen. Some rare wind phenomena will, however, cause safety issues, even in Oslo. Strong downdraft associated with thunderstorms may be the most serious threat, besides icing.

Given the assumed extremely low risk acceptance for every single flight carrying valuable and sensitive payloads over the densely populated area in Oslo, we must conclude that current drone systems cannot satisfy the requirements. Backup systems must be in place to secure the service regularity during periods of excessive weather related risk. Other missions, with longer transport distances would highlight the potential gains from drone use over road transport, but would also be associated with possibly greater mission and safety related uncertainty.

6.2 Mitigations

Using a combination of several different weather mitigations, we may get significantly closer to an acceptable level of safety and service regularity than we are today, within a reasonable time frame.

Using weather and flow models as they are, adapting the way they are made available to operators and drone computer systems, we may achieve a much higher level of predictability. We may avoid the highest icing risk and the most detrimental wind – e.g. by flying around clouds or waiting. Some residual risk will, however, remain, due to the uncertainty in the weather models, and the lack of met services that cover small scale phenomena and SLD spectrum (Supercooled Liquid water Droplets). In general, the available weather forecasts and finer scale wind models will allow us to:

1. Plan for the unavailability of a given kind of drone system

2. Plan routes that are safer and more efficient than the routes we would plan without active use of (fine scale) weather data. This depends on some level of flexibility in airspace access

3. Predict more accurately the flight time from A to B

For flight distances of some length, and provided that airspace regulation will allow some flexibility, we may soon be able to plan safer and more efficient paths. There seems to be little doubt that the large scale wind and icing forecast are reasonably valid above a certain altitude. The limitations in resolution and droplet size distribution (SLD) are of great importance when operating small drones at low level. Resolution needs to be "ten times higher" than the normal 2,5km of the operational models used today. The validity for drones of the current algorithms behind the "icing index" must be studied. When considering the met support in future work, we must investigate all aspects of the meteorology services and how they are used in drone systems:

a. The models: geographical and altitude coverage, resolution (grid, layers), how often are they run, parameters, validation

b. What (quality of) data do we need?

c. How data is made available

d. How data and information is presented to operators

e. How data is used by operators and aircraft systems

The case of flying drones between Rikshospitalet and Ullevål Sykehus is a special case in the grand scheme of drones in healthcare. The flight distance is very short (2-4 km, depending on chosen route), and we have the luxury of being able to deploy numerous stationary instruments and systems in order to reduce the risks – not only the weather related ones.

It is possible to design the drones themselves for a lower icing and wind vulnerability. But only to a certain unknown limit, and at unknown cost. Without further investigation, we postulate that there currently does not exist a drone system that will allow full, year round availability, even if it had a higher than normal thrust surplus (high maximum airspeed etc) and was equipped with a full ice protection system (IPS). For the special case of Rikshospitalet to Ullevål, we can get pretty close. Applying the full quality control regimen of manned aviation, as well as accepting the use of more costly, robust air vehicles, the levels of safety and mission performance will be “very close to 100%”. The alternatives are:

- **Drones only A:** one type of robust drone that handles “anything”

- **Drones only B**: one type of low cost drone that provides “90-something percent” of the service, and another type of more robust drone that can handle the more challenging conditions

- **Drones and some other backup**: concept A or B above, pluss a «non-drone-based” backup solution (e.g. vehicular transport) which is used quite often

An absolute requirement for any healthcare-related drone application in Norway, is that the first available versions of Ice Protection Systems (IPS) for small drones must be put into use as soon as possible. IPS will become available within a few years, but these systems will carry a significant cost in terms of weight, power draw, and drone cost but this will be acceptable and well worth it for many UAS applications. IPS must be used sparingly and intelligently on long missions, guided by on board sensing and path planning which uses icing forecasts.

Reduced risk, exploratory operations must include IPS testing. There will no doubt be great room for improvement from the very beginning, and the technology must be actively refined and adapted to user needs. A period with a steep learning curve through operational use will provide the input needed to guide further R&D. The cost, SWP (Size, Weight, Power) and practical manufacturing issues will all see rapid improvements once systems come into use, and more and more data from flights in icing conditions becomes available.

It should be noted that relying heavily on back-up solutions instead of working to make drone solutions very robust and safe, would leave the important potential in other medical/emergency drone services in bad weather unexploited. When roads are blocked, visibility is low, the risk of avalanche, explosion or active sabotage is high, other assets are also often unavailable (helicopters, ground vehicles, search teams). The developments within unmanned systems should be driven towards such difficult and critical applications. Emergency response, search and rescue etc would benefit from the establishment of "foul weather drone services".

6.3 Planning and control

The possible adverse effects of icing and wind may be minimized through the way we manage and use our drones. Current solutions are adapted to hobbyists or military users primarily. The goal must be to:

I. Avoid detrimental flying conditions

II. Ensure the proper behavior when unavoidably influenced by icing and wind

Autonomy is an often-heard buzzword. And for good reason. To achieve the performance we are after in the hospital logistics case (frequent, very safe, regular flights), there is no question that the way drones are managed and controlled today is both very inefficient and unsuitable.

