FINNISH METEOROLOGICAL INSTITUTE
Erik Palménin aukio 1
P.O. Box 503
FI-00101 HELSINKI
tel. +358 29 539 1000
WWW.FMI.FI

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IMPROVING METEOROLOGICAL INFORMATION TO AIR TRANSPORT

JAAKKO NUOTTOKARI

FINNISH METEOROLOGICAL INSTITUTE
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IMPROVING METEOROLOGICAL INFORMATION TO AIR TRANSPORT

Jaakko Nuottokari

Department of Physics
Faculty of Science
University of Helsinki
Helsinki, Finland

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Supervisor PhD Elena Saltikoff
Meteorological Research Unit
Finnish Meteorological Institute

Reviewers Professor Heikki Järvinen
and
Docent Jouni Räisänen
Department of Physics
Faculty of Science
University of Helsinki

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Jaakko Nuottokari

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ABSTRACT

Meteorological information and services supporting the various operations of air transport enable a safe, efficient and cost-effective operating environment for airspace users, air navigation service providers and air traffic management. The continuing pursuit towards an improved quality of observation, forecasting and decision support services is driven by an increasingly weather-sensitive society and growing impacts of hazardous weather events.

This thesis provides an overview of the field of aeronautical meteorological research by introducing the organisations involved, global and regional strategies, impacts of weather on air transport, current state of the art in meteorological research and decision support systems serving air transport needs with a view of where the field should evolve next. This thesis is an attempt to highlight key findings and point the reader towards the direction of further research on the given topics.

Research supporting air transport operations with the optimal use of weather information is a specialized field where advances are led by the needs of various airspace users. Research institutions for example in the United States have contributed greatly due to the severe weather impacts experienced by the National Airspace System (NAS), the ability of the Federal Aviation Administration (FAA) and the National Oceanic and Atmospheric Administration (NOAA) to direct long-term funding to solve specific aviation-related research questions. The creation and maintenance of long-lived teams of scientists and engineers working together to produce end-to-end solutions that meet the needs of the aviation industry is the key to improving meteorological information to aviation users while university research is typically shorter duration and typical does not result in operational systems.

From a global perspective, research is yet to be organised in a way that would contribute to solving aviation issues beyond single research projects and/or programmes. There is a lot more the scientific community could do to develop tailored information to decision support systems used by the aviation sector, but it would require systematic investments and the establishment of research groups focusing on the applied science questions and technology transfer. This thesis provides an overview of recommended decision support system development topics with an outline of potential milestones.

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Ilmailun käyttämän meteorologisen tiedon kehittämisestä

TIIVISTELMÄ

Tieto ilmakehän nykyisestä ja tulevasta tilasta sekä tätä tietoa ilmailun tarpeisiin tuottavat palvelut mahdollistavat turvallisen, toimivan sekä kustannustehokkaan toimintaympäristön ilmatilan käyttäjille, ilmailun palveluiden tuottajille sekä ilmatilan hallintaa toteuttaville tahoille. Vaarallisille sääilmiöille herkemmäksi kehittyvä yhteiskunta vaatii havaintojen, ennusteiden sekä päätöksenteon tukijärjestelmien jatkuvaa kehittämistä asiakkaiden tarpeisiin.

Tämä lisensiaatintutkielma tarjoaa maailmanlaajuisen yleiskatsauksen ilmailun sääpalveluiden tutkimukseen ja tuotekehitykseen pyrkimyksenään esitellä keskeiset toimijat, alueelliset ja kansalliset kehittämisohjelmat ja strategiat, sään vaikutukset ilmailulle, ilmailun sääpalveluiden nykytila sekä tulevaisuuden toimintaympäristön edellyttämät uudet lentosääpalvelut. Tavoitteena on korostaa ilmailun kannalta tärkeimpiä meteorologisia kehityskohteita ja ohjata lukija jo tehdyn tutkimuksen pariin.

Ilmailun toimintoja tukevien sääpalveluiden kehittämiseen tähtäävä tutkimus on hyvin soveltava erikoisala, missä asiakkaiden tarpeet määrittävät tutkimuskohteet. Kehitys on keskittynyt voimakkaasti Yhdysvaltoihin, mihin on syynä kapasiteetin äärirajoilla toimiva ilmatila sekä kyky rahoittaa pitkäkestoisia meteorologisia tutkimushankkeita ilmailun tarpeisiin. Meteorologian tutkijoiden ja insinöörien pitkäkestoinen yhteistyö tuottaa koko arvoketjun kattavia projekteja, joiden lopputuloksena syntyy asiakkaan tarpeisiin räätälöityjä palveluita hyödyntäen yliopistoissa tehtävää tutkimusta sekä tietoteknisten ratkaisujen kehittymistä.

Maailmanlaajuisesti katsottuna ilmailun sääpalveluiden tutkimusta ja tuotekehitystä ei ole toistaiseksi järjestetty yhtenäisen strategian tai tavoitteiden alle. Tieteellinen yhteisö pystyisi kasvattamaan merkittävästi panostaan ilmailun turvallisuuden kehittämiseksi, mikäli tuotekehityksen rahoitus organisoitaisiin paremmin ja osaaminen keskitettäisiin soveltavan tutkimuksen ryhmiin. Tämä tutkielma sisältää suosituksia päätöksenteon tukijärjestelmiin integroitavista sääpalveluista, joiden avulla säätilan vaikutus lentotoiminnalle voidaan viedä suoraan päätöksentekotasolle. Tutkielmassa esitettyjen projektiaihioiden tarkoituksena esittää konkreettisia toimenpiteitä, joilla varmistutaan tutkimuksen soveltuvuudesta loppukäyttäjien toimintaan.

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This work is dedicated to Ainu, Nooa, Miio and Maria.

ABBREVIATIONS

ABI	Advanced Baseline Imager
ABoM	Australian Bureau of Meteorology
ACAPS	US Air Force Weather Agency Coupled Analysis and Prediction System
ACI	Airports Council International
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
AFWA	US Air Force Weather Agency
AHI	Advanced Himawari Imager
AIM	Aeronautical Information Management
AIREP	Aircraft Report
AIS	Aeronautical information services
AMDAR	WMO Aircraft Meteorological Data Relay
AMS	American Meteorological Society
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider (incl. MET)
ASBU	Aviation System Block Upgrade
ASM	Airspace Management
ASOS	Automated Surface Observing System (USA)
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Services
AWD	NextGen Weather Processor Aviation Weather Display
AWOS	Automated Weather Observing System
BKN	Broken (cloud layer 6-7/8)
CANSO	Civil Air Navigation Services Organisation
CAPS	Center for Analysis and Prediction of Storms (US)
CARATS	Collaborative Action for Renovation of Air Transport Systems (JPN)
CAT	Clear Air Turbulence
CDG	Paris Charles de Gaulle airport
CIT	Convectively Induced Turbulence
CMA	China Meteorological Administration
CNS	Communications, navigation and surveillance systems
CSS-Wx	NextGen Common Support Services – Weather
DSS	Decision Support System
DWD	Deutcher Wetterdienst (GE)
EASA	European Aviation Safety Agency
ECMWF	European Centre for Medium-Range Weather Forecasts
EDR	Eddy Dissipation Rate

EFB	Electronic Flight Bag
EHS	Mode S Enhanced Surveillance
EU	European Union
EUMETNET	European Meteorological Services Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
Eurocontrol	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration (USA)
FIR	Flight Information Region
FMI	Finnish Meteorological Institute
GA	General Aviation
GANP	Global Air Navigation Plan
GDP	Gross Domestic Product
GOS	WMO Global Observing System
GTG	Global Turbulence Guidance
GTS	WMO Global Telecommunications System
HAIC	High Altitude Ice Crystals
HEMS	Helicopter Emergency Medical Services
HIWC	High Ice Water Content
HOT	Holdover Time Table
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
ISRO	Indian Space Research Organisation
ITWS	Integrated Terminal Weather System
IWXXM	ICAO Meteorological Information Exchange Model
JCAB	Japan Civil Aviation Bureau
JMA	Japan Meteorological Agency
KPA	Key Performance Area
LAPS	Local Analysis and Prediction System
LIDAR	Light Detection and Ranging
LLT	Low-Level Turbulence
LLWAS	Low-Level Wind Shear Alert System
LMA	Lighing Mapping Array
LWC	Liquid Water Content
LWE	Liquid Water Equivalent
MET	Aeronautical Meteorological Service
METAR	Aerodrome routine meteorological report
MOS	Model Output Statistics
MWO	Meteorological Watch Office
MWT	Mountain Wave Turbulence
NAS	National Airspace System (USA)
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Center for Atmospheric Research (USA)

NextGen	Next Generation Air Transport System (USA)
NMHS	National Meteorological and Hydrological Service
NOAA	National Oceanic and Atmospheric Administration (USA)
NWP	Numerical Weather Prediction
NWS	National Weather Service (USA)
OPERA	Operational Weather Radar Information Exchange (EU)
OVC	Overcast (Cloud cover 8/8)
PIREP	Pilot Report
QNH	Atmospheric pressure adjusted to sea level (from Q code, i.e. Query: Nautical Height)
QPF	Quantitative Precipitation Forecast
RHI	Range Height Indicator (weather radar)
RHWAC	Regional Hazardous Weather Advisory Center
RPAS	Remotely Piloted Aircraft Systems
RVR	Runway Visual Range
SAE	Society of Automobile Engineers
SAR	Search and Rescue
SDM	SESAR Deployment Manager (EU)
SES	Single European Sky (EU)
SESAR	Single European Sky ATM Research (EU)
SIGMET	Significant Meteorological Information
SJU	SESAR Joint Undertaking (EU)
SWIM	System Wide Information Management
SYNOP	Surface synoptic observations
TAF	Terminal Aerodrome Forecast
TBO	Time-Based Operations
TREND	Expected significant changes in the meteorological conditions at the aerodrome
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicles
UCAR	University Cooperation for Atmospheric Research (USA)
VIL	Vertically Integrated Liquid
VLF	Very Low Frequency
VMC	Visual Meteorological Conditions
WAFC	World Area Forecast Center
WMO	World Meteorological Organization
WXXM	Meteorological Information Exchange Model
XML/GML	Extensible Markup Language / Geography Markup Language

CONTENTS

1 INTRODUCTION

The aim of this work is to showcase the status of research activities on aeronautical meteorology carried out globally and to present the observing, forecasting and decision support capabilities currently available to assist researchers, institutions and funding agencies to align efforts to make the maximum use of our limited resources. Emphasis is also on gaps and future research directions available to improve our level of understanding. This work attempts to be a comprehensive description of global meteorological research and an overview of the most important and visible research specifically aimed at air transport uses. The research method is a meta study and a literature review in meteorology focusing on the meteorological applications required for safe air transport.

Meteorology as a research field has multiple specialized fields. While all research ultimately supports the overall objective of better serving society and customers, the needs and requirements of the air transport sector require special attention. Aviation weather is a special type of forecasting where the emphasis is on the 0 to 12 hours timeframe due to the near-term and high-resolution requirements by the airspace user operations. Flights and thus air navigation services and airports are constantly adapting to changing circumstances. In this timeframe, advanced Numerical Weather Prediction (**NWP**) models are good in predicting a number of aviation weather hazards. One of the main difficulties is the lack of observations at high enough space and time resolution to characterize the current state of the atmosphere as well as the forecast uncertainty increasing as scales of interest get finer and finer. In this space, the human forecaster must generate a clear picture of the very near future evolution of the weather to be able to accurately predict the weather for air transport customers. The human intervention in aviation weather forecasting is the one of the strongest bastions of the forecasters' skill to improve the forecast, but automation and technology are on their way to improve both the guidance received by the forecaster and the actual end products automatically generated by various processing methods. Ongoing developments for four-dimensional trajectory management for flights aim to have information about the exact position and time of arrival of an aircraft exchanged in real time and weather is a major factor in the accurate estimation of speed and location of the aircraft.

Air transport has become an everyday part of life for many and is a key part of the global world we live in today. The performance of the air navigation system depends on a variety of factors ranging from technical to human to the natural environment and provides an astonishing level of safety for passengers and crew. Weather plays an important role in air transport, causing safety risks, delays and economic impacts on airspace users. The weather enterprise continues to make significant efforts in advancing the state of the art of meteorological information and service to its customers.

In its end-year report, the International Air Transport Association (**IATA**, 2016) estimated that 0.9% of world Gross Domestic Product **(GDP)**, totalling $769 billion, is spent on air transport in 2017, providing employment to some 2.67 million and contributing to 2.5% of world GDP growth. Prospects for growth for airlines in the United States seem especially promising. The total weather service market in US is estimated by American Meteorological Society (**AMS**, 2012) to be worth around $4-5bn, of which $1.65 to 1.8 billion were attributed to the private sector (Spiegler 2007). Out of the private sector weather service costs, an estimated 5% ($82.5 to $90m) were related to aviation.

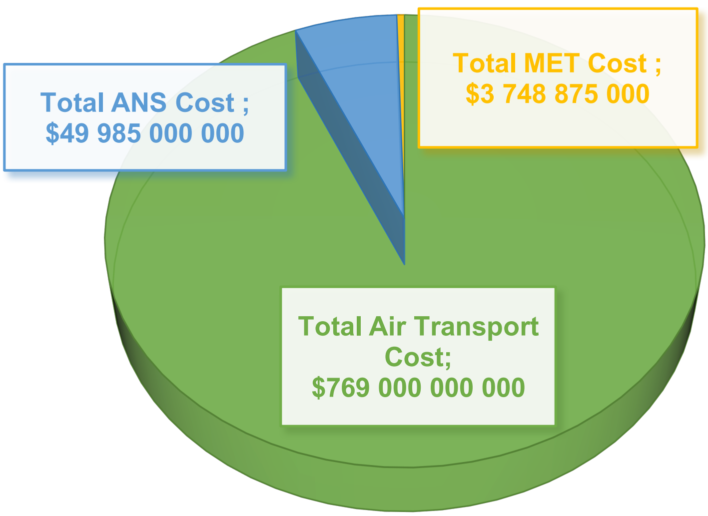

Figure 1 Estimation of global aeronautical meteorological service provision cost as a fraction of the total air transport cost

The total share of aeronautical meteorological (**MET**) costs on air transport costs range widely from country to country. Aeronautical meteorological costs are typically included in Air Navigation Service (**ANS**) costs when charged from the user. The share of MET cost of total ANS costs in Europe as estimated by Eurocontrol (2004) for 2002 was 6.7% (decreasing from 7.9% in 1998). European air transport operators paid in total €380 million for MET services in Europe in 2002.

There exist many countries where MET services are not cost recovered at all, and the cost for service provision is allocated to the national budgets. The lack of global harmonisation on cost recovery policy for MET services makes comparison difficult and distorts the overall picture, but a rough estimate of 5-10% of Air Navigation Service charges globally can be applied for MET services according to the available published literature. Global Air Traffic Management (**ATM**) costs are estimated at $10.9 billion in a report by Eurocontrol (2016) and total ATM & ANS costs roughly $50bn (6.5%) of total air transport costs. Assuming an average 7.5% MET share of the total ATM/ANS, we could estimate that roughly $3.7 billion is allocated annually to support MET service provision, excluding any government funding or military spending (see Figure 1). Since 2002, significant cost pressure has been imposed on the global meteorological community via various instruments while cost of infrastructure has increased.

The most relevant estimates on the potential impact of MET services to the societies they serve are presented by Freebairn and Zillman (2002), Frei (2010), Hautala (2008) and the UK Met Office (2007). The difficulty of estimating total cost-benefit for meteorological services is well described by Freebairn and Zillman (2002), but a serious attempt at defining a number is given by the UK Met Office (2007) where with a budget of £18.2m for aeronautical meteorological services, the weather service benefits for the Civil Aviation Authority are quantified at 20 saved lives, £95.5m saved through improved routing and an additional £3.6m from reductions in flight delays, bringing a total return-on-investment for aeronautical meteorological services to 5.5 times the initial investment not accounting any of the commercial or military services provided by the UK Met Office. The study focusing specifically on the value of the Terminal Aerodrome Forecast (**TAF**) at Zurich and Geneva airports in Switzerland by Von Grueningen et al. (2014) reveals an estimated value of $14-22m for domestic airlines per year for this product alone. Weather services are thus a sound investment for the users and a cost-effective way to mitigate the inherent risks of weather for aviation. High-quality weather services are enabled by scientific research and hence the research discussed in this piece of work contributes further to improve the return on investment and improve the safety of aviation. Funding for aeronautical meteorological research represents a small fraction of the total aeronautical meteorological service provision field. Largest funding is received from the users via grants, commercial contracts and collaboration, followed by research funding programs such as the European Union Single European Sky ATM Research (**SESAR**) program, US Federal Aviation Administration (**FAA**) NextGen program and Japanese CARATS program. These will be discussed further in the following section.

The general trend with airlines is the takeover of low-cost carriers over traditional airlines' business models also on long-haul flights operating smaller narrow-body aircraft. IATA expects a 3.7% annual compound average growth rate over the next 20 years, effectively doubling the amount of air travellers in especially emerging markets. Clearly this will lead to capacity issues and expansion plans at already busy airports. Applications are becoming ubiquitous for airlines, airports and meteorological service providers. Airspace will need to be streamlined to facilitate the increased traffic and the move towards free route airspace and cross-border cooperation is an attempt at resolving this issue. For airports, the rise of China is felt strongly, since China has added over 100 airports between 2011 and 2015 and continues an exponential growth path.

The long-term changes in weather patterns associated with climate change present additional considerations for airlines and airports. Impacts of climate change are related to e.g. rising surface temperatures and their extremes, extreme weather events, seal-level rise and changes in transport routes following changes in consumer behaviour. Growth in aviation is driven by emerging markets especially in Asia where climate change impacts need to be reviewed critically in all infrastructure investments. Increasing surface temperature maxima connected in some areas to also increased values of specific humidity can severely limit take-off performance of aircraft at airports at high altitudes or with short runways. A recent example from Phoenix, AZ, USA on 20 June 2017[1] has provided insight into the impact of high temperatures on aviation as nearly 50 flights were cancelled when temperatures reached 49°C. The flight cancellations were caused by the maximum operating temperature of Bombardier CRJ airliners of 48°C having been exceeded and thus the aircraft were deemed not airworthy. The viability of coastal airports subject to sea-level rise induced storm surges and flooding could also be at risk and needs to be considered for all new airport projects. Increased rainfall amounts may also result in flooding at airports experiencing monsoons, tropical storms and increased thunderstorm activity. Changing jet stream intensity and track and changes in many other weather patterns will add a host of local changes in the operating environment of airlines and airports.

Chapter 2 provides a short overview of weather impacts on the various air transportation user groups, Chapter 3 discusses the current state in the numerical and observation methodologies research and development, Chapter 4 introduces the various organisations involved in aeronautical meteorological research, Chapter 5 offers a review of the research on the identified meteorological phenomena, Chapter 6 presents advances in decision support systems integrating meteorological

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[1] http://www.bbc.com/news/world-us-canada-40339730 (link tested 29 Nov. 17)

information, Chapter 7 presents future challenges for aeronautical meteorological research and finally Chapter 8 presents recommendations and some key finding based on this piece of work.

2 IMPACTS OF WEATHER ON AIR TRANSPORT

The impact of weather on the operations of airspace is related first and foremost to ensuring the safety of flight and the supporting services. Airlines, airports and ATM take precautions to avoid any hazardous weather that is known to have an impact on the performance of an aircraft. The avoidance procedures to ensure safety sometimes result in additional duration of flight or closure of runways leading to a delay for the passenger. The monetary impact of weather can be estimated using the delays caused to the airspace users due to weather constraints and the economic impact this in turn results in to the operating airlines. Weather is one of the main causes of disruptions to air transport, but its effects are not the same for all users. This section presents the users of aeronautical meteorological information and the impact weather has on operations to identify the specific meteorological phenomena that will be the focus of the following section. A general overview of weather and climate impacts for the aviation sector is presented by Temme et al. (2014), identifying heat and cold waves, heavy precipitation, snowfall, large-scale storms and wind, thunderstorms, blizzards and fog as the main adverse weather conditions and includes a general outlook to the development of the frequency of these events in a changing climate.

Airspace design, climate, topography, users and their needs all contribute to the impact weather has on the functioning of air transport. The United States is known to be prone to weather-related delays in its National Airspace System (**NAS**), and the FAA OPSNET Standard Report estimates[2] that 69% of delays are caused by the weather. This results in massive economic losses for the airlines. Comparing the impact from one region to another is difficult due a lack of the same rigor of reporting weather delays as in the US in other parts of the world.

A good comparison report focusing on the weather-related Air Traffic Flow Management (**ATFM**) delay between Europe and the US is presented in a joint report by the FAA and European Organisation for the Safety of Air Navigation (**Eurocontrol**) (2013). The report highlights differences in the way weather constrains impact airports, severity of impacts, and clearly shows the impact that a few US airports (namely New

[2] https://www.faa.gov/nextgen/programs/weather/faq/ (link tested 29 Nov. 17)

York airports Newark (**EWR**), LaGuardia (**LGA**) and John F. Kennedy (**JFK**)) have in producing the large weather delays, whereas in Europe it is mainly London Heathrow (**LHR**) that is affected by winds and visibility. Overall, weather conditions in Europe are worse than the US with more hours flown in Instrument Meteorological Conditions (**IMC**) than in the United States. Visibility, wind, winter operations and thunderstorms are the main weather-related causes of ATFM delays in Europe. The situation in the US is similar, but the impact of thunderstorms and severe weather is prominent. The reasons for the higher delays in the US with similar weather constraints are speculated to be connected to the differences in airspace management. In Europe capacities are set more conservatively to allow for foreseeable events, while the US operates by presuming ideal operating conditions and thereby calling higher capacities. In Europe, 1.8% of total delay is attributed to ATM and ATFM delay and the corresponding number in the US is 6.8% of which the FAA attributes weather as the largest contributor to system delay.

2.1 TERMINAL SERVICES

At the airport terminal, snow, freezing precipitation and any thunderstorm hazard may impact ramp and taxiway operations and wind, wind shear, low ceiling and/or visibility may impact terminal runway operations. In the departure phase of the aircraft, wind, wind shear, microbursts, turbulence, icing and thunderstorms may impact departure operations. In New York Newark (EWR) and LaGuardia (LGA) airports, over 90% of the ATFM delay is caused by weather (FAA and Eurocontrol 2013). Weather is the prominent driver of ATFM delays in both Europe and the US, with 38.2% of airport delay in Europe and 72.9% in the US in 2013. A project report prepared by the Massachusetts Institute of Technology Lincoln Laboratory in 2001 by Allan et al. (2001) found that improved decision making by the New York FAA users of the Integrated Terminal Weather System (**ITWS**) provides an annual delay reduction of over 49,000 hours per year with a monetary value of $150 million per year. The report identified the meteorological phenomena leading to the documented impacts as thunderstorms, low ceiling & visibility and high surface winds which all reduce the airport capacity for take-offs and landings, increase taxi-in and taxi-out times and increase air traffic controllers' workload. A similar study for London Heathrow is presented by Pejovic et al. (2009) which concludes on the impact of thunderstorms, snow or fog, which are found to increase the chance of weather-related delay by more than 25%.

Ground operations at airports most typically include de-icing, ground handling, snow clearance from runways and taxiways, rescue crew and passenger transport. These parties have similar needs as the airports, but have specific needs on the temporal timescales to enable forward planning of capacity. Runway clearing from snow and ice, for example, requires professional staff to be available at a short notice. However, this staff may be blocked from reaching the airport in the first place if a major weather event affects an airport and its access routes. When ground handling crews have 2-3d warning on a major event, staff can be called in advance allowing sufficient crew to be available. This is especially true for rare, but high-impact events such as major snowstorms, which can be forecasted in advance out to 7-10 days before the event. Ground operations are also very susceptible to lightning and depend on the information provided by the local lightning detection network.

Remotely Piloted Aircraft Systems (**RPAS** or **UAS** or **UAV**) are being quickly adopted in oil & gas, critical infrastructure and public safety uses and many commercial companies have growing interest in using RPAS for deliveries, etc. The weather constraints for privately piloted RPAS are set partly by regulation (visual line of sight and 500ft ceiling in the US) and partly by technical constraints of the aircrafts. Typically, operation of RPAS is possible only in daylight Visual Flight Rules (**VFR**) conditions, with cloud ceiling above 500ft, maximum wind 20kt and temperatures ranging from -18°C to +40°C. The larger military aircraft are also not immune to weather and suffer from engine icing, hail damage and wind-related accidents especially during take-off and landing. Low altitudes and high sensitivity of equipment pose very specific challenges on the weather information to support operations, calling for higher resolution and better representation of cloud microphysics.

2.2 En-route Services

Airlines are involved in developing weather services that best match their requirements and provide the meteorological community with important aircraft observations. This implies the great significance of weather impacts on their operations. The important weather impacts for airlines here can be narrowed to the in-flight weather and fleet management over which the airlines have some degree of control. Aircrafts encounter many other types of hazards, including icing and strong winds[3]. One of the most

[3] https://www.bloomberg.com/news/articles/2014-12-30/how-bad-weather-can-affect-aircraft-and-what-can-be-done-qa (link tested 29 Nov. 17)

important weather impacts during the flight is moderate to severe turbulence[4]. While turbulence rarely damages the aircraft, it is a hazard and major discomfort to the crew and passengers. Turbulence itself can be generated by thunderstorms, jet streams and mountain waves. High altitude ice crystals (European term) or high ice water content (US term) (**HAIC** or **HIWC**) is becoming a major issue for airlines due to the new and more efficient jet engines being more susceptible to damages from a high concentration of ice crystals at cruising altitudes causing engine failures. The accurate forecasting of HAIC requires further research into the mechanisms behind the development of the ice crystals. Large areas of severe convection especially at hub airports generate major challenges for the airlines' fleet management operations by grounding and diverting aircraft.

Weather affects the management of air traffic in different parts of the flight in different ways[5]. During the en-route phase of the flight, jet stream winds, mountain waves, turbulence, icing and thunderstorms may impact operations. During the approach phase of the flight, wind, wind shear, microbursts, turbulence, icing and thunderstorms may impact arrival and approach operations. Ceilings and visibilities determine the type of approach (visual / instrument). From an air traffic management perspective, weather occupies space and needs to be separated from other traffic and it has been stated that *weather becomes the largest uncontrollable user of airspace*. According to the National Oceanographic and Atmospheric Administration (**NOAA**) and its National Weather Service (**NWS**), thunderstorms represent 24%, visibility 17%, wind 14%, ceiling 14%, snow 9%, freezing precipitation 8%, icing 7% and turbulence 7% of impact to delays caused by weather-induced air traffic flow management restrictions to the airspace in 2004. Weather heavily affects flow patterns and is a part of everyday life for air traffic controllers.

General aviation (**GA**) users are those users operating outside the commercial requirements, generally small aircraft, soaring flight, balloons and other recreational users of the airspace. These users represent a small fraction of the flights, but a large part of the deaths and accidents related to flying. Especially for general aviation, weather continues to be the most likely factor to result in accidents and fatalities. Weather impacts to general aviation are large primarily due to the requirement of operating under visual meteorological conditions (**VMC**) where a visual line of sight is maintained to the ground and airport during landing. As weather can change quickly, GA pilots can end up in perilous situations unless proper

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[4] https://business.weather.com/blog/flying-in-convective-weather-and-why-you-shouldnt (link tested 29 Nov. 17)
[5] https://www.meted.ucar.edu/nas/ (link tested 29 Nov. 17)

care is given to planning the flight with the most accurate meteorological information available. All the phenomena described above in the previous sections are highly valid for GA pilots. However, general aviators are especially susceptible to the risks imposed by low ceiling and visibility, thunderstorm, icing, freezing precipitation, wind and wind shear. The main tool to mitigate general aviation risks is to ensure that the pilots have the right information and are able to make the best decisions according to that information, such as presented in (FAA 2005). Rotorcraft (such as a helicopter) operation requires good weather conditions. Some of the most dangerous weather conditions for rotorcraft are low visibility, thunderstorms, winds, icing and snow[6].

The ability of rotorcraft to operate in these weather conditions is substantially lower than commercial aircraft, however many Search and Rescue (**SAR**) and medical helicopters operate also in poor weather and for these users, accurate weather information is of utmost importance. Turbulence is a special concern for SAR flights often occurring in low altitudes[7] and can potentially lead to loss of control of the craft as can any unexpected changes in air density. Helicopter Emergency Services (**HEMS**) are prone to all the hazards described in the references and often must weigh the risks of flying with the potential loss of life resulting from not flying. For these users, spatially and temporally accurate nowcasts of IMC conditions are of critical importance. However, here one must stress also the importance of representative ground observations, which often tell the HEMS operators of their ability to land in the given location. The SAR and HEMS operators have different needs due to their operations taking place outside the regular airport networks and air traffic corridors and essentially a high-resolution analysis of ground conditions would need to be available at all times.

3 Advances in the input information enabling aviation weather services

Advancing understanding on meteorological phenomena requires the theoretical background, observations and appropriate forecasting methodologies to support end users. Research and development aiming to improve the ground on which new and improved services can be built upon is the subject of discussion in this chapter. The input information is understood here to be mainly numerical weather model and Global

[6] http://www.brighthub.com/science/aviation/articles/67157.aspx (link tested 30 Nov. 17)
[7] https://flightsafety.org/asw-article/weather-impacts/ (link tested 30 Nov. 17)

Observing System (**GOS**) data and could naturally also be defined in many other ways. The distinction is made here since many aeronautical products are developed as data fusion products coming mainly from the sources discussed here. Individual forecast methods are the subject of the next chapter.

3.1 Numerical Weather Prediction

Advances in Numerical Weather Prediction (see Figure 2) over the past decades have been incremental and progressed steadily to improve our weather forecasting capability as summarised by Bauer et al. (2015). Quoting Bauer et al. (2015): *the impact of numerical weather prediction is among the greatest of any area of physical science.*

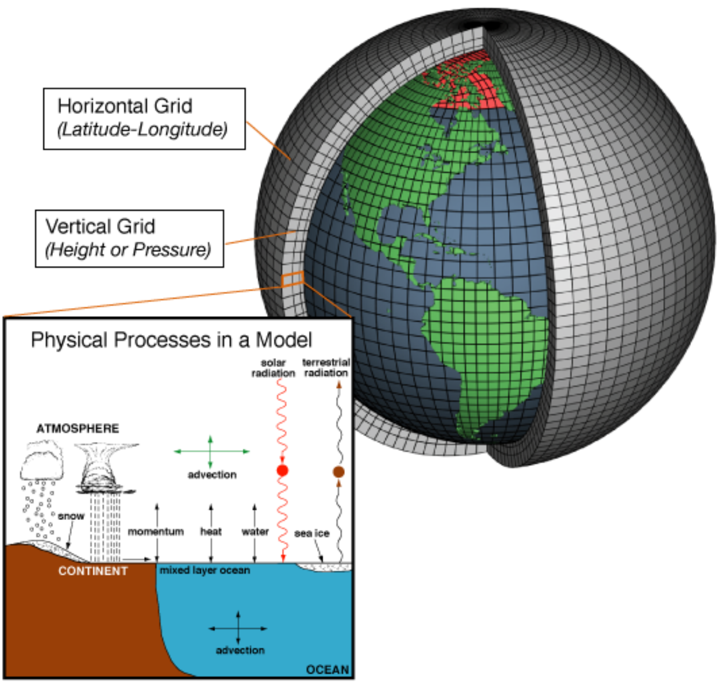

Figure 2: An illustration of the grids and processes included in a Numerical Weather Prediction model. Some advanced models include atmospheric aerosols and cloud electrification processes in addition to the ones presented in the figure. Source: https://en.wikipedia.org/wiki/Numerical_weather_prediction (link tested 29 Nov. 17)

Our current ability to accurately forecast the weather is a testament to not only great advances in computer technology and science but decades of physical research and major investment to the supporting infrastructure that is by far outweighed by economic and human benefits of these forecasts (Lazo et al. 2009). Global and regional NWP centres produce numerical forecasts at down to sub-kilometre scale ranging from rapid update to seasonal timescales and some have been specifically tailored to meet the need of the aviation community. As discussed by Bauer et al. (2015):

> *Advances in forecast skill will come from scientific and technological innovation in computing, the representation of physical processes in parameterizations, coupling of Earth-system components, the use of observations with advanced data assimilation algorithms, and the consistent description of uncertainties through ensemble methods and how they interact across scales.*

There exist ten global numerical weather prediction centres with global and limited area models in operation as presented in Table 1. Most national weather services run their own limited area model using boundary conditions from one of these eight global models. Future research foci are on physical process parameterization, analysis and forecast uncertainty formulation through ensembles, and the provision of physically consistent initial conditions for forecasting using observations as discussed by Bauer et al. (2015). For specific aeronautical meteorological applications, development is carried out both in the physical parameterizations of the numerical models and the post-processing of model output and will be further discussed in Chapter 5.

Table 1: Global numerical weather prediction centres and their models.

Country/Region	*Institute*	*Model*	*Resolution and domain*
Europe	European Centre for Medium-Range Weather Forecasts (**ECMWF**)[8]	HRES – Atmospheric model high resolution (ECMWF 2016) & ENS – Ensemble atmospheric model	HRES: 9 km, 137 vertical levels, Global ENS: 51 members, 18km, 91 vertical levels, Global
United Kingdom	UK Met Office[9]	Unified Model – Global, UKV, MOGREPS-G, MOGREPS-UK	UM: 17 km, 70 lev., Global; 10km from June 2017 onward UKV: 1.5 km inner (UK), 4 km outer (Europe), 70 lev. MOGREPS-G: 33 km, 70 lev. Global; 25km

[8]http://www.ecmwf.int/en/forecasts/documentation-and-support (link tested 29 Nov. 17)
[9]http://www.metoffice.gov.uk/research/modelling-systems/unified-model/weather-forecasting (link tested 29 Nov. 17)

			from June 2017 onwards MOGREPS-UK: 2.2 km, 70 lev. UK
France	Météo-France[10,11]	ARPEGE, ALADIN, AROME	ARPEGE: 16 km, 105 lev., Global ALADIN: 7-10 km, Europe AROME: 1.3 km, France
Germany	Deutscher Wetterdienst[12]	ICON, COSMO-EU, COSMO-DE	ICON: 13 km, 90 lev., global COSMO-EU: 7 km, 40 lev., Europe COSMO-DE: 2.8 km, 50 lev., Germany
USA	NOAA National Centers for Environmental Protection (**NCEP**)[13]	GFS, NAM, RAP, HRRR (Benjamin et al. 2016), SREF	FV3[14]: 13km, 64 lev. 2019 onwards GFS: 13 km, 64 lev., global, until 2019 NAM: 13 km, 60 lev., hemispheric RAP: 13 km, 50 lev., hemispheric HRRR: 3 km, 50 lev, regional, hourly update SREF: 16 km, 50 lev., CONUS, ensemble
Canada	Environment Canada, Canadian Meteorological Centre[15]	GDPS/GEM (Qaddouri and Lee 2011), RDPS, NAEFS	GDPS: 25km, 165 lev., global RDPS: 10km, regional
Japan	Japan Meteorological Agency (**JMA**)[16]	GSM, MSM, LFM, Ensemble prediction system	GSM: 20 km, 100 lev., global MSM: 5 km, 48 lev., Japan and surrounding LFM: 2 km, 58 lev., Japan Ensemble: 40 km, 60 lev., global
Australia	Australian Bureau of Meteorology (**ABoM**)[17]	ACCESS-G, ACCESS-R, ACCESS-C+ (Based on UKMO UM model)	ACCESS-G: 25 km, global ACCESS-R: 12 km, regional ACCESS-C+: 4 km, major cities in Australia

[10] http://www.meteofrance.fr/prevoir-le-temps/la-prevision-du-temps/les-modeles-de-prevision-de-meteo-france (all links tested 29 Nov. 17)
[11] http://www.umr-cnrm.fr/spip.php?article121&lang=en
[12] https://www.dwd.de/EN/research/weatherforecasting/num_modelling/01_num_weather_prediction_modells/icon_description.html?nn=484268
[13] http://www.emc.ncep.noaa.gov/
[14] https://www.gfdl.noaa.gov/fv3/
[15] https://weather.gc.ca/model_forecast/model_e.html
[16] http://www.jma.go.jp/jma/en/Activities/nwp.html
[17] http://www.bom.gov.au/australia/charts/about/about_access.shtml

China	China Meteorological Administration (**CMA**)	National and regional models: WRF, GRAPES (based on ECMWF model), MM5, AREM (Chen et al. 2013)	GRAPES: 25 km, 70 lev., global Others: 9 to 15 km, regional
Russia	Hydrometeorological Centre of Russia[18,19]	SL-AV	SL-AV: 25 km, 51 lev.

In addition to NWP methods, the background guidance can be provided with analysis systems, including methods such as the Local Analysis and Prediction System (**LAPS**) (Albers et al. 1996; Hiemstra et al. 2006) and its newer variational version developed by Jiang et al. (2015). Other systems include the US Air Force Weather Agency (**AFWA**) Coupled Analysis and Prediction System (**ACAPS**)[20], Nowcasting and Initialisation for Modelling Using Regional Observation Data Scheme (**NIMROD**) at the UK Met Office (Golding 1998), Oklahoma University's Center for Analysis and Prediction of Storms (**CAPS**) (Xue et al. 2000; Xue et al. 2003) and the US Rapid Refresh (**RAP**) model (Benjamin et al. 2016).

3.2 WEATHER RADARS

The science and principles of weather radars is presented by e.g. Bringi and Chandrasekar (2001) and Raghavan (2003). Weather radars have recently seen a major upgrade in technology to dual polarimetric methods, allowing for better discrimination between returned echoes, and therefore better removal of non-meteorological signals and identification of hydrometeors and non-meteorological objects such as birds and insects. Weather radars have become critical for aviation in providing information on precipitation, winds and non-meteorological objects both on the ground and at the aircraft.

The growing impact of especially convective weather to aviation users leads to an increased demand of high temporal accuracy and quality of information from radars. A proposed way to increase temporal resolution is to use phased array systems instead of the traditional pedestal and rotating antenna configurations as discussed by e.g. Fulton et al. (2017).

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18 http://polar.ncep.noaa.gov/conferences/WGNE-30/pdfs/day2/08-Report_Russia.pdf (link tested 30 Nov. 17)

19 http://www.scert.ru/conferences/cites/2015/presentation/Presentation/Session4/invited_reports/1-Tolstykh.pdf (link tested 30 Nov. 17)

20 https://www.jcsda.noaa.gov/documents/meetings/wkshp2009/Session-1a/5.Agency.Report-AFWA.ppt (link tested 30 Nov. 17)

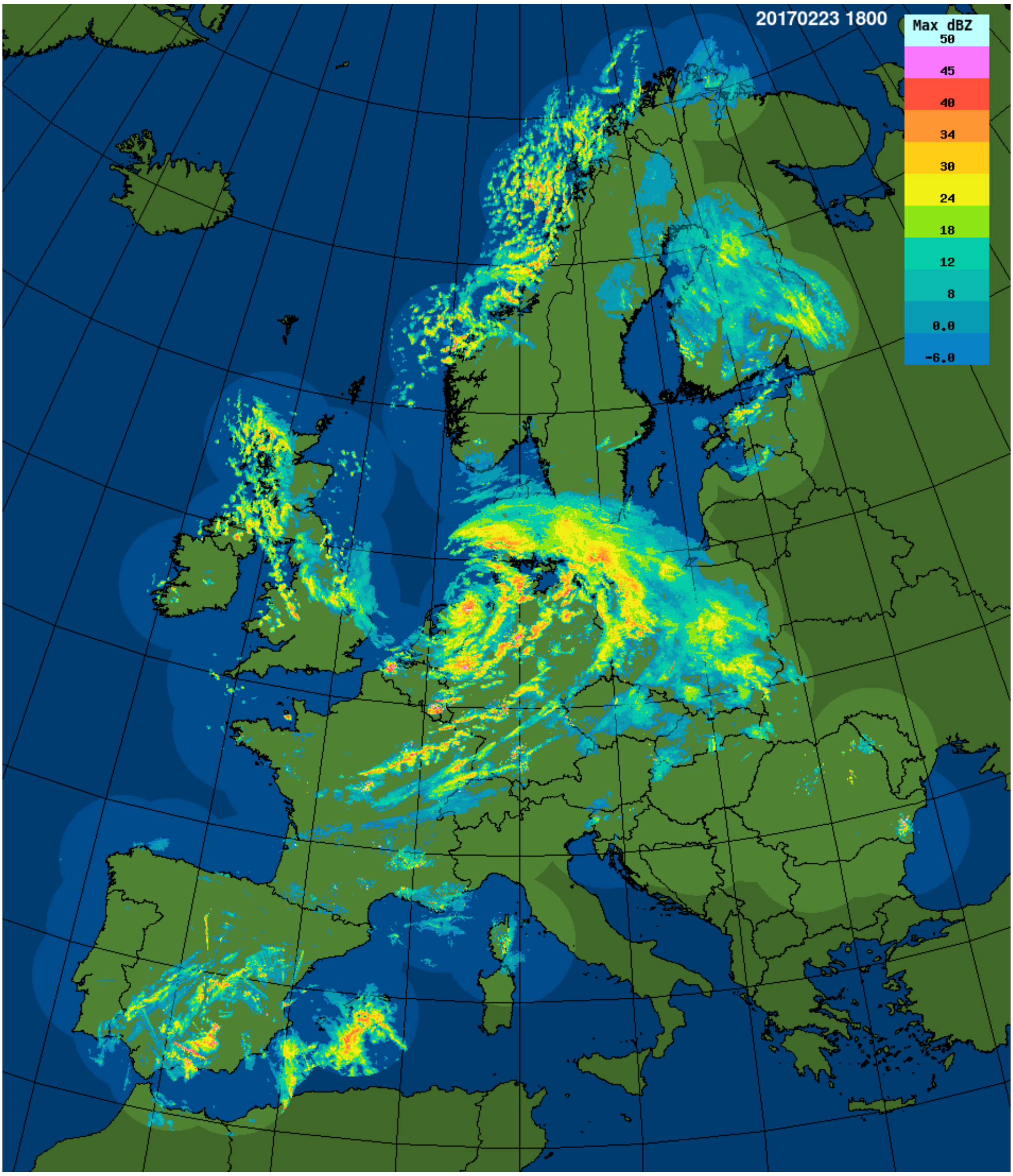

Figure 3: Weather radar mosaic image from the European EUMETNET OPERA network on 23rd February 2017 showing the maximum reflectivity as dBZ. The reflectivity information reveals a low-pressure system over the Netherlands and the extent of the operational mosaic product. Source: FMI OPERA radar image archive.

Weather radars lack coverage over the oceans and in general the areal coverage extends 200-400km from the radar location. Coverage can be improved by creating composite images of single radar images and can be achieved also as a cross-border initiative (see Figure 3). One proposed solution to partially compensate the lack of coverage over the oceans is to equip weather satellites with Doppler radars for a much greater areal coverage as discussed by e.g. Wang et al. (2017).

The added value of the four-dimensional information on the hydrometeors in the atmosphere provided by weather radar data can essentially only be achieved using an adequate number of installed radars on the ground. Weather radar output is used by operational air traffic flow managers in changing routing to runways and in optimising the airspace capacity, by airport managers to anticipate runway closure, by ground operations to activate runway clearance operations and naturally by meteorologists who use the information on precipitation coverage, intensity, melting layer, hydrometeor classification (see Figure 4), etc. to accurately forecast weather for the airspace users. Hydrometeor classification can be used to filter out non-meteorological objects from the radar images and also to discern certain meteorological phenomena such as the height of the melting layer, phase of hydrometeors within the cloud and presence of graupel or hail within the cloud indicating strong vertical movement and potential for turbulence and lightning.

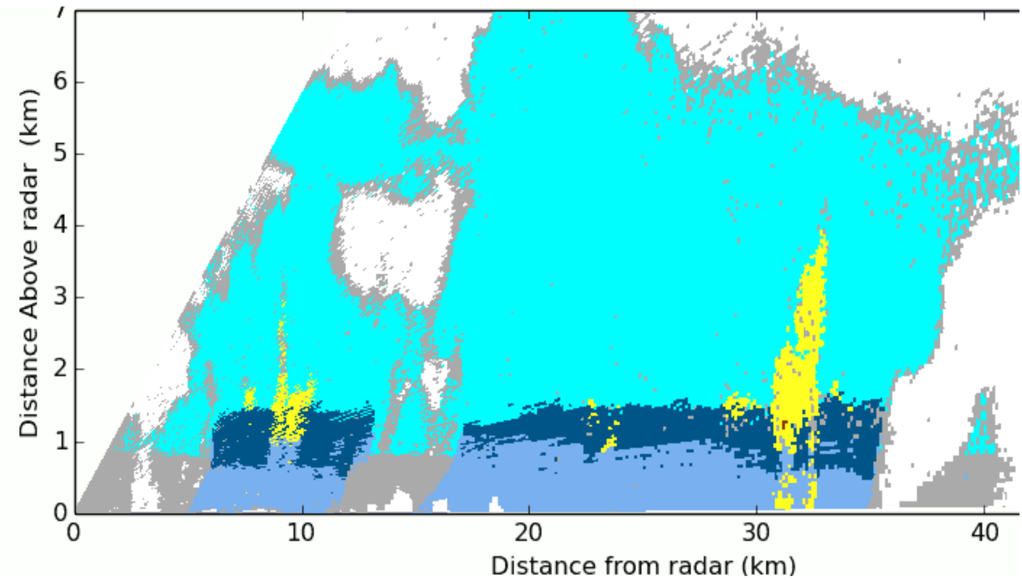

Figure 4: Dual polarization range-height indicator (**RHI**) image as a function of distance from radar and distance above radar from the Finnish Meteorological Institute weather radar installed at Ikaalinen on 10th October 2014 showing ice phase hydrometeors (turquoise), mixed phase with the melting layer (blue), liquid phase closer to the ground (light blue) and graupel (yellow) associated with an observed lightning strike likely caused by the graupel "tower" shown in the figure. Source: FMI radar archive, Elena Saltikoff.

Modern aircraft carry onboard advanced weather radars that are used as the primary source of information for the avoidance of convective weather and turbulence. The onboard radar typically has a weather display, (wet) turbulence detection, weather ahead, predictive wind shear and a ground mapping function. The navigation and vertical displays in the cockpit show the relevant weather information with an automatic mode. While information is limited to over and under 4000 ft along the flight path looking ahead of the aircraft, this gives the pilot accurate and sufficient information to circumnavigate convective systems as long as the on-board radar is turned on before encountering the convective object. The full extent of the convective system might not be evident due to the limited range of the on-board systems, making the selection of the most optimal flight path more difficult. Overall, the effective avoidance of convective cells requires advance planning before take-off for an optimal route selection.

3.3 LIGHTNING DETECTION SYSTEMS

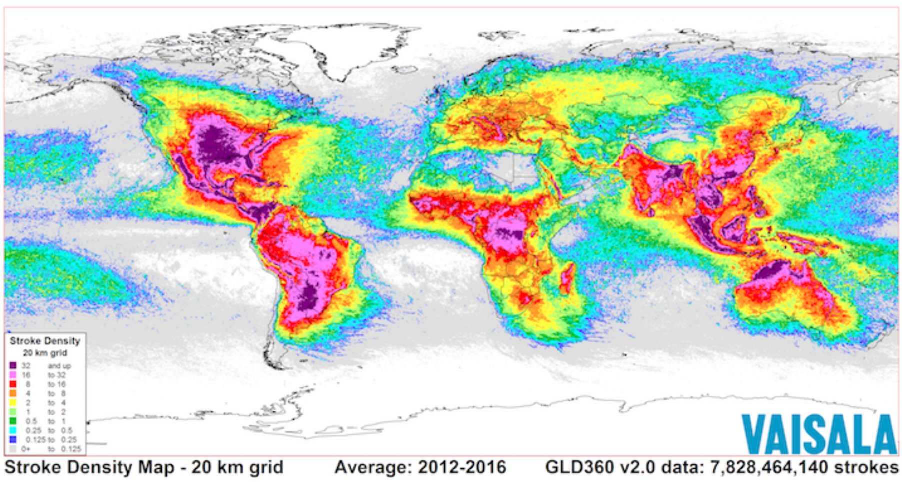

Figure 5: Global average lightning strike density map for 2012-2016 from the Vaisala GLD360 dataset, source: http://www.vaisala.com/VaisalaImages/Lightning/GLD_20km_avg_2012-2016_world_map.png (link tested 30 Nov. 17)

Lightning and the clouds producing the lightning present multiple threats to air transport. Direct lightning strikes damage aircraft and can compromise airworthiness. The safety risk associated with lightning strikes is the greatest during take-off and landing when the aircraft has the least options to divert convective lightning producing cells. Therefore, in most cases the air traffic is restricted for those areas where convective cells are reported or forecasted to produce lightning.