Professional, civilian systems could and should leverage more of the new technological possibilities within automation, autonomy and flexible human-machine interaction. Some of these improvements may be implemented within a few years, following low rate initial operations during which the requirements will become clearer.

A great deal of information is needed in order to build and maintain situation awareness (SA). Based on this SA, good decisions must be made quickly – sometimes within seconds. Managing "a hundred" missions every day, day and night, direct human control of every flight would require a prohibitively large number of capable operators – although not necessarily at every physical site. Spreading drone services to other applications will further increase the relevance of automation. E.g. the work load on police officers or rescue crews operating/using drones should be minimized.

The non-intuitive nature of drone icing and severe wind events, and the reliance on large amounts of data, calls for automated and technical solutions, which are beyond what exist today. Without going into further detail, we postulate that many tasks in the area called "command and control" must be automated. At some undefined point, the term "automation" is replaced by "autonomy". When a system has the capability to perform tasks that are sufficiently complex, it is said to be autonomous.

In logistics drone systems for healthcare, as in many others, the desire to maintain human control at some level seems to be a matter of strong societal consensus. Importantly, this does not necessarily equate to direct human involvement in every function. Automation, autonomy and direct human action and oversight will to a varying degree be needed in maintaining situation awareness, planning missions, managing a fleet of drones, recognizing and understanding faults and threats, handling emergencies etc. When, where and how humans should be involved in command and control of logistics drones, must be determined in studies supported by limited scale operations and simulations.

6.4 Handling risk

Many aspects of realizing a drone based logistics service come down to handling risk. Being a relatively new and emerging technology, drones introduce new risks. Some of these risks have not been studied in any depth. The weather is but one of several hurdles to overcome in order to unleash the full potential in using drones in healthcare logistics, or indeed in a multitude of other applications.

Drones compete with existing solutions and "ways of doing things" that are proven and reasonably predictable. For drones in healthcare, and in most other potential applications, there is no suitable turn-key system available. There is no formal "track record" for safety. New solutions must be developed as part of a holistic architectural process, well integrated with developments in the user community business model and internal processes. Safety must be documented thoroughly, and according to industry standards. This process itself carries cost and uncertainty.

Drones are used today within a developing framework of regulations and a maturing quality control culture, with risk assessment and acceptance differing from country to country, and between different communities within the same country.

Adopting the manned aviation practice of striving for failure rates on the order of "one in a million", we may defeat the cost advantage of drones in many cases. The hospital logistics case may or may not be one of those cases. The motivation for using drones has more to do with healthcare service quality and overall cost than with saving costs in the transport service itself. Using drones safely may indeed prove to be much more expensive than the current road transport solution. The financial gains of e.g. consolidating laboratory services or reducing patient treatment time may however far outway the costs incurred by introducing and operating safer drones.

In many drone applications, especially military ones, a given drone service (observation, attack, resupply) may in principle rely on the use of several or many drones. The service quality may not depend entirely on the availability or risk of loss of any given individual drone. For most medical transport missions, this point is surely mute, as every payload must have a very low risk of being lost.

A drone crash in an urban environment is a very serious occurrence, even when no one is injured. Even a descending drone using an emergency parachute would probably be considered a serious incident. We could possibly argue that the urban hospital logistics concept is the most difficult challenge there is in the drone business.

When various demonstrations of medical drone flights have “proven the obvious” – that it is possible to fly a remote controlled mission from A to B carrying e.g. real blood samples, the essential question of risk handling is largely unaddressed. When do we conclude that a drone service is unavailable? What level of residual, unmitigated risk is acceptable?

Total risk must be addressed and mitigated in a documented way before many of the envisioned drone services may become a reality. A spectrum of technological and non-technological solutions must be found, and they must be thoughtfully incorporated in user enterprise architectures.

Figure 6.1 The Norwegian Air Ambulance service has emplaced more than 100 weather cameras in Norway, in order to reduce the weather related uncertainties for their safety critical missions. A camera emplaced above Bodø in Northern Norway (right) [56].

Figure 6.2 NORCE at the North Pole, operating drones in service of scientific studies [58].

6.5 Recommended approach

Based on the previous discussion, we recommend a holistic approach, fostering improvements to aircraft design, sensors, command and control, supporting services and infrastructure. We recommend that the approach contain the following elements:

1. Limited **live, exploratory operations** over time in one or two selected rural (non-urban) locations, with a gradual, risk-controlled ramp-up.

2. All drones intended for safety critical operations must be **tested rigorously** in challenging wind and icing conditions to define envelopes and tolerances and to understand the dynamic response. Standardized and quality controlled testing must be conducted.

3. **User requirements and business models** must be studied further. Possible adaptations to the user organization and its internal processes, business model and handling of the unavoidable uncertainties, risks and limitations of drone services must be studied.

4. **Develop new solutions for planning and control**. Planning and control software at the fleet, mission and single air vehicle level. Decision support and automation/autonomy may be of paramount importance.