Lightning directly at an airport will force runway capacity to be reduced for take-off and landing. Obviously then the detection of lightning is very important for aviation and all major airports have installed lightning detection systems for accurate short-range detection. Current fixed ground-based systems detect cloud-to-ground and intra- and inter-cloud electrical activity. Very Low Frequency (**VLF**) networks can have a large detection coverage while lightning mapping arrays (**LMA**) are more restricted in areal coverage and provide better location accuracy. The European network of lightning location systems with further details is presented by Poelman et al. (2016) and the US national lightning detection network by Cummins and Murphy (2009). A global view of lightning strike density is given in Figure 5.

3.4 AUTOMATED OBSERVING SYSTEMS

Weather observations are carried out as defined by the World Meteorological Organisation (**WMO**) *Guide to Meteorological Instruments and Methods of Observation* (WMO 2014) and the International Civil Aviation Organization (**ICAO**) *Manual on Automatic Meteorological Observing Systems at Aerodromes* (Doc 9837) and can be made in person by a trained weather observer or by an automated system such as an Automated Surface Observing System (**ASOS**, USA) and Automated Weather Observing System (**AWOS**) specific to aviation use.

The responsibility of weather observations at airports is highly dependent on the state in question. In the US, observations at airports are the responsibility of the FAA, while in Europe it is either the airport, Air Navigation Service Provider (**ANSP**) or the National Meteorological and Hydrological Service (**NMHS**) who is responsible. These four variations are found across the globe and typically the local NMHS will still be maintaining the SYNOP, precipitation and climate observation networks even if it is not involved in aviation weather observations.

AWOS systems are highly standardised and offered by multiple providers as turn-key solutions. The basic suite of observations recorded are: wind speed and direction, wind gust, variable wind direction, temperature, dew point, altimeter setting (**QNH**, i.e. pressure), density altitude. The setup is normally augmented by visibility, sky condition, cloud coverage, ceiling, present weather, lightning detection (see Figure 6). Light Detection and Ranging (**LIDAR**) is a remote sensing method used for meteorological purposes to determine the height and ceiling of the cloud base (Ceilometer) or the presence of fine particles, such as volcanic ash, in the atmosphere. Some major airports also include LIDARs for the detection of especially volcanic ash.

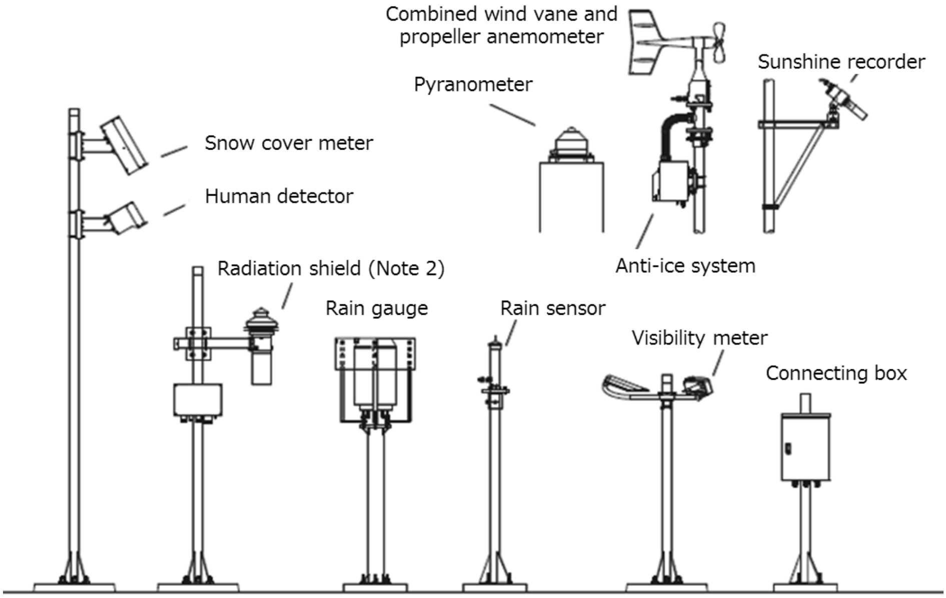

Figure 6: Surface weather observation system setup at the Japan Meteorological Agency (JMA). Runway Visual Range (**RVR**) measurement is also usually included in a typical setup and most modern anemometers use acoustic methods. Source: http://www.jma.go.jp/jma/en/Activities/surf/surface_instruments.png (link tested 30 Nov. 17)

AWOS systems have replaced manual observations in many airports. In e.g. Finland only the main international airport of Helsinki-Vantaa is manned with a human observer 24/7. AWOS information is directly displayed in the Air Traffic Control (**ATC**) tower and weather forecast offices. The information is packaged to standard METAR messages every 30 or 60 minutes and may or may not include a short-term TREND forecast issued by the forecaster. Automatic METAR messages are being issued in some airports with low traffic volumes.

Low Level Wind Shear Alert Systems (**LLWAS**) is a method used to detect wind shear at and around airports especially for landing aircraft. It is a ground based system composing minimum 6 anemometers and a processing unit calculating wind shear risk based on the readings[21]. The system was commissioned by the FAA in the 1970s following aircraft

[21]http://www.skybrary.aero/index.php/Low_Level_Wind_Shear_Alert_System_(LLWAS) (link tested 30 Nov. 17)

crashes due to wind shear and microbursts associated with thunderstorms. The US remains the predominant user of LLWAS systems due to the climate favourable to severe convection.

3.5 Weather satellites

Weather satellites complete the picture of essential weather forecasting input information. Core meteorological satellite programs give an overview of cloud properties (such as cloud top temperature) of large geographical areas at a single time either from a geostationary or polar orbiting (sun-synchronous) position. This information is complemented by satellites at low earth orbits for specific purposes. WMO maintains a listing[22] of all operational and future meteorological satellites with complete information on the instruments and their status (see Figure 7).

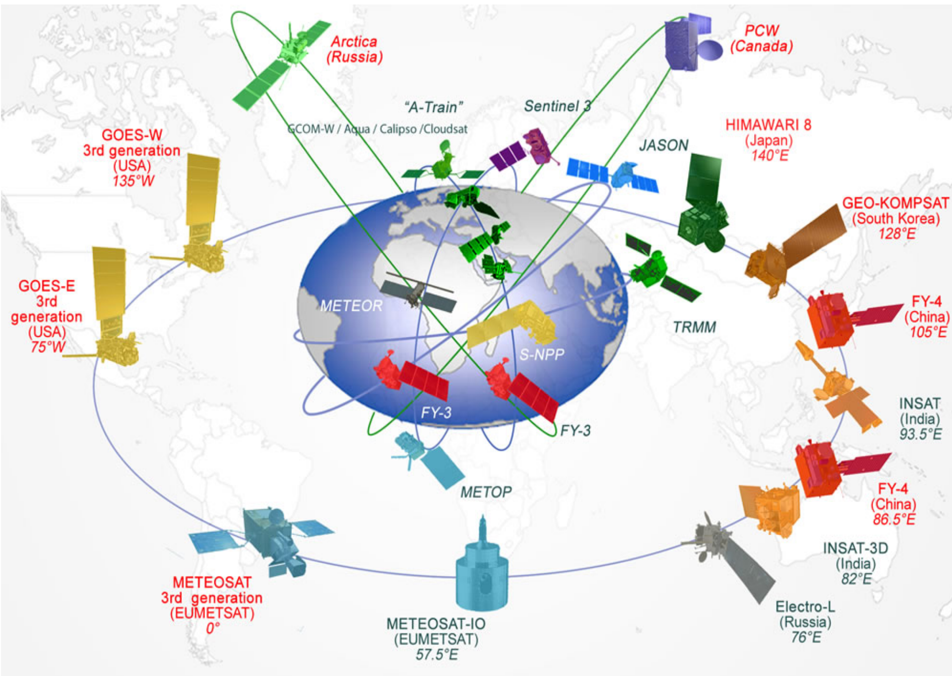

Figure 7: Schematic overview of the space-based WMO Global Observing System, source: http://www.wmo.int/pages/prog/sat/globalplanning_en.php (link tested 30 Nov. 17)

Weather satellites are mainly operated by NOAA/NASA of the United States, EUMETSAT/ESA in Europe (Germany), Roshydromet/ Roscosmos

[22] http://www.wmo.int/pages/prog/sat/satellitestatus.php (link tested 30 Nov. 17)

in Russia, Indian Space Research Organisation (**ISRO**), CMA/NRSCC in China, JMA of Japan and KMA/KARI in South Korea. Weather satellites are the most expensive part of the weather forecasting enterprise with an estimated budget of $10.8 billion[23] for the four new GOES satellites. Costs have risen considerably, considering that the budget for EUMETSAT MSG-1 / Meteosat-8 was €475 million and €1.3 billion for three satellites in total including launchers and 12-year operations costs when launched in august 2002[24]. New satellites always carry the next generation of instruments, improving our picture of the state of the atmosphere and improving the skill of numerical weather prediction models. The last satellite to be taken into operational use on 7 July 2015 is the Japanese Himawari-8 launched on 7 Oct 2015. The latest addition to the satellite constellation is the NOAA/NASA GOES-R (now GOES-16) launched on 19 November 2016 with expected entry into operation in late 2017. GOES-16 is carrying especially the Advanced Baseline Imager (**ABI**) similar to the Advanced Himawari Imager (**AHI**) onboard the Himawari-8, providing four times better resolution and more than five times faster coverage, and Geostationary Lightning Mapper continuously mapping total (in-cloud and cloud-to-ground) lightning. The latest generation imagers provide a dramatic improvement in the study and tracking of tropical cyclones.

3.6 AIRCRAFT-BASED OBSERVATIONS

Aircrafts collect temperature, pressure, location and airspeed (also humidity on some flights) data from which wind speed, direction and turbulence can be calculated. The relay of this and additional information back to the meteorological community to improve weather forecasts is led by the WMO global Aircraft Meteorological Data Relay (**AMDAR**)[25,26] programme since the 1990s (see Figure 8). The collaboration is with partner airlines using already installed equipment. The additional information is especially valuable over the oceans where no upper air observations are available and provides a significant improvement in numerical weather model performance.

Other sources of information from the aircraft are Pilot Reports (**PIREP**), Aircraft Reports (**AIREP**) and Automatic Dependent

[23] http://www.goes-r.gov/resources/faqs.html (link tested 30 Nov. 17)
[24]http://www.esa.int/Our_Activities/Observing_the_Earth/Meteosat_Second_Generation/MSG_FAQ/(print) (link tested 30 Nov. 17)
[25] https://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/About.html (link tested 30 Nov. 17)
[26] https://www.meted.ucar.edu/avn_int/amdar/index.htm (link tested 30 Nov. 17)

Surveillance - Contract (**ADS-C**) made available by the WMO. TAMDAR (Zhang et al. 2015; Zhang et al. 2016) is a data collection platform like AMDAR for which data is disseminated to participating institutions only. TAMDAR[27] is operated by Panasonic Weather Solutions based in the US. Automatic Dependent Surveillance - Broadcast (**ADS-B**) is an increasingly common equipment on board commercial aircraft for flight monitoring purposes. ADS-B has value for meteorological purposes since wind, pressure and temperature profiles can be estimated from the data as concluded by de Leege et al. (2012).

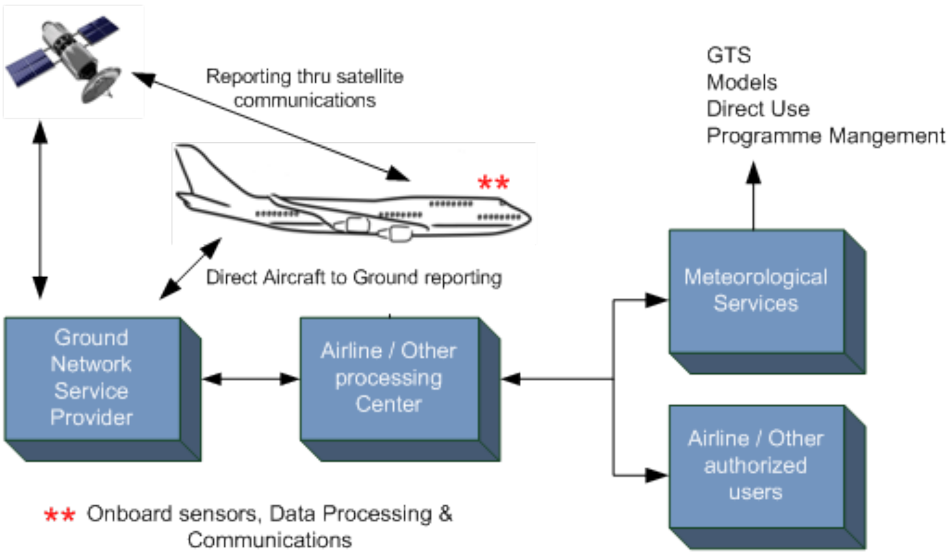

Figure 8: Components of the WMO AMDAR system, source: http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/AMDAR_System.html (link tested 30 Nov. 17)

Mode S is a secondary surveillance radar process that allows selective interrogation of aircraft according to a unique address assigned to each aircraft[28]. In Europe, Mode S Enhanced Surveillance (**EHS**) is becoming more and more used and includes many interesting sources of information that can be helpful to weather prediction such as ground speed, magnetic heading, indicated airspeed and vertical rate as discussed by Stone and Kitchen (2015). Regulation (EU) No 1207/2011 requires that all flights operating as general air traffic in accordance with instrument flight rules within the EU are equipped with mode S transponders. This information can be used to calculate wind speed and direction and temperature at high

[27] https://en.wikipedia.org/wiki/TAMDAR (link tested 30 Nov. 17)
[28] http://www.skybrary.aero/index.php/Mode_S (link tested 30 Nov. 17)

temporal resolution from all Mode S communications[29]. Research by Haan and Stoffelen (2012) present improvements achieved by using Mode S wind and temperature information in 2-3h nowcasting at Amsterdam Schiphol Airport. Mode S data errors have been quantified and suitability for assimilation into NWP models confirmed by Mirza et al. (2016) and the paper also includes a comprehensive table of previous studies. The paper by Stone and Pearce (2016) presents the collection of information at the UK Met Office, using five receivers to collect 5.7 million observations of horizontal wind and temperature over the UK. Stone and Pearce (2015 & 2016) also conclude that the data is equal to the quality of AMDAR observations. The Mode S and ADS-B data can also be used for turbulence observations as presented by Kopeć et al. (2016).

4 The actors contributing to advances in aeronautical meteorological research

Scientific research into the phenomena of importance to air transport is concentrated into research groups and individuals spread across the globe. Major efforts are being carried out in the US, Europe and Asia in universities, national research institutes, private sector enterprises and with Air Navigation Service Providers (ANSPs). Major funding is provided by the FAA and the European Union from the public sector and by airlines through en-route charges on the private side. Specific scientific challenges may also be addressed by various other funding sources. Actors are driven on the other hand by the requirement to improve the quality of the information, to enable cost efficiencies via enhanced automation, and to meet the evolving needs of airspace users on another. The following chapters elaborate each sector further and explore the various activities currently ongoing.

4.1 Large international initiatives

The development of the global air navigation system is governed by the ICAO and detailed in the Global Air Navigation Plan (**GANP**; ICAO 2016a). The GANP composes Aviation System Block Upgrades (**ASBU**) and is further divided into modules. Global plans are supplemented by seven regional air navigation plans and subsequent national plans. Overall

[29] http://mode-s.knmi.nl/ (link tested 30 Nov. 17)

responsibility for the implementation of these plans lies with the states who are the signatories to the Chicago Convention establishing the ICAO. For meteorological services, the AMET module describes the upgrades for globally interoperable systems and data and specifies meteorological services as a key enabler through the future System Wide Information Management (**SWIM**) environment.

The improvements envisaged in the plan from 2018 onwards include automated decision processes on aids for the information, translation, impact conversion to ATM operations, and ATM decision support of meteorological input and by 2028 to implement the tactical avoidance of hazardous weather, aircraft based capabilities to detect weather and to display weather to enhance situational awareness. The GANP does not include specific meteorological phenomena of interest, but does define the trend towards more integration of meteorological input to the decision-making processes. There is no set agenda into which topics aeronautical meteorological research should focus, apart from the developing field of space weather research and improvements in the global capability to forecast the impacts of volcanic ash events. Since these events are not purely meteorological events and the required research is highly concentrated to few research teams, they are left out of the consideration for the purposes of this work.

The larger research and development initiatives build upon the ideology of the ICAO GANP and aim to ensure that those objectives are met along with any regional or sub-regional objectives. Three such programs are identified here, noting that there are likely several more at a national level. It should be noted that especially for aeronautical meteorological research and development, the NextGen and SESAR programme are not harmonised in their timing or content. SESAR currently lacks comprehensive weather input to its current phase. The total strategic centralized investment in aviation weather research and development activities is roughly tenfold in the US compared to Europe as presented in the following two chapters.

4.1.1 SESAR

The Single European Sky ATM Research (SESAR) project is the technological pillar of the Single European Sky (**SES**) legislation[30]. The content of the project draws from the European ATM Master Plan, the components are developed and validated by the SESAR Joint Undertaking

[30] https://ec.europa.eu/transport/modes/air/sesar_en (link tested 30 Nov. 17)

(**SJU**) and deployed by the SESAR Deployment Manager (**SDM**) (See Figure 9). The key results of the first phase of SESAR implemented from 2014 to 2016 are given in Table 2. The second SESAR "2020" phase is in implementation from 2017 to 2020 with a more limited MET service provider involvement.

The SESAR project meteorological component has been coordinated by EUMETNET, a grouping of 31 European National Meteorological Services. The main part of the meteorological development in SESAR has been to ensure a harmonised and consistent set of meteorological information to the user by harmonising model output and providing a technological solution to retrieve all information. SESAR only funds research projects through its Exploratory Research projects, where the number of meteorological initiatives has been low. Hence, the focus in SESAR is on the technological development towards the SWIM environment by ensuring that meteorological information is exchanged in a uniform way.

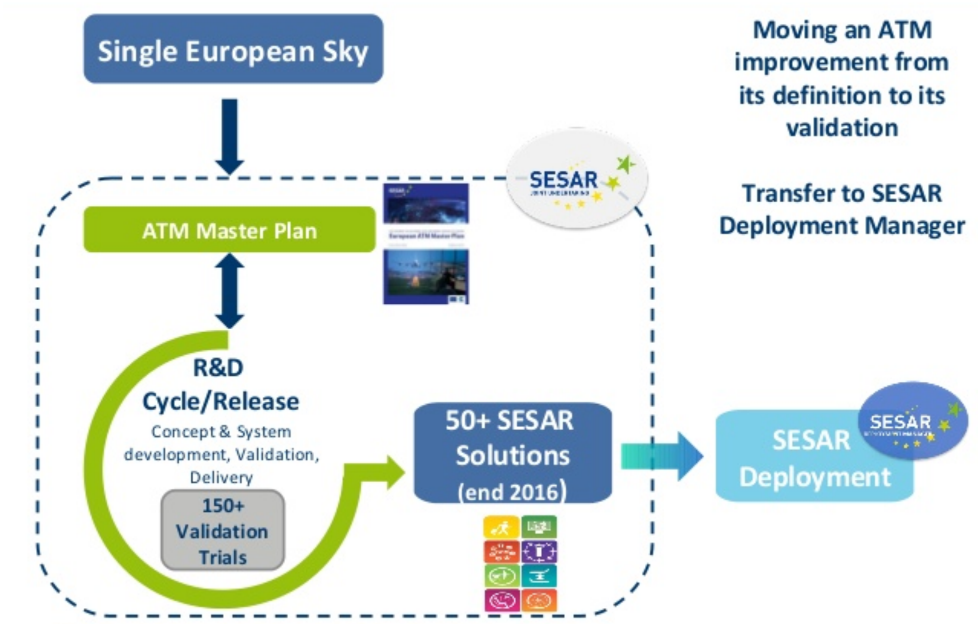

Figure 9: SESAR Research and Development Lifecycle. Source: SJU at 2016 World ATM Congress, Madrid, Spain

The SESAR Industrial Research programme itself is built in a way that makes the participation of NMHSs difficult by requiring a major investment. The result is that there is no specific meteorological agenda within SESAR and this is being set in a delayed mode by the EUMETNET community and by individual project proposals. Aeronautical meteorological research in Europe continues to be carried out mostly in projects funded from other sources. The following meteorological projects have been funded through the SESAR project:

Table 2: Weather-related SESAR projects

SESAR funding	*Institute*	*Title*	*Scope*
Large Scale Demonstration (2013-2014)	Thales, DSNA, Brussels Airlines, UK Met Office, Météo France & Deutcher Wetterdienst (**DWD**)	TOPMET	Demonstrate improved accuracy in the monitoring and forecasting of adverse weather conditions, such as thunderstorms and severe ice.
Large scale Demonstration (2015-2016)	Thales, DSNA, Airbus, Brussels Airlines, Air France, HOP! Regional, Air Corsica, Austro Control, Croatia Control, ENAC, Airports de Paris, Finnish Meteorological Institute (FMI), Météo France & DWD	TOPLINK	Demonstrate the benefits for ATM stakeholders (ANSPs, Airlines, Airport operators) of the deployment of new SWIM services, including Meteorological Services, Aeronautical Information Services, cooperative Network Services, and Flight Information Services
Industrial Research (2014-2016)	Météo France, UK Met Office, DWD, FMI, MET.no, KNMI, SMHI, Belgocontrol, NLR and Thales Air Systems	WP11.2	Meteorological sub-work package 11.02 (Meteorological Information Services)
Exploratory Research (2016-2018)	University of Seville (Spain), University Carlos III of Madrid (Spain), University of Salzburg (Austria), MeteoSolutions GmbH (Darmstadt, Germany) and AEMET (Agencia Estatal de Meteorología)	TBO-MET (Meteorological uncertainty management for trajectory-based operations)	Address the problem of analysing and quantifying the effects of meteorological uncertainty in Trajectory-based operations (**TBO**)
Exploratory Research (2016-2018)	FMI, DLR, Austro Control	PNOWWA (Probabilistic nowcasting of winter weather for airports)	Produce methods for the probabilistic short-term forecasting of winter weather and enable the assessment of the uncertainty in the

	ground part of 4D trajectories

The SESAR Deployment component of the main project provides funding for deployment projects making use of the developed and validated outcomes of the previous phases and does not include new research or development of the meteorological capability. Deployment is the final step towards having the new functionality in use by all customers. Total investment to aeronautical meteorological research and development from SESAR is difficult to assess since small components can be included in numerous projects. For the first phase of SESAR and the Work Package 11.02 coordinated by EUMETNET, the total budget was €6.8 million over a three-year period, thus roughly €2.3m annually over 2014-2016. The SESAR Deployment projects amount to a total of €16.4 million over the 2017-2020 timeframe.

4.1.2 NextGen

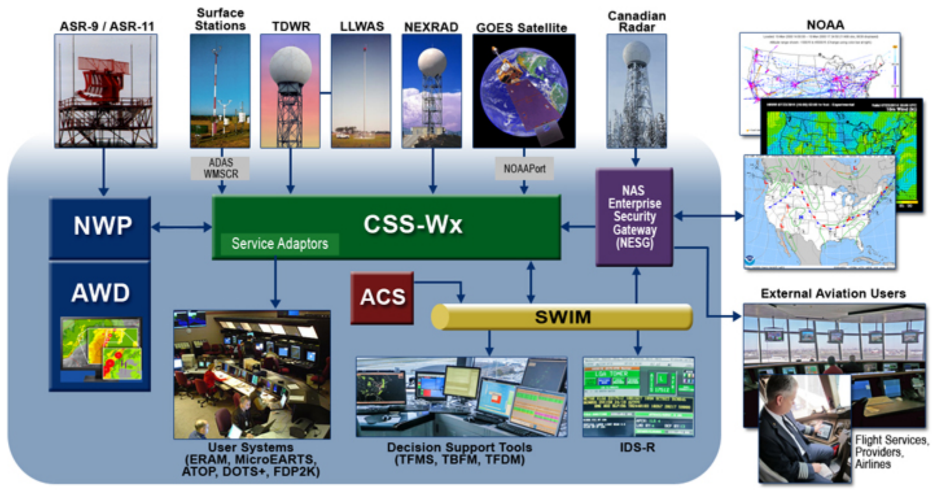

Figure 10: *NextGen Weather Architecture Diagram. Source:* https://www.faa.gov/nextgen/programs/weather/images/nextgen-architecture-diagram.jpg (link tested 30 Nov. 17)

The Next Generation Air Transportation System (**NextGen**) is an FAA program developed to modernize the US national airspace system with the help of the air transport industry. NextGen is a series of initiatives designed to make the airspace system more efficient spanning from short-term (2004-2012), mid-term (2012-2020) to long-term (2020-2030 and beyond) goals and visions with a total budget of about $37 billion by 2030 and expected cost savings of $106 billion[31]. The NextGen Weather Components[32] are the NextGen Weather Processor (NWP), NWP Aviation Weather Display (**AWD**) and Common Support Services (**CSS-Wx**) as presented in the Figure 10.

The NextGen NWP provides weather information translated to impacts on route blockage and airspace capacity constraints from 0-8h in advance combining remote sensing data, surface and aircraft observations and numerical model output. The information is displayed via the AWD for en-route and terminal users. The AWD consolidates many legacy systems into a new weather display architecture. The NextGen NWP output falls under four different categories: mosaic, analysis, predictive and translation products. Mosaic products improve especially the spatial consolidation of weather radar information. Analysis products focus on especially storm information (motion vectors, storm extrapolated position, growth trends, echo top tags, lightning), wind shear safety (microbursts, gust fronts, tornado detections and terminal alerts) and terminal wind analyses (wind profiles, 3D grids). The predictive products extend from 0 to 8 hours and are thus within the nowcasting timeframe and include precipitation, precipitation type, echo tops, icing, turbulence and fronts. Confidence and accuracy scores are also presented. The translation products convert mosaics and predictive products into translated impact areas called Convective Weather Avoidance Fields (Polygons).

The CSS-Wx provides a single source of weather data via SWIM to the US National Airspace System (NAS), facilitates consistent weather information, increases weather access, reduces interface development costs and reduces infrastructure costs. The CSS-Wx includes the NOAA weather models (RAP, HRRR, SREF, NAM, etc.), aviation forecasts, traditional alphanumeric codes (TAF, METAR, PIREP, etc.) and remote sensing images in addition to the NextGen NWP products. The CSS-Wx should reach initial operating capability in 2019.

NextGen Weather is sponsored by the FAA Aviation Weather Research Program that sponsors applied research by awarding grants to universities, research institutions and private enterprises to develop the capabilities. For Fiscal Year 2017 (FAA 2016), the NextGen NWP WP1 budget was $27.8m, CSS-Wx Phase 1 $3.3m and another $1.16m for weather forecast improvements, but weather is dispersed throughout the FAA budget in multiple parts and total investment is much greater. In addition, the FAA Weather Program budget is $17.9m and the NextGen Weather Information in the Cockpit (**WTIC**) program is at $4m bringing the total annual weather-related investment by the FAA to roughly $54.2

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[31] https://www.faa.gov/nextgen/ (link tested 30 Nov. 17)
[32] https://www.faa.gov/nextgen/programs/weather/ (link tested 30 Nov. 17)

million excluding any observation and remote sensing system upgrades and maintenance.

4.2 Public Institutions

The role of public agencies in aeronautical meteorological research is great due to the fact that air traffic management, air navigation services, meteorological services, universities, regulation and even airlines have in the past been public property. While air transport is moving forward into a more and more market-oriented approach, the task of aeronautical meteorological research remains mostly in public institutions' hands. The involvement of the private sector becomes larger the closer the research and development efforts get to customer operations. Many private companies thrive in the final interface of decision support tools and interaction to airlines, ANSPs and airports.

4.2.1 National Meteorological and Hydrological Services (NMHSs)

According to the World Meteorological Organization (WMO) Statement on National Meteorological and Hydrological Services[33],

> *The National Meteorological and Hydrological Services own and operate most of the infrastructure that is needed for providing the weather, climate, water and related environmental services for the protection of life and property, economic planning and development, and the sustainable exploitation and management of natural resources.*

And further,

> *With regard to the civil aviation sector, NMHSs provide data, products and services that contribute to the safety of aviation and the economical operation of the sector both nationally and internationally. The measurements and forecasts of conditions en-route and at, or on the approach to, terminal aerodromes are useful for minimizing aircraft operating costs. By increasing the operating efficiency of flights, NMHSs also contribute to a*

[33] https://www.wmo.int/pages/about/documents/WMOStatement_NMHSs_en.pdf (link tested 30 Nov. 17)

reduction in the negative impacts of aircraft emissions on global climate change and stratospheric ozone.

The WMO has 185 member states and 6 territories, most of which have an identified NMHS. However, not all NMHSs are providers of aeronautical meteorological services and in these cases the function is typically given to the ANSP responsible for air navigation services or airport operation. Very few countries have enabled a fully private MET service provision for the services provided under ICAO Annex 3 (ICAO 2016b). Furthermore, not all NMHSs carry out research and development activities with a specific aim at improving their services and products for air transport. Appendix 1 presents a list of those NMHSs actively engaged in aeronautical meteorological research and development activities and Table 3 provides a listing of known projects focusing on aviation weather research and development. The Appendix shows that some 21 out of 185 (11%) of WMO member NMHSs are actively engaged in aeronautical meteorological research. It should be noted that this information is subject to some controversy since it is very difficult to gain insight into ongoing research where results are not made publicly available.

Table 3: List of identified projects ongoing at NMHSs for aeronautical meteorological research listed by country, organization and focus area of the research

	Organization	*Project Name*	*Related Focus Area(s)*
UK	UK Met Office	Development and verification of ensemble aviation hazard forecasts	Weather Integration Into Decision Making
		Upper-Level Turbulence Forecasts	Turbulence
		High-resolution Fog Forecasting in London	Ceiling and Visibility
		Global Icing Potential Forecasts	Icing - Inflight, Ground, and Engine
KOR	National Institute of Meteorological Sciences (NIMS)	Near-cloud turbulence diagnostics	Turbulence
		300-m weather prediction model for the Incheoninternational airport (IIA-300m)	Numerical Weather Prediction (NWP)
	Aviation Meteorological Office	Doppler radial velocity patterns for the prediction of wind shear and microburst in the Incheon international airport	Radar Algorithm Development
JPN	Japan Meteorological Agency	Ensemble-Based Forecast Indices for Area Forecast Using the Mesoscale Ensemble Prediction System	Numerical Weather Prediction (NWP)
FI		Probabilistic precipitation type forecasts	Winter weather

	Finnish Meteorological Institute	Probabilistic Nowcasts of Winter Weather at Airports (PNOWWA)	Winter weather
		Aircraft Ground Deicing	Weather Integration Into Decision Making
		Cold-season lightning risk for aviation	Lightning
		Dual Polarization	Radar Algorithm Development
DE	Deutscher Wetterdienst	Global Turbulence Guidance	Turbulence
		Icing	Icing - Inflight, Ground, and Engine
FRA	Météo-France	3D Convection (ASPOC)	Convection
		MET-GATE	SWIM
NL	KNMI	Ceiling and Visibility at Schiphol	Ceiling and Visibility
		MODE-S Data Center	Aircraft Observations
USA	NOAA NWS Meteorological Development Laboratory (MDL)	Neural Networks for Bias Correction	Statistical Modelling
		Decision Support Tools	Decision Support
		Localized Aviation MOS Program (LAMP)	Statistical Modelling
		National Blend of Models	Weather Information Applications

As an example of a long-term plan for aeronautical meteorological research, the long-term vision for the future of air traffic systems in Japan is titled the Collaborative Actions for Renovation of Air Traffic Systems or **CARATS** (JCAB 2010). Established in 2010, it sets up targets for increasing safety, increasing efficiency of operations, responding to environmental issues, addressing capacity, etc. For aeronautical meteorological development, the objectives are to promote the utilization of weather forecast information, enhance precision of meteorological forecasting using data monitored by aircraft, utilization of meteorological forecast information on an aircraft, etc. The CARATS MET Working Group is tasked with collaboration between airlines, research institutes, manufactures, Japan Civil Aviation Bureau (**JCAB**), JMA and other government organizations. For aeronautical meteorological services, CARATS objectives are improved weather observation capabilities, improved weather forecast capabilities, quantification of the impact of severe weather on capacity and other aircraft operations and MET information sharing infrastructure. Research is focused on especially the development of a high-resolution numerical model and a graphical TAF. The meteorological part of the CARATS program is mainly implemented by the Japan Meteorological Agency (JMA).

4.2.2 GOVERNMENTAL RESEARCH INSTITUTES

Some governmental research institutes take active part in aeronautical meteorological research via government grants, research funding and/or industry partnerships. These institutions are normally functioning outside the operational weather forecasting domain and focus on applied research to specific user needs. The institutions include, but are not limited to the listing provided in Table 4 below.

Table 4: List of identified projects ongoing at public institutions for aeronautical meteorological research listed by country, organization and focus area of the research

	Organization	*Project Name*	*Related Focus Area(s)*
USA	National Center for Atmospheric Research (NCAR), Research Applications Laboratory (RAL), Aviation Applications Programme (AAP)	Advanced Operational Aviation Weather System (AOAWS)	Convective Wind Shear, International Aviation Weather System, Terminal Area Weather
		Dual Polarization	Radar Algorithm Development
		Advanced Satellite Aviation Weather Products (ASAP) Program	Icing - Inflight, Ground, and Engine
		Aircraft Ground Deicing	Weather Integration into Decision Making
		Alaska Ceiling and Visibility Analysis (CVA-AK) Product	Ceiling and Visibility
		Aviation Digital Data Service (ADDS)	Convective Weather - Aviation, Dissemination
		Aviation Turbulence Forecasting (GTG and GTG2)	Turbulence
		Brunei LLWAS Acquisition	International Aviation Weather System
		Common Support Services Weather (CSS-Wx)	Dissemination
		Consolidated Storm Prediction for Aviation (CoSPA)	Convective Weather - Aviation

	Diagnose Convectively–Induced Turbulence (DCIT)	Turbulence
	Doppler Radar-based Wind Shear Detection	International Aviation Weather System
	Ensemble Prediction of Oceanic Convective Hazards (EPOCH)	Convective Weather - Aviation, Oceanic/Remote Weather
	Ensemble Weather	Weather Integration into Decision Making
	Experimental Aviation Digital Data Service (ADDS)	Dissemination
	Global Weather Hazards	Dissemination, Oceanic/Remote Weather
	Graphical Turbulence Guidance Nowcast (GTGN)	Turbulence
	Helicopter Emergency Medical Services (HEMS) Tool	Dissemination
	High Ice Water Content (HIWC) Research	Icing - Inflight, Ground, and Engine
	In Situ Turbulence	Turbulence
	In-Flight Icing Product Development Team	Icing - Inflight, Ground, and Engine
	Joint Airport Weather Studies Project (JAWS)	Convective Wind Shear, Terminal Area Weather
	Juneau Airport Wind System (JAWS)	Terminal Area Weather, Terrain–Induced Wind Shear and Turbulence
	Large Scale Convective Storm Likelihood Predictions	Convective Weather - Aviation
	Lightning Impacts on Aviation	Convective Weather - Aviation
	Low Level Wind Shear Alert System (LLWAS)	Convective Wind Shear, International Aviation Weather System, Terminal Area Weather
	Mobile Meteorology (MobileMet)	Dissemination
	NASA Icing Remote Sensing System (NIRSS)	Icing - Inflight, Ground, and Engine, Terminal Area Weather
	National Ceiling and Visibility Analysis (NCVA)	Ceiling and Visibility
	NCAR Turbulence Detection Algorithm (NTDA)	Radar Algorithm Development
	Nowcasting for ATEC Ranges	Convective Weather - Aviation, Numerical Weather Prediction (NWP) and Data Assimilation
	Oceanic Convection and Nowcasting	Oceanic/Remote Weather
	Oceanic Convection Diagnosis and Nowcasting	Oceanic/Remote Weather
	Probabilistic Storm Prediction for Aviation	Convective Weather - Aviation

	Probabilistic Weather Integration With Air Traffic Management	Weather Integration into Decision Making
	Radar Icing Algorithm (RadIA)	Icing - Inflight, Ground, and Engine, Radar Algorithm Development, Terminal Area Weather
	Thunderstorm Auto Nowcasting	Convective Weather - Aviation
	Turbulence Characterization	Turbulence
	UAS Turbulence	Turbulence
	Weather Technology in the Cockpit (WTIC)	Dissemination
	Windshear and Turbulence Warning Systems	Convective Wind Shear, International Aviation Weather System, Terminal Area Weather, Terrain–Induced Wind Shear and Turbulence
NOAA National Centers for Environmental Prediction (NCEP) Aviation Weather Center (AWC) & Environmental Modeling Center (EMC)	World Area Forecast System (WAFS) upgrades	Upper Wind, SigWx
	Global Graphical Turbulence Guidance (G-GTG) for world area forecast systems (WAFS)	Turbulence
	Low level wind shear guidance and wind compression in aviation operations	Wind shear
	Derived variables from total lightning to support aviation	Lightning
	CDM Convective Forecast Planning (CCFP) Guidance	Convective Weather - Aviation
	Global Icing Ensemble Prediction	Icing - Inflight, Ground, and Engine
	Clear Air Turbulence Indices	Turbulence
	Neural Networks for Bias Correction	Statistical Modelling
NOAA ESRL Global Systems Division (GSD)	High-Resolution Rapid Refresh (HRRR) model	Numerical Weather Prediction (NWP)
	Aviation Forecast Verification Tool	Forecast Verification
NOAA Storm Prediction Center	Convective Nowcasting Algorithm	Convective Weather - Aviation
NOAA NSSL	Severe weather and aviation related products per FAA NextGen requirements	Convective Weather - Aviation
	Evaluating and advancing dual-pol algorithms specific to FAA NextGen requirements	Weather Radar
	Multi-Radar/Multi-Sensor System (MRMS)	Weather Radar

	CSU Cooperative Institute for Research in the Atmosphere (CIRA)	WAFC Turbulence Guidance development	Turbulence
		Forecast guidance tools for NWS forecasters	Weather Information Applications
		Integrated Support for Impacted Air Traffic Environments (INSITE)	Weather Integration into Decision Making
		Integration of Aviation Hazards watch and warning tools	Weather Information Applications
		Cloud Cover Layer from weather satellites	Satellite Algorithm Development
		Multispectral satellite image enhancement	Satellite Algorithm Development
		Cold Air Aloft detection using JPSS satellites	Satellite Algorithm Development
	Desert Research Institute (DRI)	Icing Conditions	Icing - Inflight, Ground, and Engine
	US Army	Simulating Wintertime Near-Surface Icing Conditions	Icing - Inflight, Ground, and Engine, Terminal Area Weather
	US Air Force	Lightning Climatology	Lightning
	NASA	Initial Storm Electrification	Lightning
		Nowcasting Method for Estimating Probability of High Ice Water Content	Icing - Inflight, Ground, and Engine
Japan	Japan Aerospace Exploration Agency (JAXA)	Airport Lightning	Weather Integration into Decision Making
DE	German Aerospace Center (DLR)	Wake Vortices	Wake Vortice
		Hybrid Wind Nowcasting for a Seamless Prediction of Wind Profiles	Wind

It is evident from the table above that the United States has a very strong input to aeronautical meteorological research and this may be attributed to the following factors:

1. While aviation weather research has been funded by a number of sources, the FAA has been a consistent sponsor of aviation weather research over the past 30 years with specific foci on the greatest hazards: turbulence, icing, C&V and thunderstorms
2. There is a strong and thriving airline industry willing to buy value added services from private industry with a solid return on investment and airlines do not pay for services provided by the government
3. Due to the geographical extent of the country, air transport is commonplace and affordable

4. US National Airspace System is heavily congested especially in the East Coast and thus vulnerable to weather disruptions
5. US climate is prone to extreme weather from tornadoes to blizzards
6. Research institutions' compensation and career opportunities attract the best scientists
7. Federal government continually seeks opportunities to improve efficiency, reduce cost and improve safety of the National Airspace System through improved weather analysis and forecast products

4.2.4 UNIVERSITIES

Universities as places of higher education and research are naturally involved in many research initiatives related to aeronautical meteorology. However, the funding for many aeronautical meteorological projects is not freely available for competition as is usually the case for research funding. Funding is directed at very applied research solutions where the technology is transferred to the customer or third party. Universities play a role in this aspect, but play a much bigger role in developing the underlying scientific understanding of the atmospheric sciences then used by the applied research institutions. Table 5 provides a simple overview of some of the projects currently underway at select universities.

Table 5: List of identified projects ongoing at universities for aeronautical meteorological research listed by country, organization and focus area of the research

University	*Project Name*	*Related Focus Area(s)*
Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL)	Ceiling and Visibility Forecasting	Ceiling and Visibility
	Consolidated Storm Prediction for Aviation (CoSPA)	Convective Weather - Aviation
	Corridor Integrated Weather System (CIWS)	Weather Information Applications
	Integrated Terminal Weather System (ITWS)	Weather Information Applications
	NEXRAD Level III products	Radar Algorithm Development
	Terminal Convective Weather Forecast (TCWF)	Convective Weather - Aviation
	Wake Turbulence Mitigation for Departures (WTMD)	Wake Vortex
	Wind Forecast Algorithm (WFA)	Crosswind

State University of New York	Turbulence aspects of the Global Aircraft Data Set (GADS) experiment	Turbulence
University of Colorado & Cooperative Institute for Research in Environmental Sciences (CIRES)	Probabilistic HRRR and RAP forecasts	Numerical Weather Prediction
	Weather Impacts on UAS Operations	Weather Information Applications
University of North Dakota	Convectively-Induced Turbulence from Varied Resolution Full-Physics Models	Turbulence
	Weather Impacts on UAS Operations	Weather Information Applications
North Carolina A&T State University	Gravity wave breaking	Turbulence
University of Wisconsin	Clear Air Turbulence	Turbulence
	Next Generation Satellite Imagery to Support Aviation Forecasting	Satellite meteorology
University of Alabama	Convective wind forecasting from C-Band Weather Radar	Radar Algorithm Development
University of Oklahoma Cooperative Institute for Mesoscale Meteorological Studies (CIMMS)	Weather Radar Research to support Aviation	Radar Algorithm Development
Yonsei University	Development and verification of regional and global Korean Aviation Turbulence Guidance (KTG) systems	Turbulence
Pukyong National University	Improving Deterministic Time-Lagged Ensemble Forecasts by Applying Blended Nowcasts	Nowcasting
University of Innsbruck	Low-Visibility Conditions with Tree-Based Statistical Models	Statistical Modelling
National Cheng Kung University	Improving upper air nowcasts with ADS-B data	Aircraft Observations

4.3 PRIVATE COMPANIES

Private enterprises play a crucial role in aeronautical meteorology as they bridge the gap between data providers and airspace users, often with years of in-depth understanding of the business models of various customers. Table 6 lists some examples of research projects carried out by private companies to illustrate what projects exist today.

Table 6: List of identified projects ongoing at private companies for aeronautical meteorological research listed by country, organization and focus area of the research

	Company	Project Name	Related Focus Area(s)
	I. M. Systems Group, Inc. (IMSG)	Enterprise Integrated Aviation Weather System (eIAWS™)	Weather Integration into Decision Making
	The Weather Company, an IBM Business	Decision Support Tools for Airlines	Weather Integration into Decision Making
	The MITRE Corporation	Convective Weather Constraint Awareness	Weather Integration into Decision Making
		Ensemble Forecasting for Strategic Traffic Flow Management	Weather Integration into Decision Making
	McCann Aviation Weather Research, Inc.	Hail aloft	Convection
	WxOps, Inc	Transported Convective Turbulence in Long-Haul Aircraft Operations	Convection
	AvMet Applications Inc.	Wind Compression Guidance	Weather Integration into Decision Making
USA	Scientific Computing Associates, LLC	Observation intercomparison at airports	Upper air
KOR	Green Simulation Co., Ltd.	Development of high resolution wind forecast technique for supporting aviation forecaster	Wind
FRA	LEOSPHERE	Measurements of Wind and Turbulence	LIDAR

Comprehensive information on the exact content of research and applications developed in private companies is hard to find freely and there is no real incentive to make results public in many cases. Publishing requires additional work that is not always funded by the awarded contracts. Some parts of the research may also be deliberately kept secret to gain a competitive advantage. Information on private companies' activities is mainly collected from appearances at international conferences.

4.3.1 Airlines

Some airlines employ their own meteorologists while some choose to contract this out to a company provider and some also engage in product development. However, all rely on the research advances achieved by the large national research centres around the globe especially for the most expensive infrastructure such as the numerical models, weather radars, weather satellites and ground observations. Where many meteorologists add value for airlines is in the decision support function, translating weather impacts into operational outcome.

Delta employs 25 meteorologists[34] and actively collects and processes observations from its aircrafts. Surface forecasters concentrate on hub airports while the upper air forecasters focus on the en-route hazards that could affect the performance of the fleet. Delta has partnered with the FAA and researchers in the past to improve ground information affecting hub airports. United is by many measures the largest airline in the world and employs a team of forecasters in its operations room with 3-4 forecaster constantly on duty[35]. American Airlines has a business arrangement with the Weather Company (an IBM Business) to provide meteorologists to their operations centre.

Lufthansa has been active in implementing on-board observation equipment for the meteorological scientific community for 20 years[36] and is also funding innovative services for the avoidance of turbulence areas on long-haul flights via a real-time datalink to the pilots' Electronic Flight Bag (**EFB**). Air France has been actively engaged in SESAR projects, performing demonstration flights for TOPMET and TOPLINK projects and works closely with Paris airports and Météo-France on new solutions. British Airways works closely with the UK Met Office and has a contract with The Weather Company. In general, airlines focus on the cost-saving and safety-enhancing potential of weather events and aim to make this process better. Airlines really make a difference in providing observations to the meteorological community[37].

4.3.2 WEATHER COMPANIES

Private weather companies, the largest of which is The Weather Company (an IBM Business), spend a lot of time and energy on research and development to improve their proprietary information benefiting their customers. As can be expected, detailed information regarding the research projects carried out are not available and one can merely speculate on the contents. In addition to The Weather Company, there exist commercial providers such as the MeteoGroup and StormGeo, who

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34 http://news.delta.com/deltas-25-meteorologists-keep-eyes-skies (link tested 30 Nov. 17)
35 https://weather.com/news/news/united-airlines-ceo-comments-farmers-almanac (link tested 30 Nov. 17)
36 http://www.lufthansa.com/mediapool/pdf/47/media_1985959147.pdf (link tested 30 Nov. 17)
37 http://www.weatherwise.org/Archives/Back%20Issues/2015/July-August%202015/airlines_full.html (link tested 30 Nov. 17)

develop and operate aeronautical meteorological services. The private sector in aeronautical meteorological service provision has a key role in the translation of meteorological information into the operations of airlines and air traffic control. There is room for much greater scope of public-private partnership models for research and development activities subject to funding mechanism to support such activities. The private sector focuses much more on developing a comprehensive understanding of the customer added value generation whereas the public sector is in a unique position to focus on science and high-performance computing usually beyond the reach of the private sector.

4.3.4 Air Navigation Services Providers

An Air Navigation Service Provider (ANSP) can be a public or a private entity carrying out some or all the tasks required to enable air transport. Air Navigation Services (ANS) include Air Traffic Services (**ATS**), Communications, navigation and surveillance systems (**CNS**), Aeronautical information services/aeronautical information management (**AIS**/**AIM**) and meteorological service for air navigation (MET). The term Air Traffic Management (ATM) includes Airspace Management (**ASM**) and Air Traffic Flow Management (ATFM) functions that are the responsibility of the state. While those NMHSs providing MET services are considered ANSPs, special attention is given to those entities performing multiple functions here.

According to a study conducted by EUMETNET, roughly 30% of MET service providers in Europe are not NMHSs, but the function is integrated into the local air traffic service provider (Sondij 2015). Many of these institutions are a part of EUMETNET and take active part in e.g. SESAR projects carrying out their own research projects, including but not limited to Belgocontrol, Austro Control, ROMATSA and Croatia Control. The integrated service providers have the added advantage of demonstrating and quantifying the added value of meteorological information to air traffic management, tailoring solutions that improve common decision-making capabilities, and having economic stability from air traffic revenues. All the mentioned organisations rely on the meteorological infrastructure provided by the NMHSs.

4.3.5 INTERNATIONAL TECHNOLOGY COMPANIES

Large global technology companies are gaining interest in branching out to the aviation sector and they can leverage existing high-capacity infrastructure previously only available at select NMHSs. Technology companies carry the required expertise and investment budgets to create new innovations also in aeronautical meteorology. One such example is Panasonic, who have previously developed aircraft observation equipment, but have made an investment to run a global numerical weather model with the aim of serving the aviation community[38].