5. **Met services**: Available meteorology services should be actively explored as-is, and adapted further for drone operations support, subject to a cost-benefit analysis.

6. **Onboard sensing** (insitu and remote sensing) of ice buildup and local flying conditions should be standard on all professional drones in Norway. The specifications for such sensor suites must be a result of a cost-benefit analysis.

7. **IPS** (Ice protection Systems) must be put into use as soon as possible, as standard equipment on all professional drones used in Norway. These solutions must be rigorously tested and actively evolved.

8. **Offboard sensors** should be distributed in the area of operations, in order to reduce uncertainty, and provide data for assimilation and validation.

9. **Simulations** of operations, with weather included. Weather and the effects on the aircraft must be represented and visualized well

Relevant work is underway in all the above areas. Experience from arctic and Antarctic scientific operations is increasing, and will continue to do so at a higher pace (e.g drone operations by NORCE as part of the Troll Observing Network – TONe [59]). Emergency services and "first responders" are using drones to an ever increasing extent, all over Norway, and in many other countries. User awareness, understanding and demand is likely to increase quickly.

Balancing the allocation of research funds to the different mitigating technologies, testing etc may be a challenging task. Suboptimizing and uncoordinated resource allocation seems to be quite likely, unless a national coordinating role is filled. Going after "the last ten percent" of performance in e.g. the route planner or the IPS may not be a good idea until the whole architecture, including the user community is in place, plenty of statistics have been collected and the users business models are more developed.

Figure 6.3 (Left) High Tech Campus Eindhoven - Autonomous drones field lab [60]. (Right) Urban Air Mobility (UAM), as envisioned by Airbus [61]. A number of serious efforts, besides those in healthcare, are underway to realize drone transport in urban environments. These will become strong drivers for weather robust and safe solutions.

7 Conclusion

Current small drones will occasionally be severely affected by icing and wind in Oslo. A 24/7/365 drone service, providing blood sample transport between two major urban hospital locations in Oslo, may nevertheless be realized, using emerging drone system technology.

Achieving the technological and organizational maturity to implement and exploit a full-scale drone based logistics concept will require a holistic and active approach to risk mitigation and R&D. Testing and small scale operations must take place in (semi)rural locations over a number of years.

Most drone flights will be unproblematic in the Oslo area, even for small drones. In other parts of the country, the weather challenges will be much more severe. Maritime and arctic operations will be especially challenging. The occasional serious incident/accident may be unavoidable, the weather being just one of several risk factors. This may be the case, even when mitigations are in place. Back-up assets will be required to be on call to uphold the logistics flow.

Ice protection systems (IPS) must be used from autumn until late spring. Specific drone vulnerabilities and responses must be thoroughly studied, and accounted for in new systems for planning and control. A high level of automation is necessary.

Sufficient meteorological and fine-scale wind models are available, albeit with important performance limitations, which are partially unknown. They should be used actively “as-is”, in support of initial operations. Drone systems and meteorological services must co-evolve following a period of exploratory, risk-controlled operations.

OUS and other similar health care entities in Norway must expect that the full vision of drone logistics can be met at the earliest five years from now – probably closer to ten years from now.

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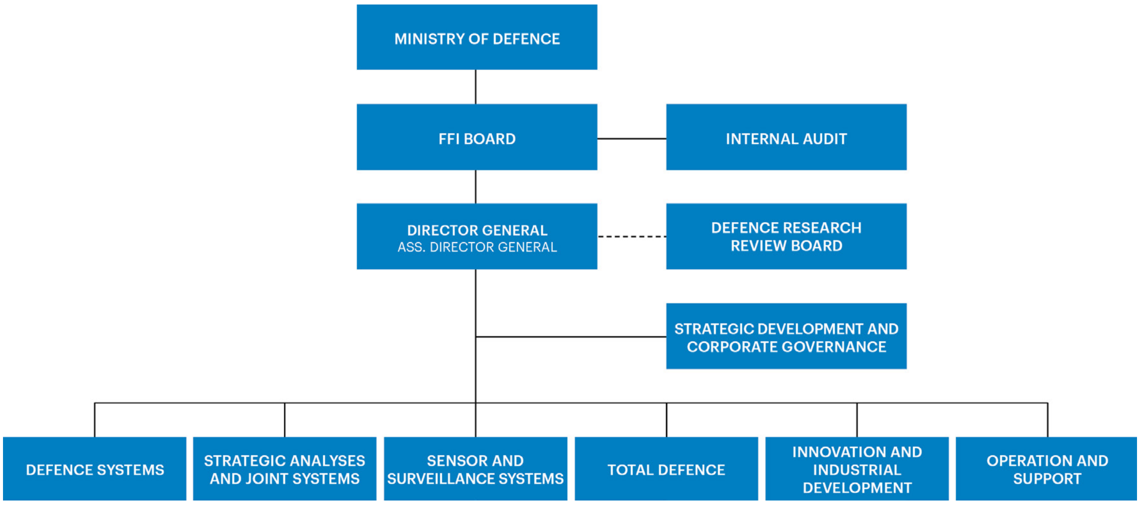

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