Jeppesen, Lufthansa Systems (LIDO), Air Routing International, Universal Weather and Aviation and UAS International Trip Support are flight planning companies that incorporate weather information into their systems used by pilots and airlines to plan the flight. Some, such as LIDO, have advanced meteorological features incorporated, showing severe to moderate turbulence areas and levels for the pilot to circumnavigate these hazards. The development of meteorological information in the cockpit is under growing interest with many meteorological information providers and systems manufacturers integrating these features.

Schneider Electric is a multinational company specializing in the energy sector and automatization. It provides forecast and observation services for airlines and airports globally. DTN has patented algorithms for turbulence, icing and convection and invests in research and development of meteorological information[39].

4.4 INTERNATIONAL ORGANISATIONS

The role of international organisations in air transport is to ensure common standards and practices to enable safe and efficient flight. There are various international organisations that represent the interests of the airlines (IATA), air traffic management (CANSO), airports (ACI) and meteorological services providers (WMO, EUMETNET).

As described at the beginning of this section, the International Civil Aviation Organization (ICAO) sets the global agenda and standards for civil aviation. The meteorological services to be provided globally are described mainly in the Annex 3 to the Chicago Convention. Within the European Union, the regulation in ICAO Annex 3 is transposed to EU legislation by the European Aviation Safety Agency (EASA). The WMO coordinates the

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[38] https://arstechnica.com/science/2016/04/tv-maker-panasonic-says-it-has-developed-the-worlds-best-weather-model/ (link tested 30 Nov. 17)
[39] https://www.dtn.com/products/#weather (link tested 30 Nov. 17)

global cooperation in observations, weather services and research carried out by its 185 members. The WMO has a separate Aeronautical Meteorological Programme working closely with ICAO and the Commission for Aeronautical Meteorology, which is organized every four years to set the global agenda.

It should be noted that there is no single international agency tasked to coordinate aeronautical meteorological research or to ensure sharing of information and research results. WMO organises an *Aeronautical Meteorology Scientific Conference* of which the first was held in 1969 and the second in 2017. In addition, WMO organises information events, such as the Technical Conference (TECO-2014) on Aviation Meteorology on 7-8 July 2014 in Montréal, Canada and the *European Conference on Meteorology for Aviation* (ECMA-2015) held on 13-14 October 2015 in Vienna, Austria. The only regular global conference is with the American Meteorological Society (AMS) who organises the *Conference on Aviation, Range, and Aerospace Meteorology* every two years. Yonsei University in Korea has organised five workshops on aviation meteorology to date[40].

4.5 International standardisation

Because of the high operational importance of weather information and the long history of aviation before the computer era, most aeronautical meteorological information is still disseminated via alphanumeric codes and simple black-and-white images. These formats are standardised in the ICAO Annex 3 and WMO No. 49, Vol II. From the point of view of the provider of the information, complex atmospheric circumstances currently present at an airport (METAR), forecast of the weather at the airport in the next 24 hours (TAF) and any significant weather events (SIGMET) in the airspace must be compressed into very short and highly rigid code formats. Information is bound to be lost in the process. From the user's perspective, the information must be properly understood and interpreted back to operational constraints using only the very short piece of code. International standards are finally evolving to new formats to allow more information to be carried over to users in a way in which it can be directly ingested into any system.

[40] http://atmosdyn.yonsei.ac.kr/program_2016 (link tested 30 Nov. 17)

4.5.1 SWIM

System Wide Information Management (SWIM) is a technology enabler that provides the IT standards, infrastructure and governance necessary for airspace systems to share information, improve interoperability, and reuse information and services[41]. It is being implemented in the US via the NextGen program and in Europe by SESAR Deployment projects. SWIM information includes among other meteorological information, but is by no means restricted to it[42]. Many of the research applications developed today are connected to SWIM via definition or funding. In many ways, meteorological information is leading the proliferation of information in the SWIM environment.

4.5.2 (I)WXXM

The ICAO Meteorological Information Exchange Model (**IWXXM**) is the future format replacing the traditional alphanumeric codes in XML/GML languages. This change will become operational January 2020 and will ensure that the basic meteorological information will be available in a SWIM-compliant format. The implementation of IWXXM requires at a minimum an upgrade to the current message switching system handling data communications to and from the service provider. The new standard format will make it easier for any user to extract parts of the weather information most important to their operations and hence enable new and innovative products and services.

5 ADVANCES IN DETECTION AND FORECASTING OF METEOROLOGICAL PHENOMENA

Atmospheric sciences study the Earth's atmosphere, its processes and the effects other systems such as oceans and forests have on the atmosphere. Meteorology research supports weather forecasting through advances in understanding atmospheric chemistry and atmospheric physics via observations and numerical modelling. Aeronautical meteorological research is a field of applied meteorological research focusing specially on the impacts of weather on air transport and the specific phenomena that impact airspace users. The notion extends here also to the core research

[41] https://www.faa.gov/nextgen/programs/swim/overview/ (link tested 30 Nov. 17)
[42] http://www.eurocontrol.int/swim (link tested 30 Nov. 17)

into the most important meteorological phenomena, which may be carried out under entirely different premises initially, but have an application for aeronautical meteorology. The purpose of this section is to present to the reader the current state of the art of the research areas in question and to function as an overview of current activity. The section includes the analysis and forecasting of the phenomena in question as these two are often closely interlinked and it can prove difficult to develop forecasting capabilities for phenomena without a well-documented physical process.

Nowcasting is the accurate depiction of the current atmospheric conditions and an extrapolation to the near future in the first 6-hour timeframe to support those customers that need information for decision support in the near future (Mass 2012). This applies specifically well to aviation where the onset or cessation of e.g. fog or thunderstorm events is of crucial importance. Nowcasting methods can generally be divided into radar-based extrapolation, model-based and knowledge-based systems (Wilson et al. 2010). Recent developments on radar-based nowcasting methods titled the Collaborative Adaptive Sensing of the Atmosphere (CASA) are presented by Ruzanski et al. (2011). Radar-based nowcasting systems generally fall under area-based, object-based, statistical and probabilistic approaches and tend to perform well in the first two hours of the forecast.

5.1 TURBULENCE

Turbulence is defined by Encyclopædia Britannica[43] as: *small-scale, irregular air motions characterized by winds that vary in speed and direction* caused by thermal, orographic and dynamical sources acting separately or in combination[44] to form e.g. clear air turbulence (**CAT**), mountain-wave turbulence (**MWT**) low-level turbulence (**LLT**) and convectively induced turbulence (**CIT**) (See Figure 11). An overview of the processes, detection and prediction of turbulence for aviation is presented by Sharman and Lane (2016) in their book entitled *Aviation Turbulence*.

[43] https://www.britannica.com/science/atmospheric-turbulence (link tested 30 Nov. 17)
[44] http://oiswww.eumetsat.org/WEBOPS/iotm/iotm/20091109_turbulence/turbulence.pdf (link tested 30 Nov. 17)

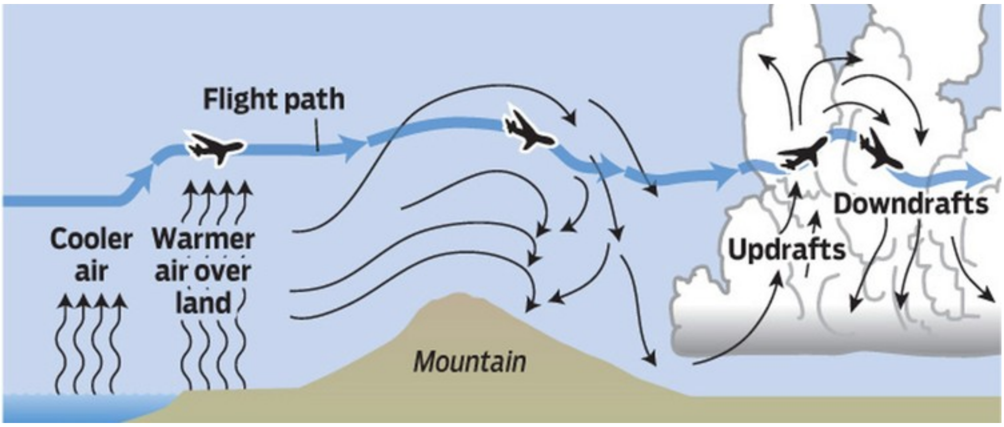

Figure 11: Schematic of convective and mountain wave turbulence with associated altitude changes experienced by an aircraft in the vertical motion or air, source: http://www.mypalmbeachpost.com/weather/how-worried-should-air-travelers-about-turbulance/9BwPT5vE5i0w1uboEi51eN/ (link tested 30 Nov. 17)

The significance of turbulence to the operation of an aircraft is determined by the size, wing span, weight and speed of motion of the aircraft. The intensity is typically classified using a three-tier system for light, moderate or severe turbulence. Intensity is classified according to observed changes in accelerometer reading, maximum derived equivalent vertical gust or the Eddy Dissipation Rate (**EDR**). The cube root of EDR has been recognised as the standard for reporting (and forecasting) turbulence in the ICAO Annex 3 Meteorological Service for International Air Navigation (ICAO 2016b). EDR cube root peak values below $0.1m^{2/3}s^{-1}$ amount to nil turbulence, 0.1 to 0.4 correspond to light turbulence, 0.4 to 0.7 for moderate turbulence and values over 0.7 to severe turbulence. The in-situ estimates of EDR are available from some airlines (Sharman et al. 2014) and spectral width estimates are available from ground and onboard weather radars. The prediction of EDR is discussed in the two articles by Pearson and Sharman (2017) and Sharman and Pearson (2017), including the forecasting of non-convective turbulence and nowcasting convective and non-convective turbulence. The specific Graphical Turbulence Guidance (**GTG**) product is described by Sharman et al. (2006) and evaluated over East Asia by Kim et al. (2011) showing good skill in identifying turbulence areas. This product is now under development to be used by the World Area Forecast Centers (**WAFC**s) as the global turbulence guidance product.

Research by Gill (2014) presents verification results of the global turbulence guidance issued by the WAFCs and an ensemble-based method to improve those results (Gill and Buchanan 2014). The study by Kim et al. (2014) looks at severe turbulence experienced in the cirrus anvils of banded convection associated with an oceanic cyclone. Cirrus banding and turbulence near a convectively enhanced upper-level jet stream mechanism are explored further by Trier and Sharman (2016). The climatology of EDR measurements from some 200 commercial aircraft from 2013 onwards mostly at cruise level altitudes is discussed by Sharman et al. (2014). A real-time diagnosis of turbulence associated with thunderstorms using weather radar, satellite, lightning detection, and numerical weather prediction models is presented by Williams (2014). The Diagnose Convectively-Induced Turbulence (DCIT)[45] and NEXRAD Turbulence Detection Algorithm (NTDA)[46] also provide real and near-real time turbulence guidance for airspace users. An illustration of the trade-off between flight time and fuel used to turbulence avoidance manoeuvres in a combined wind and turbulence prediction system is given by Kim et al. (2015). Another paper by Kim et al. (2016) explores how teleconnection between weather patterns, as represented by the North Atlantic Oscillation (NAO), can be used for long-haul strategic planning by taking into consideration wind optimal routes and turbulence potential for transatlantic flights along the great circle route. A study from Korea by Kim and Chun (2016) evaluates the Korean Aviation Turbulence Guidance (KTG) using aircraft observations represented by the derived equivalent vertical gust velocity.

Growing interest in the impact of climate change to air navigation has resulted in a number of studies quantifying changes in the general circulation pattern and related effects to specific phenomena. For turbulence, the study by Williams and Joshi (2013) concludes that the frequency of clear air turbulence will increase significantly in the next 50 years due to the strengthening of jet stream velocities. The strength of the turbulence will also increase within the transatlantic flight corridor leading to potential increases in flight duration and fuel consumption. A further study by Williams (2017) estimates changes in the different severity categories of wintertime clear air turbulence on the transatlantic routes, concluding that especially future severe turbulence cases are seen to increase with increases in all categories from light to severe due to climate change.

[45] https://ral.ucar.edu/projects/diagnose-convectively%E2%80%93induced-turbulence-dcit (link tested 30 Nov. 17)

[46] https://ral.ucar.edu/projects/ncar-turbulence-detection-algorithm-ntda (link tested 30 Nov. 17)

5.2 In-cloud Icing

Icing while airborne is a potentially dangerous scenario as this has a multitude of effects for the airworthiness of the aircraft. Icing has a cumulative effect, decreasing thrust, decreasing lift, increasing weight and increasing drag as the ice builds up on the surfaces. There are clear, mixed, induction and rime icing observed at aircraft, of which rime icing is the most typical form of icing encountered by pilots and clear ice the second most typical (See Figure 12). Icing is not caused by ice in the clouds, but supercooled liquid water droplets that strike the leading edge of an airfoil and freeze on impact. The mechanism for the formation of conditions favourable to icing begins with water in liquid form cooled rapidly typically by lifting and condensation. The lack of activated ice nuclei enables the droplets to remain in liquid form. Liquid Water Content (**LWC**) may be used as a proxy for determining the conditions favourable to icing, but is typically only useful in stratiform clouds. Icing typically occurs in temperatures between -8° and -12°C ranging from 0° to -20°C. Icing can be caused by descent of an aircraft from sustained flight in below freezing air to warm air through a cloud. Icing patterns change with droplet size, but in relation to icing hazards droplet size is not as important as LWC and temperature. Rime icing forms in the stagnant air at the leading edge of the airfoil and is typically easier for de-icing equipment to remove.

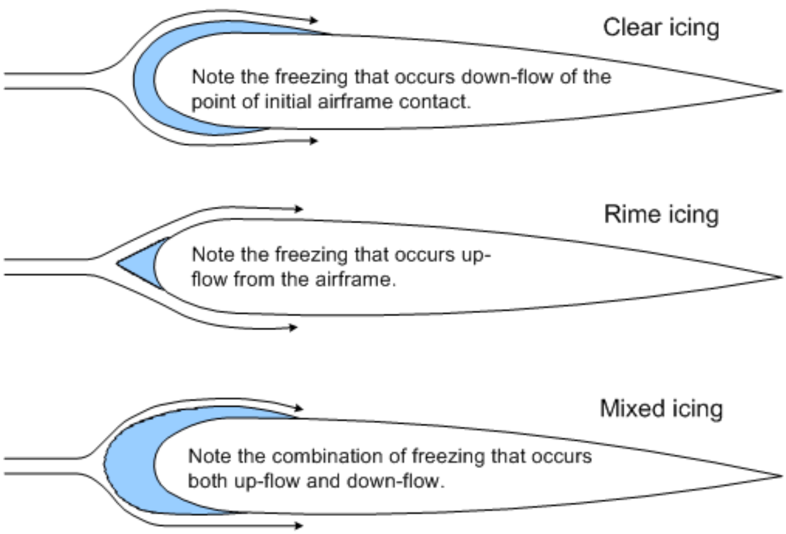

Figure 12 Different types of ice accumulation on an aircraft wing based on the depiction found in Fig. 9-5 of Air Command Weather Manual, source: https://www.tc.gc.ca/eng/civilaviation/publications/tp12775-training-1652.htm (link tested 30 Nov. 17)

Clear icing grows larger in the eddies of the leading edge of the airfoil to form peaks and thus a larger impact on the airflow around the airfoil. In stratiform clouds, cloud droplets are small and rime and mixed icing the most common with maximum values in the upper part of the cloud and a large horizontal extent. In cumuliform clouds, cloud droplet sizes are bigger, icing is found in the updraft portion of the cloud, heavy rime most frequently in cloud tops, clear icing in building Cu clouds and rime in fully developed Cb clouds with a relatively small horizontal extent. This generalisation does not cover the mixed-phase clouds of all types that may harbour sufficient amounts of supercooled water.

Research into icing has been conducted using a research aircraft as documented in Sand et al. (1984) observing the features discussed earlier. Field projects, such as the Winter Icing and Storms Project (WISP) by Rasmussen et al. (1992) have provided further insights into the processes leading to the formation and depletion of supercooled liquid water using a number of observation methods in Colorado, USA. An accident involving an ATR72 near Roselawn, USA in the presence of supercooled cloud droplets is reported by Marwitz et al. (1997). Studies have since been carried out in Europe as presented by Amendola and Mingione (2001). One of the first documented numerical approaches is discussed in Schultz and Politovich (1992) for an automated process for icing forecasting using the manual forecaster aids as a first step. The shape of ice formation on airfoil and the effect on drag is presented in Shin and Berkowitz (1994). This study is further expanded for the case of helicopters operating in VMC conditions considering especially areas below stratus clouds by Fuchs and Schickel (1995). The paper by Bernstein et al. (1997) presents a statistical analysis of the observed icing in connection to airmass origin, location relative to fronts, troughs and low-pressure centres, precipitation type, cloud cover, lightning/thunder, fog, radar reflectivity and synoptic-scale forcing mechanisms. The most likely locations for icing over the US are further explored by Bernstein et al. (1998). Parameters important for in-flight monitoring and methods for detection of ice accretion is presented by Melody et al. (2000). A review, correlation, and assessment of test results available in the public domain which address the aerodynamic performance and control degradations caused by various types of ice accretions on the lifting surfaces of fixed wing aircraft are presented by Lynch and Khodadoust (2001). A method currently in operational use for the diagnosis of icing conditions in the US, the Current Icing Potential (CIP), is presented in the seminal paper by Bernstein et al. (2005) and an extension for volumetric coverage over surrounding an airport by Serke et al. (2016). The Forecasted Icing Potential (FIP) provides a guidance product for future icing conditions and is discussed by Wolff et al. (2009).

One neural network approach to forecasting icing intensity is presented by McCann (2005) showing the potential of this approach. The comprehensive climatology of icing conditions aloft is presented in two papers by Bernstein and Le Bot (2009) and Bernstein et al. (2007) for the US and the rest of the world using surface observations.

5.3 Ceiling and Visibility

The term "ceiling and visibility" is a frequently used expression in aviation to describe the vertical and horizontal line of sight at an airport and more specifically the height of the lowest cloud base with BKN/OVC coverage of the sky (ceiling) as shown in Figure 13 and the greatest safe distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognised when observed against a bright background (visibility). These two parameters are reported and often forecasted separately, but they are connected by nature in phenomena such as fog, which impairs both ceiling and visibility. Meteorological conditions with reduced ceiling and visibility also include snowstorms, heavy precipitation and stratus clouds to mention a few. Since airport operations and aircraft have operating minima for ceiling and visibility given by international and national regulation, there is considerable interest in the observation and forecast of both parameters. The observation of cloud ceiling in a modern AWOS is usually achieved with the ceilometer using laser technology. The visibility is reported in both the traditional visibility reading and the Runway Visual Range (**RVR**) on three locations of a runway, providing estimates on the distance a pilot can see down a runway when touching down and taking off.

The notion of predicting ceiling and visibility with statistical methods is discussed early on by Allen (1969), depicting a way forward using central computing methods to give guidance to forecasters. There was growing interest at the time in exploring statistical methods to improve guidance given to forecasters and the Model Output Statistics (**MOS**) methods were introduced by Glahn and Lowry (1972). These methods were applied for aviation purposes and especially ceiling and visibility early on by Bocchieri et al. (1973 and 1974). An analysis to the various causes of low ceiling and visibility and the identification of the most affected US airports is provided by Clark (1995). A paper by Vislocky and Fritsch (1997) explores the methods for probabilistic nowcasts of ceiling and visibility and identifies an observations-based, MOS-based and persistence (climatology) –based method concluding that the observations-based system outperforms the other in the very near term (1-3h). An observation-based statistical probabilistic system for ceiling and visibility is further discussed in the study by Leyton and Fritsch (2003) and specifically for the New York area in Leyton and Fritsch (2004).

Figure 13: Illustration of a ceiling height, the base height of lowest broken (**BKN**) or overcast (**OVC**) layer or vertical visibility into surface-based obscuration. Source https://www.meted.ucar.edu/oceans/wx_obs/media/graphics/flickr_ceilings_keepitsurreal.jpg (link tested 30 Nov. 17)

Performance of numerical models and the importance of data assimilation are explored by Stoelinga and Warner (1999). An operational combination product using satellite, ground observation and numerical model guidance information to output a ceiling and visibility is the FAA's National Ceiling and Visibility (NCV) product presented by Herzegh (2006) and Herzegh et al. (2004). The development of specific ceiling and visibility forecast methods for the heavily congested Northeast US airspace is discussed by Clark (2006). An analogue fuzzy logic method for ceiling and visibility at Canadian airports is discussed in Hansen (2007) and a more recent study in Europe by Tuba and Bottyán (2017). A further statistical method showing improvements over MOS and logistic regression using neural networks is presented by Marzban et al. (2007). A local ensemble prediction system for ceiling and visibility at Paris-Charles de Gaulle airport for different fog types is presented by Roquelaure et al. (2009). The statistical method of Bayesian model averaging is applied to ceiling and visibility forecasting to produce probability density functions by Chmielecki and Raftery (2011). More recently, major efforts have been made to statistically combine (meld) visibility forecasts from MOS and numerical weather model methods providing good outcomes as documented by Glahn et al. (2015 and 2017). A similar data fusion of surface, satellite and terrain information to produce a graphical analysis of ceiling and visibility currently operational is presented by Herzegh et al. (2015) and a method to statistically determine cloud base height from satellite observations is described by Miller et al. (2014).

Fog is an extreme case of poor ceiling and visibility, often forcing closures of runways and diversion of aircraft to other airports. Fog forecasting is often the key challenge for an aviation weather forecaster, often more difficult to nowcast than convection due to the difficulties in correctly representing the topography and microphysical processes with adequate resolution in numerical models. Concentrating only on the most recent research on fog, a one-dimensional forecast method for radiation fogs and low-level stratiform clouds is presented by Bott and Trautmann (2002) and for Spanish airports by Terradellas and Cano (2007). Research at the Paris Charles de Gaulle Airport (CDG) by Bergot (2007) concludes that detailed 1-D models, including detailed physical parameterizations and high vertical resolution, can reasonably represent the major features of the lifecycle of fog (onset, development and dissipation) up to +6 h. The one-dimensional model is extended into the local ensemble prediction system for fog and low-cloud forecasting at Paris Charles de Gaulle airport (**CDG**) and represented in the papers by Roquelaure and Bergot (2009) and Roquelaure et al. (2009). A dedicated field campaign at CDG to explore the physical processes of fog is presented by Haeffelin et al. (2010) covering more than 100 fog situations at the airport and a quantification of the meteorological conditions favourable to radiative fog formation by Menut et al. (2013) from the same campaign. Scenarios for the formation, development, and dissipation phases of stratus fog events near Paris, France are discussed by Dupont et al. (2012). Large Eddy Simulations of 2m horizontal and 1m vertical resolution and the small-scale structure of radiation fog is discussed in the paper by Bergot (2013) and the effect of urban canopy by Bergot et al. (2015). The significance of vertical resolution using the AROME model for CDG fog forecasting is discussed by Philip et al. (2016).

A review paper by Gultepe et al. (2007) summarizes achievements up to 2007 in understanding fog formation, observations and forecasting and the papers by Koračin et al. (2014) and Gultepe et al. (2017) provide a review of marine fog. The use of high-resolution model in the United Kingdom to better represent fog using a 1 km horizontal resolution is presented by Tang et al. (2009). The challenges of fog forecasting in frost conditions is the focus of the paper by van der Velde et al. (2010), further re-iterating the requirement of high resolution in numerical models in order to be able to accurately depict fog conditions. A diagnostic multi-variable fog-forecasting method with case studies for eastern China is presented by Zhou and Du (2010) using an ensemble approach. Fog and visibility nowcasting methods have been developed for several airports using various methods such as neural networks, decision-trees, etc. A few recent examples include research by Dutta and Chaudhuri (2015), Gultepe et al. (2014) and Pasini et al. (2001).

5.4 Convective Weather

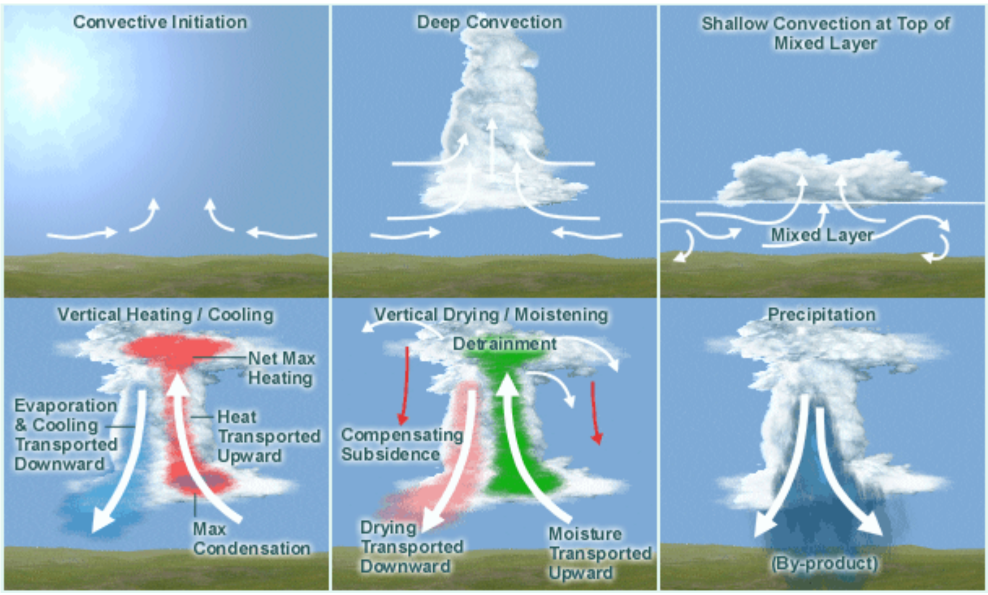

Figure 14: Convection and associated thermodynamic processes represented by convective parameterizations in numerical weather models, source: https://www.meted.ucar.edu/bom/mprecip_clouds/print.php (link tested 30 Nov. 17)

As has been discussed in previous chapters, convective weather causes many issues for air transport due to the large vertical and horizontal area where aircraft cannot fly and airports must restrict capacity (See Figure 14). There is a wealth of research into convective weather, a search in Web of Science database for the word “convection” within the meteorology and atmospheric sciences category yields 14 300 research articles. Since convection is such an important constraint to airspace capacity in the US, many different observation, analysis and forecast methods have been developed and identified. Those sources with the most relevance for aviation presenting the methods and forecasting techniques currently in use are presented here. For convection, probabilistic model-based forecasts have been reported to outperform probabilistic radar-based approaches after 2.25-3.5h. These methods are presented by Kober et al. (2012), Scheufele et al. (2014), Sun et al. (2014) and Wilson et al. (1998).

Tornadoes are naturally avoided by aircraft as they already stay clear of the cumulonimbus clouds generating these funnel clouds. Airports do not have the luxury of avoiding tornadoes and can be hit as was the case in e.g. Lambert-St. Louis International Airport on 22 April 2011 and an EF4 tornado. An overview of tornado forecasting leading up to 1993 is given in the book by Doswell et al. (1993), a more recent one by Bradford (2000) and a recent overview for the British Isles by Knightley (2016). Tropical storms are synoptic scale convective systems and as such produce similar impact to air transport as mesoscale or local thunderstorms, i.e. turbulence, icing, lightning strike risk, hail, wind shear and high winds.

5.4.1 SHORT-TERM PREDICTION OF CONVECTION

There are algorithms that nowcast convection using tracking and advection (like TITAN and CIWS, also called extrapolation), there are nowcast systems that try to nowcast convection initiation (Autonowcaster developed at NCAR), there are high-resolution NWP models with advanced data assimilation used to prediction 2-12 hours and there are systems that combine extrapolation and NWP forecasts such as the CoSPA system.

A radar-based methodology for the real-time automated identification, tracking and short-term forecasting of thunderstorms called TITAN is presented by Dixon and Wiener (1993) with results of the operational evaluation of the method. TITAN is used to estimate the performance of WRF for tropical convection by Caine et al. (2013). The building blocks for the forecasted warnings of convective events are laid out by Stensrud et al. (2009) and the progress and challenges related to three-dimensional data assimilation and ensemble forecasts in Stensrud et al. (2013). A specific forecast system for convection in aviation, called the consolidated storm prediction for aviation (CoSPA) has been developed in the US since 2006 to consolidate forecast products in a cooperative effort between MIT Lincoln Laboratory, NCAR and NOAA ESRL Global Systems Division. CoSPA is described in articles by Pinto et al. (2010) and Wolfson et al. (2008). The specific issue of convection initialisation in the 0-12h timeframe is explored by Burghardt et al. (2014) with a high-resolution (429 m) model.

The resolution of convection in mesoscale numerical weather models and the effect of grid size is discussed by Weisman et al. (1997), concluding that a grid size of around 4 km is sufficient to represent the convective features. Vertically integrated liquid water (**VIL**) has been established as the main proxy for convection in aviation weather forecasting and the rationale is presented in Crowe and Miller (1999). The use of VIL for an experimental airport-specific aviation convective weather forecast product at Dallas Fort Worth airport developed by MIT Lincoln Laboratory is discussed by Hallowell et al. (1999). The verification of precipitation patterns of the WRF model for convective systems is discussed by Davis et al. (2006) and the skill of a French mesoscale model ALADIN is discussed by De Troch et al. (2013). The skill of the HRRR model to forecast mesoscale convective systems is evaluated against radar-retrieved vertically integrated liquid by Pinto et al. (2015), showing increasing skill in recent model version changes.

5.4.2 Lightning Risk

Lightning climatologies have been compiled for decades to better understand the areas most prone to lightning to develop mitigation methods and better forecast these incidents. The study by Clodman and Chisholm (1996) focused on cloud-to-ground lightning in the Great Lakes region, Hodanish et al. (1997) present a 10-year climatology for Florida and Bentley and Stallins (2005) present a 12-year climatology for Georgia. A similar climatology for Romania is presented by Antonescu and Burcea (2010), for Estonia by Enno (2011), for South-West Indian Ocean by Bovalo et al. (2012) and for the Nordic Lightning Information System (NORDLIS) by Mäkelä et al. (2014). Satellite-derived climatologies have also been compiled for a global coverage of lightning intensity, identifying areas in Africa and India as the hotspots for annual lightning activity as presented in Cecil et al. (2014).

Research by Gremillion and Orville (1999) focuses on the Kennedy Space Center in Florida to identify lightning initiation from weather radar signatures, concluding that median lag time for thunderstorm warning was observed at 7.5 minutes. The electrification process, regional variations in lightning patterns and the role of aerosols are discussed by Sherwood et al. (2006) with the finding that small diameter ice crystals at cumulonimbus cloud tops is associated with climatological maxima of lightning activity. Storm electrification is generally accepted to be associated with areas of strong updraft and the resulting non-inductive charging process. Strong evidence for the flux hypothesis which states that total lightning frequency is roughly proportional to the product of the downward mass flux of solid precipitation (graupel) and the upward mass flux of ice crystals is presented in the paper by Deierling et al. (2008).

Methods for forecasting lightning can be associated either with implementing a storm electrification model or by proxy using the flux hypothesis described above since these processes are not represented in general numerical weather prediction models. The flux hypothesis is demonstrated to perform well using model fields of vertically integrated hydrometeors and upwards fluxes of precipitating ice hydrometeors in the mixed-phase region at the -15°C level in the study by McCaul et al. (2009). This method was since implemented into operational runs of the WRF model. Later modifications to the algorithm to accommodate cold season lightning and heavy convection areas are outlined by McCaul et al. (2012) and Lynn et al. (2012). The BoltAlert® system[47] processes radar, temperature, and lightning data to derive statistically calibrated lightning probability and lightning safety guidance for specifiable locations.

5.5 WIND

Wind fields used by airspace users are generated using numerical weather prediction models. For global default datasets used by most flight planning companies, these wind fields are generated by the Washington and London WAFCs, located at the Aviation Weather Center in Kansas City, USA and the UK Met Office in Exeter, UK, respectively. The upper air winds forecast methods in use at the UK Met Office are discussed by Rickard et al. (2001) and the characteristics of the Global Forecast System (**GFS**) are given in the previous chapters. Many aeronautical meteorological service providers running regional models provide upper air wind information to local users via dedicated products, but global air navigation relies on the WAFC data. WAFC charts shall be disseminated to users, is mandatory in the ICAO Annex 3 and in future EU regulations. The advantage of using a single authoritative source for wind information is to avoid conflicting information between various airspace users potentially resulting in discrepancies in flight plans. For low-level winds, the regional models and local effects become important and are provided by the local models. WAFCs follow the ICAO ASBU development cycle and roadmap.

[47] https://ral.ucar.edu/solutions/products/lightning-potential-boltalert (link tested 30 Nov. 17)

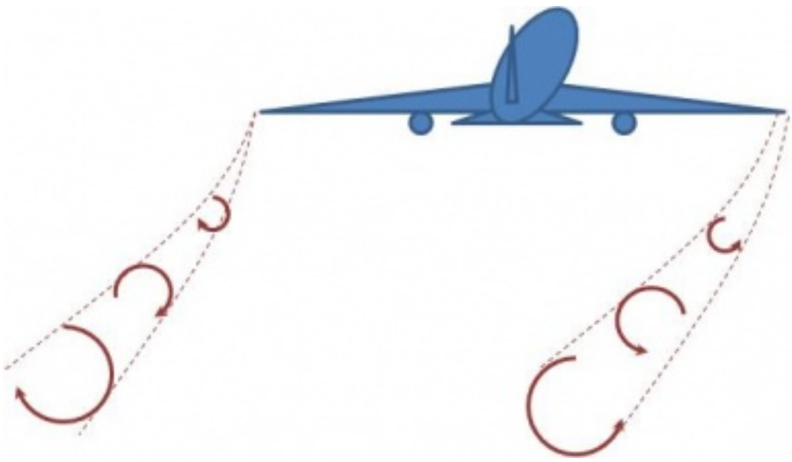

Figure 15: Schematic representation of wake vortices emanating from aircraft wingtips. Source: https://www.skybrary.aero/images/thumb/Wake.jpg/400px-Wake.jpg (link tested 30 Nov. 17)

Strong and gusty winds can cause serious issues for aviation as has been discussed earlier. The notion that a single observation represents the wind field at an airport is discussed by Wieringa (1980). This notion seems incorrect especially for large airports in regions with complex terrain or some other surface heterogeneity. Low level wind shear is a big problem in those parts of the world that often experience low-level jets. This can cause aircraft performance issues and also make dealing with arrival air traffic tricky due to compression effects. Specific forecast methods have been introduced to mitigate the risk of low level wind shear, most notably the Low-Level Wind Shear Alert System (**LLWAS**) documented by Goff (1980) and developed at NCAR[48] since the 1970s, commercialised by equipment manufacturers (Adamson 1990) and tailored to specific locations such as Juneau airport in Alaska[49]. An example of the dangers of wind shear during approach and the meteorological conditions leading to the scenario are presented for Hobart Airport in Tasmania, Australia by Mills and Pendlebury (2003).

Wake Vortex turbulence is defined as turbulence which is generated by the passage of an aircraft in flight[50]. Potentially hazardous turbulence in the wake of an aircraft in flight is principally caused by wing tip vortices (See Figure 15). This type of turbulence is significant because wing tip vortices decay quite slowly and can produce a significant rotational influence on an aircraft encountering them for several minutes after they have been generated. The most apparent risk of encountering wake

[48] https://ral.ucar.edu/projects/low-level-wind-shear-alert-system-llwas (link tested 30 Nov. 17)
[49] https://ral.ucar.edu/projects/juneau-airport-wind-system-jaws (link tested 30 Nov. 17)
[50] https://www.skybrary.aero/index.php/Wake_Vortex_Turbulence (link tested 30 Nov. 17)

vortices is during low separation between aircraft during departure and especially at landing to an airport. Wake vortex encounters can lead to serious safety risks and have led to aircraft crashes. Therefore, mechanisms have been put in place to identify conditions favourable for the generation of wake vortices and systems to mitigate their impacts. One such wake vortex warning system including a glide-path extension for Frankfurt airport in Germany is presented by Gerz et al. (2009) and Konopka and Fischer (2005). Every 10 minutes the system delivers minimum safe aircraft separation times for the next hour, which are translated into operational modes for runways aiming at tactically improving capacity to reduce delays. Research by Kwong et al. (2008) uses data collected from LIDAR observations at Hong Kong airport to forecast wind velocities and wind shear. The frequency of wake vortex encounters is considered for upper levels in a study by Schumann and Sharman (2014) and the risk is demonstrated to be associated mostly with medium-size aircraft on parallel routes during descent.

A fairly elaborate statistical wind forecast for Reus airport, Spain, is presented by Traveria et al. (2010). A comparative approach using seven different approaches of post-processing wind speed forecasts is presented by Sweeney et al. (2013) resulting in a method providing improvements over the used operational methods. A high-wind incident over Europe is discussed by de Villiers and White (2014) using the WRF model. The questions around crosswind and lower level winds at airports can only be resolved with very fine scale numerical models as presented in e.g. Keller et al. (2015) for Denver International Airport involving an aircraft excursion from the runway due to high crosswinds not detected by the operational forecast model.

Changes in wind fields on the Northern Hemisphere for cross-Atlantic routes at cruising altitudes brought on by climate change are presented in the study by Williams (2016). The study finds that Eastbound flight times decrease while Westbound flight times increase with the total round trip flight time increasing and resulting in overall increase in flight times and fuel consumption.

5.6 Snowstorms and Winter Weather

Winter is perhaps the second most challenging season apart from the convective season in many areas. Some airports will see both severe convection and heavy snowfall during a year. The impacts of winter weather are different and affect ground operations at airport level mostly and can be mitigated by ensuring the right equipment and personnel are in place to deal with the snow. Forecasting winter weather is also somewhat easier as the weather patterns are often associated with frontal systems and low pressures, both of which are forecast with good skill by numerical models. The most challenging aspects of winter weather forecasting are to correctly forecast ceiling & visibility, icing, onset and cessation of snowfall, precipitation phase and shallow convection at edges of water causing cloud-to-ground or induced lightning. Some of these events are rare, difficult to observe and difficult to forecast, such as freezing drizzle or triggered lightning. Many of the improvements in accurately forecasting these parameters are associated with improved microphysical schemes in the high-resolution numerical models employed for forecasting. Other methods include statistical and other post-processing methods to calculate the parameters from the model output fields. Since ceiling & visibility and icing have been discussed earlier, this chapter will discuss snowstorms, precipitation phase and lightning phenomena in the cold season.

5.6.1 SNOWSTORMS

In a snowstorm, heavy snowfall can lead to reduced visibility and accumulation of snow on the ground causing issues with runway friction and ground operations. The overall damage associated with snowstorms in the US is estimated to have been $21.4 billion in the 1949-2001 timeframe with most frequency in the Northeast (Changnon and Changnon 2005) and an increasing trend in the suffered losses as a consequence of these events. Several severe snowstorms have been researched in detail, such as presented in the papers by Bosart (1981), Browning (1983), Lackmann (2001), Sanders and Bosart (1985) and Zhang et al. (2002). Many of the studies of snowstorms also assess the skill of models available at the time to capture these events. A study by Liao and Zhang (2013) discusses the synoptic scale forcing at play during a major snowstorm in southern China. Modern numerical weather prediction models have in general good skill in forecasting heavy snowfall with the specific exception of convective events, such as lake-effect snow and orographic effects. A database created by NASA has collected snowstorm information into a searchable resource and contains a wealth of information highlighting the nature of snowstorms as presented in the climatological study by Kuo et al. (2016). Most recent advances in understanding snowstorms include e.g. the use of research aircraft and airborne cloud radars such as the HIAPER cloud radar used to study a snowstorm over Boston presented in a paper by Rauber et al. (2017).

Lake-effect snow is a phenomenon leading to heavy snowfall accumulations when cold air flows over a warmer body of water. The colder air causes water to evaporate into the air and warm it and this warmer air rises and cools as it moves with the flow. As the rising moist air is cooling, it condenses into cloud droplets generating snowfall downstream from the body of water. The phenomenon is called lake-effect, since it is encountered often in the Great Lakes region of the US regularly causing accumulations of over 30cm in 24 hours. However, the same effect can be observed wherever cold air flows over a warmer body of water and is often encountered in coastal areas in high latitudes. Due to the high impact, low probability nature of this event, a great number of researchers have addressed this issue. The paper by Steenburgh and Onton (2001) goes to great detail in dissecting a lake-effect event on 7 December 1998 in Great Salt Lake. The results of a lake-effect convection experiment using a wealth of observation methods is presented in the paper by Schroeder et al. (2006). The role of orography in lake-effect snow is explored by Alcott and Steenburgh (2013). While the main emphasis of published research on lake-effect snow is in the United States, many studies are available for Europe and Asia, such as the research carried out by Umek and Gohm (2016) for Lake Constance located between Austria, Germany and Switzerland. Lake-effect snow is captured by modern cloud resolving high-resolution numerical models reasonably well, but is more difficult to represent in global numerical weather models due to coarse grid resolution and associated parameterisations.

5.6.2 Precipitation Phase

Humidity present in warm rising air condenses over cloud nuclei upon encountering adiabatic cooling or colder air in the vertical motion field. Depending on the thermodynamical forces present, the path of the hydrometeor can take many forms. In the upper regions of the cloud the droplets freeze and form ice crystals, within the cloud where more moisture is present the hydrometeors are typically a mix of ice and snow in the co-called Wegener-Bergeron-Findeisen (or cold-rain) process.

Depending on the temperature profile of the atmosphere, in the lower parts of the cloud the hydrometeors can fall into the ground in many forms. Precipitation can be e.g. ice pellets, snow, graupel, hail, snow, sleet (mixture of rain and snow) or water. If the surface on which the hydrometeors land on is below freezing, the supercooled water droplets can freeze on impact creating a layer of ice on the surface. Freezing rain, freezing drizzle or freezing fog can form via the cold-rain or warm-rain process or the deposition from water vapour to ice depending on the atmospheric conditions and the droplet size (See Figures 16 & 17). The main factor that determines the observed precipitation phase is the temperature profile, which in turn is a result of multiple factors such as frontal systems or advection. Freezing rain can turn runways into ice skating rinks when large amounts of water freeze in impact to form a sheet of clear ice on top of surfaces.

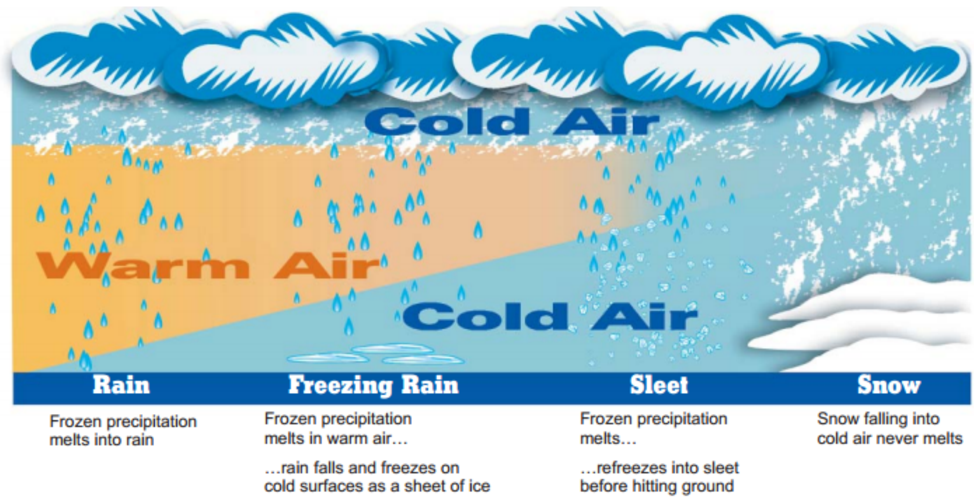

Figure 16: Winter precipitation types, source: http://www.weather.gov/grb/typesofwinterwx (link tested 30 Nov. 17)

Freezing precipitation in winter storms is the topic of a paper by Stewart and King (1987), depicting the typical structures and synoptic situation encountered during freezing precipitation events. Huffman and Norman (1988) describe the supercooled warm rain process of freezing rain and discusses the main predictors. The weather radar signature of a freezing rain event suggests a detectable pattern that can be used in nowcasting of the phenomena as proposed by Prater and Borho (1992). Further studies by Zerr (1997) present observational and theoretical aspects of freezing rain and provide some guidance for forecasting methods. An overview of freezing precipitation conditions in Europe including a climatological review is provided by Carriere et al. (2000). Three papers by Rauber et al. (2000, 2001a and 2001b) explore warm rain and melting processes in freezing precipitation, climatology of freezing precipitation based on sounding and synoptic analysis and a test of the Czys method. The study by Coleman and Marwitz (2002) explores a particular case in great detail. Rasmussen et al. (2002) studies freezing drizzle formation, Robbins and Cortinas (2002) look at the local and synoptic freezing rain environments, Changnon (2003) studies the effect of the urban heat island concluding that it reduces freezing-rain occurrences by 10-30% in the mid-latitudes, Jeck (2011) presents a detailed study of the characteristics of the associated low-ceiling, stratiform clouds in freezing-rain cases and Deng et al. (2012) focuses on freezing rain over Guizhou, China. A method using quasi-vertical profiles from a C-band weather radar in Vienna, Austria to detect and nowcast freezing rain is presented in a study by Kaltenboeck (2016).

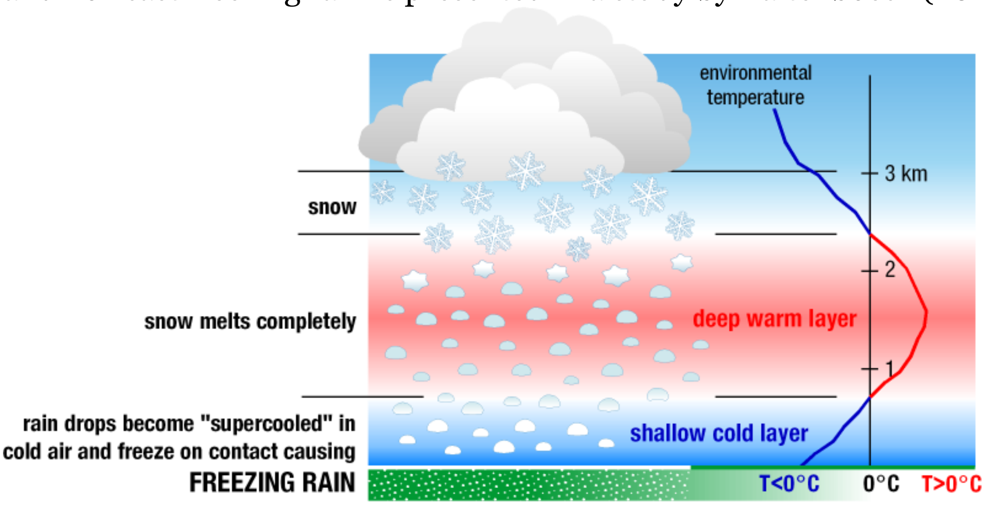

Figure 17: Freezing rain falls when snowflakes melt completely before reaching the surface, and refreeze upon contact with anything that is at or below 0°C, source: http://www.weather.gov/grb/typesofwinterwx (link tested 30 Nov. 17)

Several forecasting algorithms have been developed to forecast freezing precipitation. One of the first was developed by Ramer (1993) and it determines precipitation type using vertical profiles of pressure, temperature, relative humidity and wet-bulb temperature. The initial phase of precipitation is determined based on the wet-bulb temperature of the highest saturated level, which is assumed to be the precipitation generation zone. Ramer's algorithm determines a fraction of ice (I) at the ground using an empirically-derived relationship based on 2084 soundings from a variety of cool-season precipitation events. Another method developed by Baldwin et al. (1994) determines precipitation type from an observed vertical sounding. Warm and cold layers aloft are identified by calculating areas bounded by the 0°C isotherm and the sounding wet-bulb temperature (Tw). Warm and cold areas are calculated individually and are used in combination with surface temperature to identify precipitation type. The precipitation type diagnosis depends on the surface temperature, the coldest temperature in a saturated layer, and the magnitude of areas bounded by the sounding Tw curve and certain temperature thresholds. The method by Czys et al. (1996) depends on the ratio of the time that a sphere of ice resides in a warm layer (based on an empirically-derived particle size and terminal fall velocity and the average depth pressure and Tw of that layer) to the time it takes to achieve complete melting. The algorithm developed by Bourgouin (2000) determines if there is sufficient energy to melt or freeze hydrometeors. Positive and negative areas in the model sounding are computed, bounded by the 0ºC isotherm and the environmental temperature curve > 0ºC and < 0ºC, respectively. The precipitation type (snow, freezing rain, ice pellets, or rain) is determined by the magnitude of the positive and negative areas. A simple method applied for Japan is presented by Matsushita and Nishio (2008).

5.6.3 THUNDERSNOW, TRIGGERED LIGHTNING AND COLD-SEASON LIGHTNING STRIKES

The phenomenon of lightning during a snowstorm is sometimes referred to as a thundersnow event and an overview is given by Schultz and Vavrek (2009). In an earlier study by Schultz (1999) the relationship of lake-effect snow and lightning was explored. As noted by Crowe et al. (2006), thundersnow events are often accompanied by very heavy snowfall accumulation on the ground. An overall climatology over the US over a 30-year period is provided by Market et al. (2002) noting a peak of detection in March and an overall tendency of thundersnow to be associated with a transient mid-latitude cyclone, coastal cyclone, arctic front, lake-effect event or upslope flow. Events have been reported also in Southern Europe as documented by Bech et al. (2013) for Catalonia, Spain. Research by Kumjian and Deierling (2015) reveals in-depth details about these events, concluding that the thundersnow events are in general weaker, ordinary thunderstorms lacking any warm cloud depth.

The impact to aviation is specifically addressed in a study into cold-season induced lightning strikes in Finland Mäkelä et al. (2013), where it is noted that the events are hard to predict and often catch pilots, airlines and air traffic control by surprise. This creates a dangerous situation as many induced lightning hits have been reported in take-off corridors where the pilot has little options for avoidance of the electrified cloud and the cloud can be hard to detect.

Only a few forecast methods for airspace users to avoid electrified clouds in the cold season are available. A Model Output Statistics (MOS) based probabilistic method forecasting winter thunderstorms for Amsterdam Schiphol airport developed by the Royal Netherlands Meteorological Institute (KNMI) is presented in a paper by Slangen and Schmeits (2009). A study on the North Sea helicopter operations in the

United Kingdom is presented by Wilkinson et al. (2013) aiming at improving the safety of the North Sea oil operations' helicopter transfers.

6 ADVANCES IN METEOROLOGICAL INPUT FOR DECISION SUPPORT SYSTEMS

As has been discussed throughout this paper, weather plays a key role in everyday decisions made by air traffic controllers, airline operation centres, pilots, ground handling staff, etc. professionals working in air transport. Traditionally, weather information has been a separate product or information stream viewed from a stand-alone system and the interpretation of the impact of weather information has been accomplished by the human operator in charge of making the day-to-day decisions based on that information. With digitalisation and standards for data exchange, more and more weather information is becoming integrated into systems used for operational purposes (Rusu et al. 2012). The properties of a Decision Support System (**DSS**) were coined by Sprague Jr (1980) as follows:

- DSS tends to be aimed at the less well structured, underspecified problem that upper level managers typically face;
- DSS attempts to combine the use of models or analytic techniques with traditional data access and retrieval functions;
- DSS specifically focuses on features which make them easy to use by non-computer-proficient people in an interactive mode; and
- DSS emphasizes flexibility and adaptability to accommodate changes in the environment and the decision-making approach of the user.

Some of the very early implementations of DSSs were in the aviation industry with gate assignment for United Airlines. This example and a more comprehensive review of decision support systems is given in the book by Sharda et al. (2014). Since then, weather information has also been extensively deployed and integrated into DSSs especially in the US where airport capacity can be severely compromised in adverse weather.

6.1 AIRCRAFT DE-ICING OPERATIONS

Aircraft Ground De/Anti Icing procedures serve three purposes[51]: removal of any frozen or semi frozen moisture from critical external surfaces of an aircraft on the ground prior to flight; and/or, protection of those surfaces from the effects of such contaminant for the period between treatment and becoming airborne; and/or, removal of any frozen or semi frozen moisture from engine intakes and fan blades and protection of external surfaces from subsequent contamination prior to take-off. The prevailing weather conditions must be assessed, and if further adherence of contaminant to the airframe surfaces is currently occurring or anticipated prior to the time at which it is expected that the aircraft will get airborne, then a suitable ground anti-icing fluid should be applied.

The forecast of Liquid Water Equivalent (**LWE**) has proved useful since these values can be used to assist aviation de-icing decision-making activities. The Weather Support to De-icing Decision Making (WSDDM) system provides LWE nowcasts and is in operational use at several major airports in the US.

This operational decision support system to support aircraft de-icing operations was developed by NCAR for Denver, Chicago and New York LaGuardia airports based in high temporal resolution observation of liquid equivalent snowfall rate at the airport to provide guidance for de-icing crews in a simple color-coded manner as reported by Rasmussen et al. (2001). The application of liquid water equivalent estimations from weather radar has since been shown Ruzanski and Chandrasekar (2012) to improve accuracy by 14% in Colorado, US and reduce runtime for the nowcasts.

6.2 AIRPORT CAPACITY

The factors considered by an airport capacity model to accurately depict capacity of an operational airport include in the case of the Integrated Airport Capacity Model (IACM) (Kicinger et al. 2011) weather forecasts, predicted demand, airport adaptation and operational standards and procedures as input information to a model that has modules for terminal capacity, runway configuration, runway capacity and a forecast integrator to output the estimated probability of achieving a set capacity value. Weather constraints play a large role in this consideration and more intelligent weather considerations have been recently developed by

[51] http://www.skybrary.aero/index.php/Aircraft_Ground_De/Anti-Icing (link tested 30 Nov. 17)

Kicinger et al. (2016). A typical runway can handle roughly 30 aircraft taking off and/or landing in an hour and in cases such as the San Francisco International Airport, low cloud will immediately reduce this capacity by half by disabling the second parallel runway due to runway separation minimum requirements under Instrument Landing System (**ILS**) conditions from 60 to around 30 flights per hour. Strong crosswinds will typically disable some runway configurations as will thunderstorms at approach sectors. Therefore, correctly forecasting weather parameters and integrating them to airport management tools allows for the air traffic controllers to develop a holistic view of the evolution of an airport capacity.

Research by Smith et al. (2008) takes the Terminal Aerodrome Forecast (TAF) and uses support vector machines to predict future airport capacity at the most constrained US airports affecting the performance of the national airspace system. The Paper by Klein et al. (2009) presents a calculation of arrival delays and cancellations due to terminal weather forecast inaccuracy at airports, concluding that a financial benefit of $330 million would be gained by improving the accuracy of terminal weather forecasts at the 35 busiest[52] airports in the US. The paper by Hunter (2010) describes an approach to use both air traffic management and meteorological data to model the impact of weather on airport capacity. The airport delay predictor model developed by Klein (2010) can also be used as a decision support tool and to evaluate different weather forecast products. A runway resource allocation model using quantified forecast accuracy information to calculate the probability that a runway satisfies safety constraints given the predicted wind, ceiling and visibility is presented by Li and Clarke (2010). Work related to the SESAR programme by Barbaresco et al. (2011) discusses a more dynamical wake vortex separation based on current meteorological conditions to optimise runway throughput and reduce delays. The impact of weather on airport capacity is explored using ensemble learning with the bagging decision tree statistical method in the paper by Wang (2011).

An airport-specific decision support system directly associated with weather, specifically low marine stratus is presented by Reynolds et al. (2012) for San Francisco International Airport (SFO) summertime operations, aiming to directly forecast the timing of the stratus situation that leads to the loss of the second parallel runway from operations due to the low separation between the runways. This system has been in operational use since 2004 and since 2008, following changes to the FAA ground delay programme, it has provided quantifiable reductions in ground and airborne holds at SFO.

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[52] http://aspmhelp.faa.gov/index.php/OEP_35 (link tested 30 Nov. 17)

6.3 Route planning

The study by Evans (2001) proposes a system for the US where re-routes and, routes for near term departures are frequently revised based on automatically generated storm predictions coupled to traffic flow and traffic conflict decision support systems with review and very limited swapping of routes by pilots and airline dispatch. The FAA funded Corridor Integrated Weather System (CIWS) design, development and validation results are described by Klingle-Wilson and Evans (2005). In a later paper by Evans and Ducot (2006), the benefits and operational implementation are discussed and it is concluded that the CIWS enables the FAA users to achieve more efficient tactical use of the airspace, reduce traffic manager workload, and significantly reduce delays. The maximum flow rates for capacity estimation in level flight with convective weather constraints are discussed by Krozel et al. (2007). Research and development of the DIVMET model to identify weather avoidance routes to Hong Kong airport is presented by Sauer et al. (2016) illustrating that the impact of weather can be quantified in terms of object avoidance patterns for approaching aircraft. MIT Lincoln Laboratory has developed a decision support tool to help air traffic managers to determine when to close and reopen departure routes during periods of convective weather called the Route Availability Planning Tool (RAPT) (DeLaura 2012) that has made a big impact on airspace management. It indicates on a colour scale the level of blockage imposed by weather on specific routes.

7 Future challenges for aeronautical meteorological research

Meteorology is an exact science, but nonetheless weather forecasts will never become perfect due to imperfect global areal and temporal coverage of ground observations and computing limitations on numerical modelling. Furthermore, air transport will never be completely risk-free. With those two notions in mind, there remains a great deal of research and development work to be done to make the information better and ensure that the better information leads to better decisions down the line. Weather forecasting for air transport will continue to be driven by technological advances along the roadmap painted in Section 4.1 and aircraft will become more connected to real-time information. The crucial question will be exactly what information is useful to the pilot, the airline, the air traffic controller or the de-icing manager and how the weather information integrates to the decision support systems. Future challenges call for a strong effort between meteorological data providers and end users to come together to define the next generation of global standards in an interconnected world. Airspace users must also be awakened to the reality that there is much more, better and suitable information available for their needs than the currently provided WAFC maps, METARs, TAFs and SIGMETs. This may require rigorous cost-benefit analyses, but more than anything it will require the consolidation of effort between the meteorological service providers and adequate funding to support these ends.

From the science perspective, our numerical modelling skill will continue to improve through improved representation of physical processes in the models and ensemble methods, new weather satellites will challenge weather radars in the resolution of precipitation observation leading to very accurate observations of global precipitation patterns, weather radars will be able to better classify hydrometeors linking to nowcasting systems, and localised parameter-specific methods tailored to Terminal Manoeuvre Areas will better identify potential hazards for aviation. Scientific advances are incremental and slow, and given the few current research and development funding opportunities for aeronautical meteorological research the field is most likely to follow the overall trends of meteorological research. The role of the aeronautical weather forecaster in the forecasting process is likely to experience the largest change. When looking at the ability of human forecasters to improve quantitative precipitation forecasts (**QPF**s), improvements are accomplished through pattern recognition, physical realism, awareness of model biases and past model performance, run-to-run consistency, collaboration, and consensus as presented by Novak et al. (2011).

The aim of this chapter is to explore the risk reduction potential of improved weather services for aviation by looking into the open research questions and decision support systems, focusing on the process needed to enable these improvements result in improved safety and cost-efficiency. The sub-chapters can be viewed as presenting potential milestones or Key Performance Areas (**KPA**s) for a research and development project with the aim of highlighting the interplay between end user needs, systems and meteorological service provision.

7.1 Improving Terminal Manoeuvring Area wind forecast accuracy

The first example to be presented involves an input source to airport capacity estimation systems and runway configuration decision support tools. Wind speed and direction between surface and 3000 ft (1 km) is typically critical in the selection of the used runway configuration which in turn directly affects the capacity of the airport. While current numerical weather models generally perform quite well in wind forecasts, airports situated near e.g. orographic features or large bodies of water (or both) are still difficult to forecast accurately. Improvements in the four-dimensional field of wind speed and direction, where the fourth dimension is time, have the potential to improve the capacity management of an airport. Motivation for this case study comes from the special role played by the 3000 ft wind at Heathrow Airport, impacting the capacity of the runways and thus the airport for traffic. This in turn can divert flights to other nearby airports, delay or even cancel flights causing a ripple effect across the European airspace.

Figure 18 is a schematic representation of a development process in collaboration with the end user to achieve reduced holdover time leading to reduced fuel burn and reduced arrival and departure delay caused by an airspace restriction procedure. A development initiative must take into account the exact preconditions of the airport and surrounding terminal manoeuvring area and must have detailed information of the systems and processes in place at that airport for runway configuration allocation and airport capacity restrictions. The local history of wind-induced airport capacity restrictions should be established as a base line to determine the benefits of the introduced improvements. This can be achieved in a way of a feasibility study providing a solid justification for the project including the aforementioned actions.

The following actions form a meteorological research and development component where the focus is to improve the resolution of the four-dimensional wind grid. The underlying assumption here is that such an improved model resolution would in turn provide a higher quality wind assessment. This may not always be the case, especially where the wind climatology is typically easy to predict and less prone to external forcing. Here the question of return on investment must be weighed against the added cost of additional computing time required to run a higher resolution numerical model. The potential added value must be established together with the local customer and end user. Added value is typically hard to define, but such an exercise will develop mutual understanding of the operating environment. Simply changing model resolution without due diligence on the effect on a multitude of parameterisations involved could actually result in a loss of skill in the forecast model. Therefore, the change must be verified properly and all other meteorological parameters must also be considered. In the end, the assumption is that a higher model resolution will be able to better forecast changes in circulation in the atmospheric boundary layer and take finer scale local phenomena into account, such as sea breezes, orographic flows and inflow/outflow areas of convective systems. A comprehensive verification exercise against earlier model results and observations resulting in a technical report outlining the performed changes with the associated verification results should be a required step in any project to enable the spread of best practices and scientific findings.

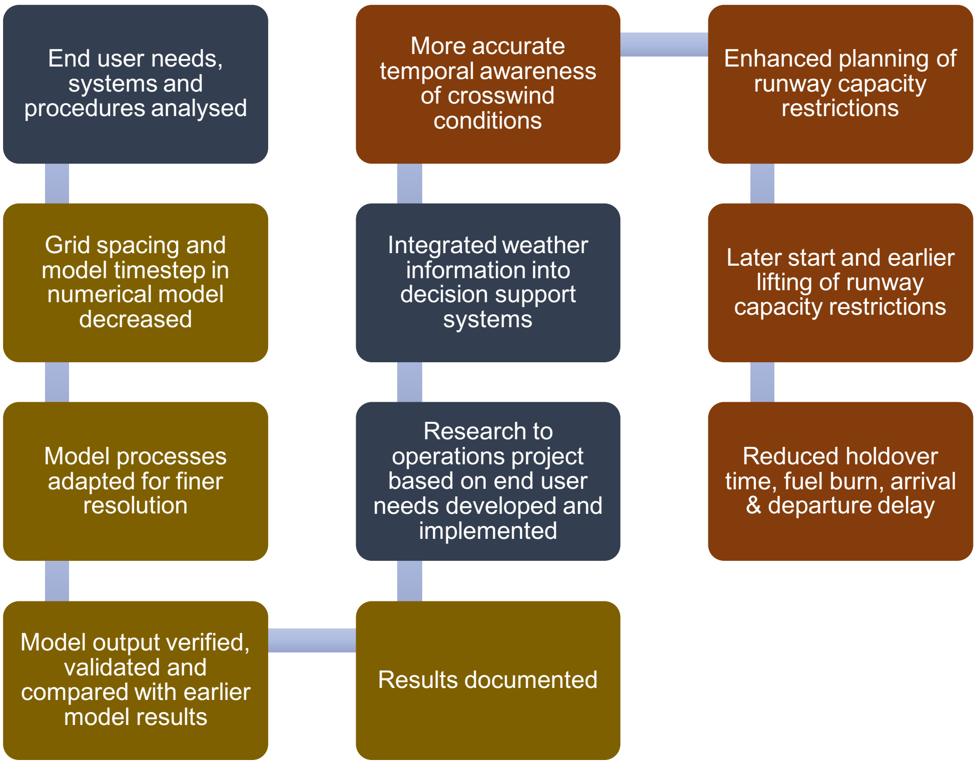

Figure 18: Schematic representation of the required steps leading to improved Terminal Manoeuvring Area wind service for aviation. Meteorological components indicated in brown and added value in dark red background colour.

Following the meteorological development phase, a research to operations project must be established taking into account the findings and confidence in the improved forecast information. The information in itself is not useful unless it has an impact on the behaviour of the end users using the information. The optimal use of the meteorological information is ensured by integration into the proper decision-making systems and processes. An airport might, for example, use a system such as the ones described in section 6.2. If such a system has already been in use, the project must clearly communicate the changes in the new data stream and what the user can expect to see based on the new information. If no such decision support system is in place where meteorological information is directly inputted, the project must establish the methods by which the improved meteorological information is to be used by the end user. What should be avoided at all cost, is to keep any existing arrangements whereby a meteorological service provider issues a text-based wind forecast to a single point at the airport to be used by e.g. the air traffic control. As a minimum, the end product should interpret the meteorological conditions as actionable information to the end user based on their pre-defined criteria, such as cross-wind maxima at certain runway configurations given in a color-coded graphical product.

The expected positive impact on the operations of the airport will result from the optimal use of the provided decision support by the human operators. The underlying assumption is that the improved wind field will result in more temporally accurate, and thus efficient, runway configurations as demonstrated by e.g. Météo-France using a 100 m grid resolution for Paris CDG airport. Restrictions could actually increase as a result, but this would lead to reduced holdovers for incoming air traffic and hence reduced fuel burn and arrival delay. The optimal situation for all concerned entities is for the aircraft and passengers to be able to complete the flight with minimal disruptions and for the additional wait to happen at the terminal.

7.2 Impact of improved turbulence guidance for airspace users

The second example in this chapter focuses on a quite different use case altogether for meteorological information. As has been described earlier in this study, turbulence is one of the major meteorological hazards for air traffic. As a meteorological phenomenon, turbulence is in itself somewhat elusive and can be difficult to forecast accurately. Since turbulence is not a general societal weather hazard in the sense of severe convection for example, the research and development of solutions was started rather late and the solutions are really only developed for air transport users and typically mostly verified against aircraft or pilot observations. There are no direct systematic observations of turbulence and the field relies on the aircraft observations. In many senses turbulence research and development should be raised higher in the priority of meteorological services providers and not left only to the responsibility of World Area Forecast Centres (WAFCs).

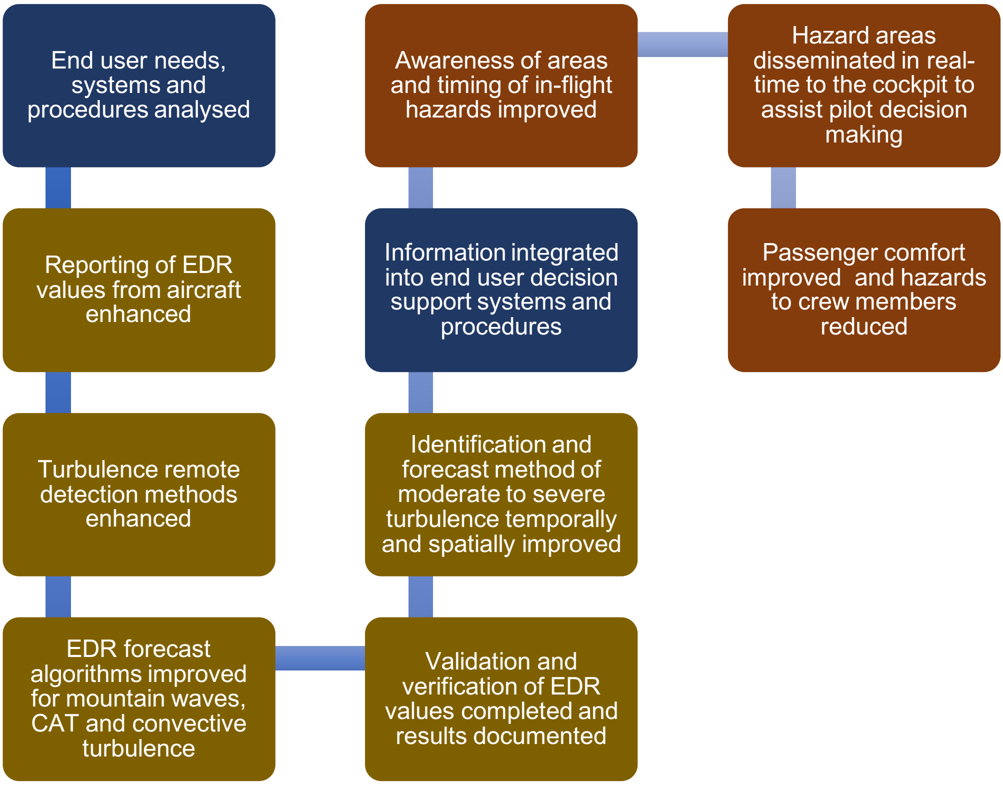

Figure 19: Schematic representation of the required steps leading to improved in-flight turbulence service for aviation. Meteorological components indicated in dark brown and added value in dark red background colour.

Motivation for this case study can be drawn from incidents such as the recently reported (The Guardian, CNN, Daily Mail, Aviation Herald[53], etc.) encounter with severe turbulence by the Aeroflot flight SU270 from Moscow to Bangkok on 1 May 2017 in Myanmar airspace which left 27 injured and sent 25 to the hospital. In this case, the media reports state the cause to be Clear Air Turbulence (CAT) and note that the on-board weather radar had not picked up any signal of severe weather. The pilots were thus unaware of the hazardous circumstances which they entered. The question remains whether or not this turbulence could have been detected or forecasted at all. Via personal communication with the turbulence researchers at the National Center for Atmospheric Research (NCAR), the

[53] http://avherald.com/h?article=4a861a24 (link tested 30 Nov. 17)

general opinion is that the turbulence in question was associated with severe convection also supported by the CIMSS Satellite Blog[54] which tracked the flight path on top of a rapidly developing thunderstorm. This raises the opportunity to improve the avoidance of such severe turbulence cases by ensuring the pilots have the right information in the cockpit during the flight. This would require the turbulence areas to be detected, classified and forecasted and then transmitted rapidly to the cockpit for the pilots to review. This could turn out to not have been sufficient in the case of this flight since the thunderstorm developed rapidly directly in the flight path of the airplane, but this risk should have been possible to identify from a numerical weather prediction forecast.

An outline of a possible research and development initiative is given in Figure 19. The process for end user needs analysis and process review described in the beginning of section 7.1 essentially holds true for turbulence guidance as well. Otherwise, the development of a service whereby the risk of moderate to severe turbulence is accurately analysed, forecasted and disseminated to the cockpit is very different from the previous example. A critical question becomes what are the policies regarding datalink to the cockpit, what systems are in use, if an existing Electronic Flight Bag (EFB) provider is willing or able to accommodate new weather information or if there is another way of providing the service to the airplane. These policies will be airline specific and will depend on the available technologies. The pilots will also have to be willing and able to use the information provided to them and should thus be consulted from the very onset of the project all the way to the final end solution.

The meteorological project (Figure 19, brown boxes) requires a reliable input against which any new forecast method would be verified. All modern regional aircrafts are equipped with a number of sensors that measure parameters that can be combined to enhance the current automated reporting of turbulence metrics from the aircraft. Especially the EDR values are of critical importance to be recorded at good temporal resolution throughout the flight and ideally downlinked to ground stations for assimilation into weather forecast models. The airlines should be engaged to help realise the value of open real-time data exchange and the associated improvements in the meteorological services. The second important issue related to forecasting turbulence is an accurate areal and temporal analysis of current icing conditions. The aircraft-derived EDR observations are naturally a key element in this, but traditional PIREPs and meteorological remote sensing methods such as weather radar and satellite information should also be used in providing the added coverage. Especially geostationary weather satellites can be used to identify

[54] http://cimss.ssec.wisc.edu/goes/blog/archives/23875 (link tested 30 Nov. 17)

convective areas and statistical methods can be used to calibrate the satellite-based observations with turbulence observations to give a more accurate interpretation of cloud top temperature to turbulence measures.

The improved analysis of turbulence can then be used as a verification field in the development of numerical turbulence guidance methods. Current geographical resolution in turbulence guidance is typically very coarse and can easily omit smaller convective situations leading to a loss in forecast skill. Mountain waves require an accurate depiction of orography and a numerical model structure which follows the surface in mountainous regions. Cloud-resolving models and improved turbulence parameterisation can bring improvements in the representation of convective initiation and resulting convection. The verification and validation of new turbulence algorithms against improved observations of turbulence should result in a substantial increase in forecast skill. Since several turbulence metrics are available in literature and since it has been shown by Sharman and Pearson (2017) that a weighted multi-algorithm approach for each specific turbulence criteria provides the best forecast results, perhaps the best approach for turbulence forecasting is given in figure 1 of Pearson and Sharman (2017) where a turbulence nowcast 3D grid takes input from the turbulence EDR forecast model, airborne real-time turbulence observations, ground-based radar observations, inferred turbulence from convective induced turbulence detection methods, METAR winds, Aircraft Situation Display to Industry (ASDI), ADS-B deviations and satellite features to output a turbulence nowcast product to users.

Once the information has been integrated into the decision support tools of the customer and an uplink to the cockpit establishes, the pilot can have at his/her disposal an effective tool for the avoidance of turbulence areas. Airline company policies dictate as to what information is given to the pilot and hence this step is under the responsibility of the airline, but demonstrations of such service provision to Lufthansa pilots for trans-Atlantic flights already exists with good results. A company promise to customers and crew members for a smoother and safer flight should be a substantial competitive advantage not yet seized by most of world’s leading airlines.

7.3 IMPROVING DATA DISSEMINATION OF CONVECTIVE WEATHER TO THE COCKPIT

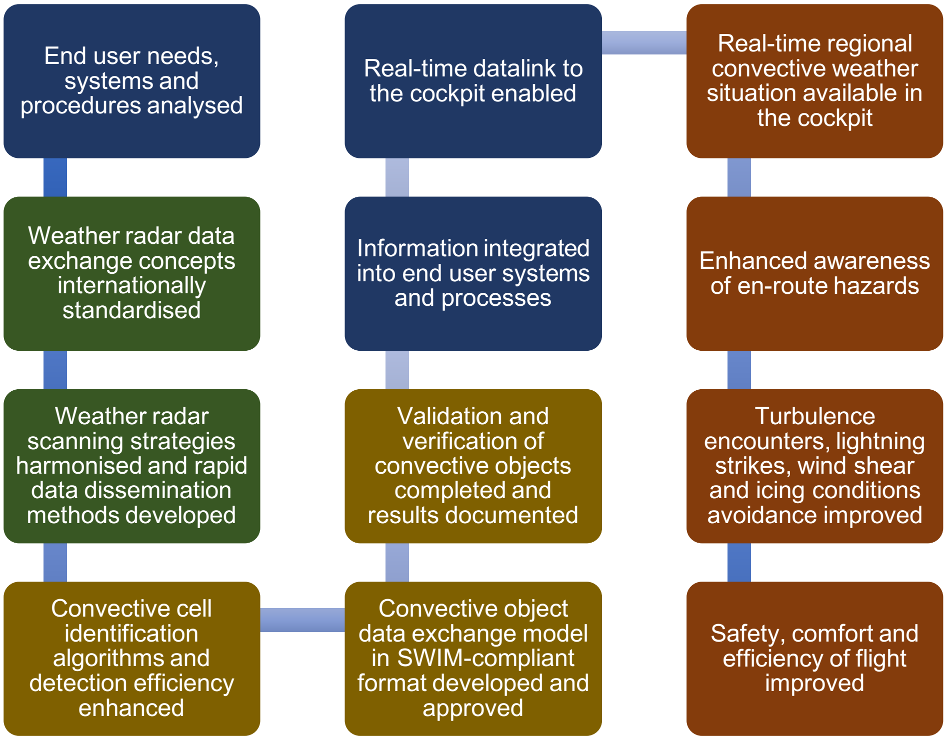

Figure 20 Schematic representation of the required steps leading to improved convective weather in-flight situational awareness for aviation. Boxes shaded with dark green indicate international data cooperation steps, dark brown boxes the meteorological development issues and dark red the added value to the end user.

Many technical parts of a development towards enhanced convection information in the cockpit are similar to turbulence development described in the previous section. Especially the dissemination of information to cockpit deserves the same remarks as before. Observation and forecasting of convection at a regional scale has its own challenges outside the USA, where no single actor collects, processes and disseminated the observations to the end users. In Europe, for instance, a great deal of effort is required to enable real-time exchange of weather radar information, which is the primary tool for convection observations and nowcasting. Therefore, this section highlights a different challenge in the research and development of weather information to air transport related to observations and data exchange (see Figure 20).

Following a comprehensive end user analysis, an assessment of the benefits of convection avoidance and the information required to enable convection avoidance behaviour, the enabling procedures for regional convection analysis and detection are to be established. The European Network of National Meteorological Services (**EUMETNET**) has established the Operational Weather Radar Information Exchange (**OPERA**) Programme to enable the creation of a European-wide weather radar mosaic image similar to the NEXRAD national composite in the US. The European mosaic product is typically a maximum radar reflectivity product where the maximum reflectivity in each grid point is collected from the network of radar and combined into a single image.

Weather radar data exchange would be very important in South America, Asia and the Middle East and a regional product would be of tremendous value in these regions. In the African continent, weather radars are relatively sparse and without a major effort to increase coverage, only small portions of the continent will be covered by a regional composite. Nevertheless, exchange standards and cooperation efforts should be started in these regions that often experience severe convection. Especially Asian air traffic volumes are growing fast and convection is present almost throughout the year.

Standard convective cell detection algorithms for the specific use of convection avoidance by air traffic are available and an international consensus should be reached in line with the acceptance of EDR as the turbulence metric. Such a standard convection identification and tracking across the globe would enable airspace users to have confidence in the convection nowcasts and ensure that they are consistent and harmonised across regions. Radar technology limitation may inhibit the use of such algorithms, but a lower technology option such as maximum reflectivity could serve as a backup. Taking into account the fact that not all countries in the world are in the position to process weather radar information in a way to extract convective cells, this task should be given to a regional weather radar processing centre with funding from the airspace users. The central processing of lightning detection information would also add tremendous value to the aviation weather products and a central processing function for both radar and lightning information should be combined. In data sparse areas, lightning information can provide valuable information complementing both radar and satellite sources. Efforts should be directed in opening the lightning detection data for all meteorological purposes.

Once the areas of convective weather are available as a regional product from the national weather radars, this information needs to be converted into a SWIM-compliant data format as a GML georeferenced weather object. Such objects are easy and simple to exchange and transmit to the cockpit for integration into EFBs and air traffic management systems. The convective weather object definition and model should be internationally standardised and approved by WMO and/or ICAO. Finally, an industrial validation should be carried out for the information to ensure global interoperability between providers and end users. The integration into cockpit and data exchange methods follow what has been said earlier for turbulence.

The availability of convective weather hazards information in the cockpit will allow for better avoidance of lightning strikes and icing in addition to turbulence. When the information is available to the pilot and air traffic control in real time and not only in the flight planning phase, the flight paths can be optimised earlier with fewer detours and shorter deviations from an optimal flight path. This will in turn result in a shorter route and less fuel consumed when compared to a situation where the pilot simply reacts to the weather hazard along the flight path.

7.4 Enhanced liquid water equivalent forecast to de-icing operations

Winter conditions have multiple consequences for airport operations and air traffic management. The general process of improving meteorological forecast information to end user described in the previous chapters applies to many winter conditions as well and is given in Figure 21. Low visibility and ceiling associated with winter weather patterns is one of the most difficult challenges for numerical weather prediction model algorithms to solve as has been discussed in previous chapters. However, visibility and ceiling are present in the forecast throughout the year and remain year-round challenges. In order to highlight a forecast challenge specific to winter, the case of aircraft de-icing is presented here.

The phrases de-icing and anti-icing are used to describe the two different steps associated. By definition de-icing refers to the removal of ice from the airframe before the flight while anti-icing refers to the process of applying fluids to the airframe to prevent further ice to develop before the take-off. This distinction is often not made everywhere and de-icing refers to both processes where the airframe is cleared and fluid applied at the same operation in a holding position before take-off.

The application of de-icing fluids is expensive (fluid cost $4-6/litre with total cost of $1500 to $25000/airplane), labour intensive and adds a delay to the flight duration for the passenger. The process is only needed in certain weather conditions and thus the de-icing crew needs to be called in only for those days when de-icing is performed. The holdover times and procedures associated with the fluids applied to the airframe are standardised by the Society of Automobile Engineers (**SAE**) and the de-icing/anti-icing operations mandated by ICAO Annex 6 and Annex 16[55]. The fluids fall under four classes (Type I, II, III & IV) depending on their effectiveness in given atmospheric conditions (temperature, type of precipitation and rate of precipitation) and the holdover times vary from a few minutes to several hours.

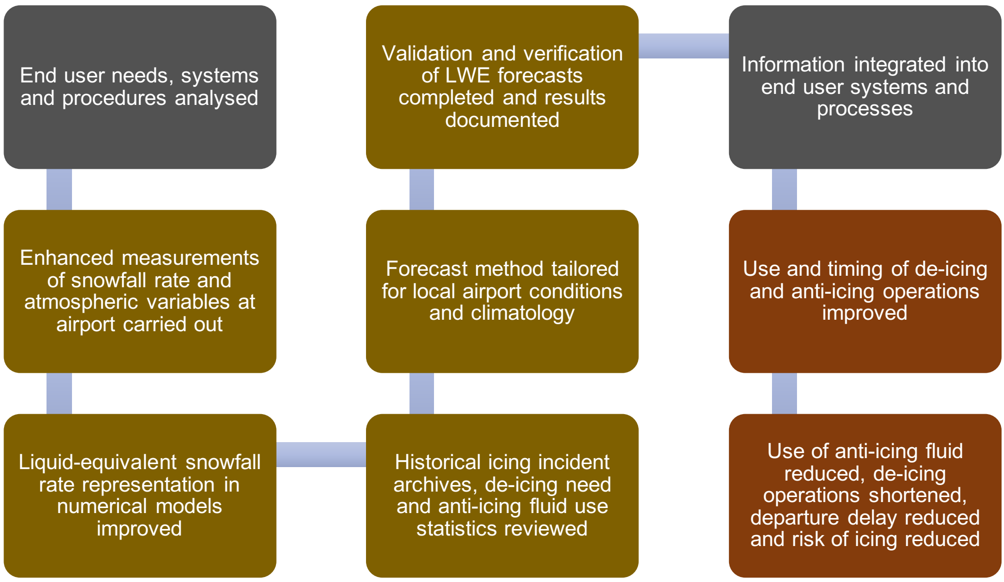

Figure 21: Schematic representation of the required steps leading to improved de-icing and anti-icing service for aviation. Brown shading indicates meteorological development milestones and red shading the added value for end users.

The first forecasting challenge for de-icing operations is the advance planning required by the ground handling companies to ensure adequate resources are deployed at the airport when de-icing is called by the pilots. With too little advance warning, the de-icing crew needs to be called in within hours' notice, they need to be paid more to be available on short notice and they may not make it to the airport on time since other transport modes might also be affected by adverse weather. For this purpose, ground companies need forecasts of snow or freezing precipitation 2-5 days out and a general indication of peak intensity during the day in question. A probabilistic approach tailored to the end users' operational thresholds could be very useful as this also contains information about the forecast

[55] https://www.icao.int/safety/airnavigation/OPS/Pages/Aircraft-Ground-De-IcingAnti-Icing-Operations.aspx (link tested 30 Nov. 17)

confidence. The second forecasting challenge is the nowcast (0-6h) of precipitation type and intensity, which is needed during the application of the anti-icing fluids. The ground handling companies can use this information to have a nowcast of the de-icing fluids to be used using the meteorological information converted directly into fluid type forecasts. For the aircraft pilots, the holdover time tables (**HOT**) can be replaced by real-time observations on the ground to improve the accuracy provided in the HOTs, such as the NCAR WSDDM algorithm.

The meteorological development project should start by ensuring high quality observation data is available at and around the airport. Freezing detection sensors and dual-polarimetric weather radar data are especially useful to provide reliable information on the precipitation type and intensity. Measurement history will provide the base line for future development of meteorological algorithms. This base line should then be used to enhance the parameterisation and representation of liquid water equivalent (LWE) which is an excellent proxy for de-icing need for an airframe both in the nowcasting timeframe and medium-range planning.

A statistical approach using a history of de-icing fluid use and de-icing need will help in calibrating the forecast accurately to previous incidents, will improve accuracy and reduce bias. The past realised de-icing operation data requires for good cooperation with the ground handling companies and such a project in general can only be realised in close collaboration from the start. With the observation and de-icing climatology available, the forecast method can be tailored for the airport in question with the required accuracy. The actual forecasts should then be verified against true de-icing operations at the airport in question to ensure of the usability of the product. A successful project will result in an all-round more efficient de-icing process and less take-off delay for the passengers.

7.5 Detailed no-fly zones for rotorcraft and RPAS operators

Helicopters are especially useful in operations where landing needs to take place into any terrain and where hovering is required. The most important applications to society are associated with search and rescue, police and border patrol and emergency medical services. These missions typically need to take place also in adverse weather and often without ground observations on the meteorological conditions. At the same time, helicopters are very susceptible to icing, low visibility and cloud base height and cannot withstand a lightning strike. The operating constraints imposed by meteorological conditions are much stricter than with commercial jetliners. As the size of the aircraft decreases going into Remotely Piloted Aircraft Systems (RPAS), weather resilience decreases and ever stricter meteorological restrictions apply. As has been mentioned earlier, small RPAS can generally only fly in optimal weather conditions.

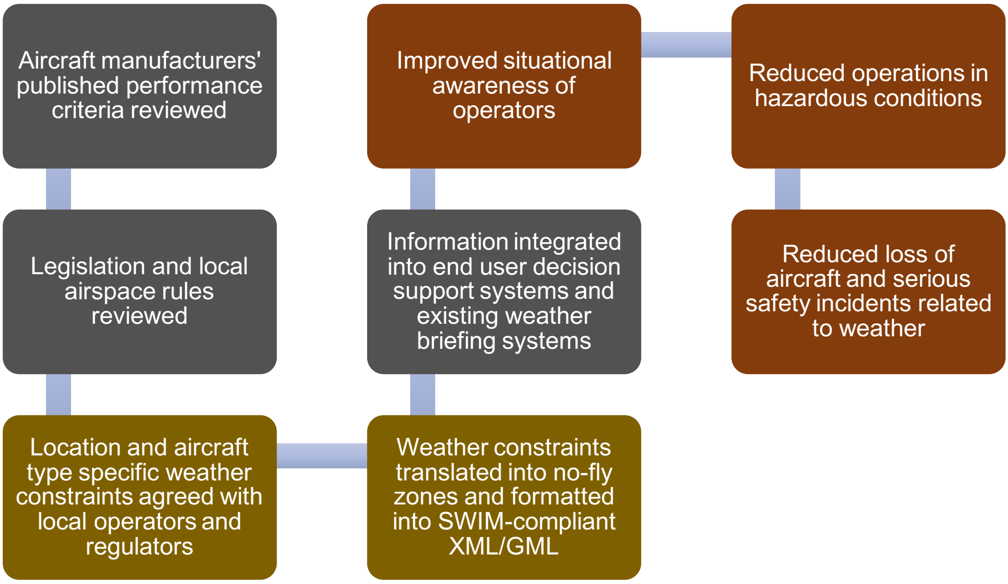

Figure 22: Schematic representation of the required steps leading to no-fly zones for rotorcraft and RPAS operators. Brown shading indicates meteorological development milestones and red shading the added value for end users.

Both helicopters and RPAS manufacturers publish tolerances for meteorological conditions and these can be combined with the pilots' guidelines on safe flight and operator policies to create meteorological operating constraints specific to the aircraft and operator. In essence, the question becomes more about the visualisation of meteorological information and providing a decision support service tailored to the user needs taking into account also the national legislation and local airspace regulation.

The meteorological development project needed to achieve the decision support capability would benefit from all of the other actions described in this chapter (see Figure 22). The main task is to translate the operational requirements into weather parameters and then back into impacts. The dissemination of impacts could be given as simple areas with horizontal, vertical and temporal extent where the operator in question should not fly with a given type of aircraft. This information is to be disseminated complying to the SWIM standards using the generally accepted GML data formats. The relevant meteorological parameters depend on the definition of operational boundaries and should generally be available from a regional limited area model.

While helicopter pilot licences require training on weather impacts on operation, RPAS operators do not generally require any formal training and in many nations a pilot licence is also not required. This can lead to lack of awareness on safe operating conditions and for this reason the service to provide information on safe flying environments should be made easily and freely available to all. With adequate training and awareness, and where needed regulations, on the weather information made available to operators, safety of flight is improved both in terms of aircraft, crew and equipment.

SIGMET is the closest equivalent of a product needed for RPAS operators. SIGMET could be altered in a way to be adaptive to the aircraft type or use the strictest rules for small RPAS. However, the product should not be in the traditional alphanumeric format since this would be illegible to most operators but rather be a visual product in line with a Significant weather chart. Such a chart could include permanently restricted areas for RPAS flight and be automatically generated. Most RPAS manufacturers include the ability for *geofencing* their equipment via hardware configurations to inhibit their flight into restricted airspace. Ideally, such technology could be used to generate a *weather-geofence* to inhibit flight into areas of significant weather determined by international standards.

7.6 Weather constraints translated to effective decision support products for Air Traffic Management

Examples of efficient decision support tools for air traffic flow management have been given earlier in this study and the aim of this chapter is to highlight the best parts of these applications to promote the research and development of more integrated weather input to air traffic management systems. Figure 23 gives a schematic representation of a development initiative for improving the integration of meteorological information into decision support systems. The professionals involved with air traffic management, especially air traffic controllers, are operating under tremendous stress and have very little time to ingest new information concerning a weather constraint. Instead, meteorological information needs to be a parameter in the various algorithms providing decision support tools for the controllers. The change from looking at meteorological information separately to full integration will reduce the awareness of the particular weather situation at hand, but will ensure that weather is taken into account in a systematic way in decisions and that no end users can overlook weather constraints.

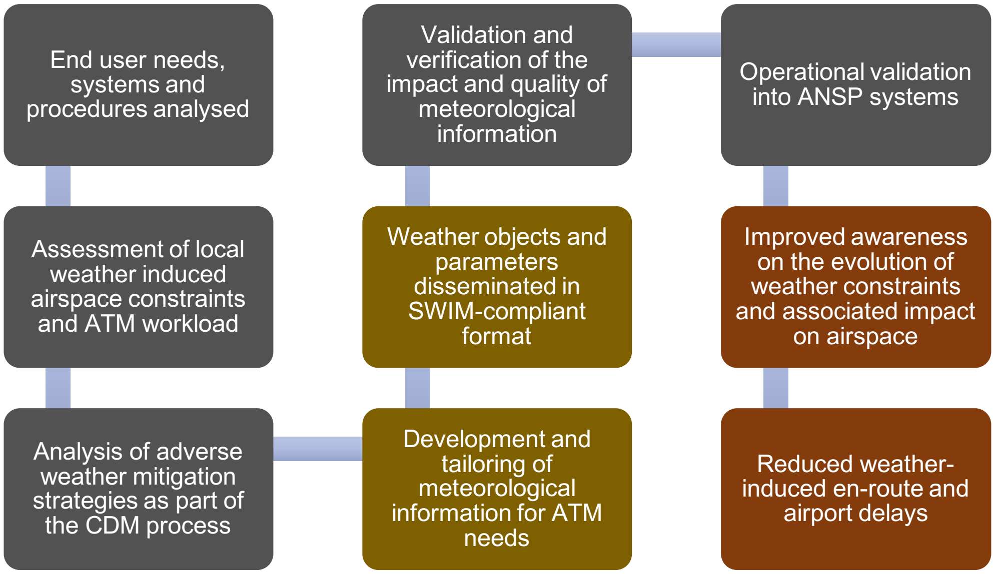

Figure 23: Schematic representation of the required steps leading to improved consideration of weather impacts on air traffic management. Brown shading indicates meteorological development milestones and red shading the added value for end users.

In ATM support efforts, the exact quantification of impacts by weather becomes a key priority. Impact analysis requires access to historical performance data where correlations to specific meteorological parameters can be established with various statistical methods. The mitigation strategies need to also be very clearly defined when an algorithm is deployed to provide decision support, e.g. the process of what is the optimal runway configuration with 25 kt wind from the East and what capacity effect it has or how much capacity is reduced when visibility is below 1000/3000/5000 ft should be clearly known when developing support systems. One such example mentioned earlier in this study is the Integrated Airport Capacity Model by Kicinger et al. (2016) with a functional scheme given in Figure 24.

The IACM model uses weather forecast information for runway configuration and capacity estimation along with a host of other information sources. The end user only sees the hourly airport capacity forecast for each runway configuration and can make decisions based on that information rather than looking at each individual variable and forming the picture in their head. Such decision support systems have tremendous potential for airport and airspace management. Meteorological information is not yet used in all decision support systems even though weather plays a crucial role in operations. An open and transparent exchange of such systems and the development of international best practices could greatly enhance these services for air traffic management. The forecasted capacity should also be continuously verified against true capacity and forecast skill and bias examined regularly to ensure of the quality of the forecast. Organisations such as the Network Manager in the EU would benefit from having a forecasted capacity situation from all European airports available at any given moment.

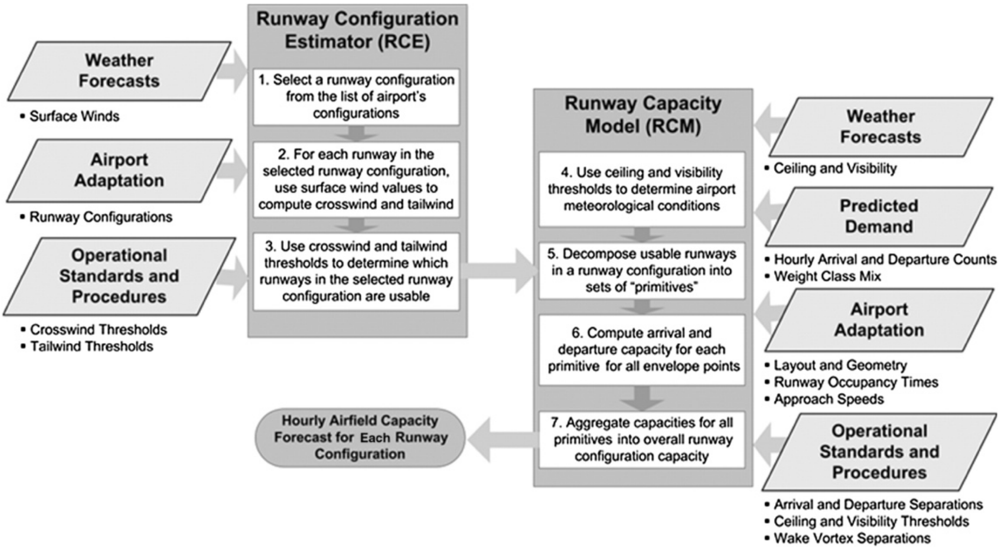

Figure 24: Schematic representation of the Integrated Airport Capacity Model (IACM) from Kicinger et al. (2016).

Ultimately, accurate meteorological information in collaboration with other information sources should lead to improved situational awareness at airport and airspace management level and hence result in better utilization of airport and airspace capacity leading to less delays for airlines and passengers. It should be noted that for large and severe weather hazards, no mitigation action can prevent airspace and runway closures, but decision support system can provide an accurate forecast of return to full capacity or a forecast of onset of reduced capacity.

7.7 SUPER HIGH RESOLUTION NUMERICAL WEATHER PREDICTION MODELS FOR AIRPORT DOMAINS

Terrain disrupted airflow and phenomena affected by orography such as fog and low-level wind shear cannot be accurately depicted in global models and thus require statistical methods and the increase in horizontal and vertical resolution of the model to improve the representation of phenomena important for aviation weather forecasting. Examples of the implementation of dedicated super high-resolution models are found in Hong Kong as presented by Chan and Hon (2016) where The Aviation Model (AVM) with up to 200 m spatial resolution is deployed to account for the complex terrain at the airport and to especially account for the complex winds in and around the airport terminal manoeuvring area. The UK Met Office has deployed a 333 m spatial resolution model (The London Model) and the improvements into the local representation of fog and the stable boundary layer are documented by Boutle et al. (2016). At Paris Charles de Gaulle airport, a super high resolution AROME Airport model operating at 500 m spatial resolution is deployed with the specific aim of improving wake vortex forecasts also associated with Time Based Separation operations at the busy airport. The results are reported by Hagelin et al. (2014) and a clear improvement in wind speed and direction is noted.

The research, development and operational deployment of super high resolution numerical models is not a simple task and is usually carried out to address a specific operational requirement at an airport. They have been demonstrated to add value and to tackle forecasting phenomena otherwise difficult to numerically predict accurately. Such a project should be weighed by the added value provided and the cost of such a project. Consideration should also be given to increasing the temporal resolution of limited area models by increasing the data assimilation and update cycle of the model. Nowcast models have been discussed in Section 3.1 of this thesis and there are much more examples of rapid update cycle models than super high-resolution models potentially due to easier implementation and lower computational cost. Increases in the spatial and temporal resolution of numerical weather prediction models serve to especially improve aviation weather forecasting due to the nature of aviation operations at airports and the sensitivity to small-scale phenomena and thus the increased resolution in models is highly recommended to be undertaken by meteorological service providers. A process with key performance areas is provided in Figure 25.

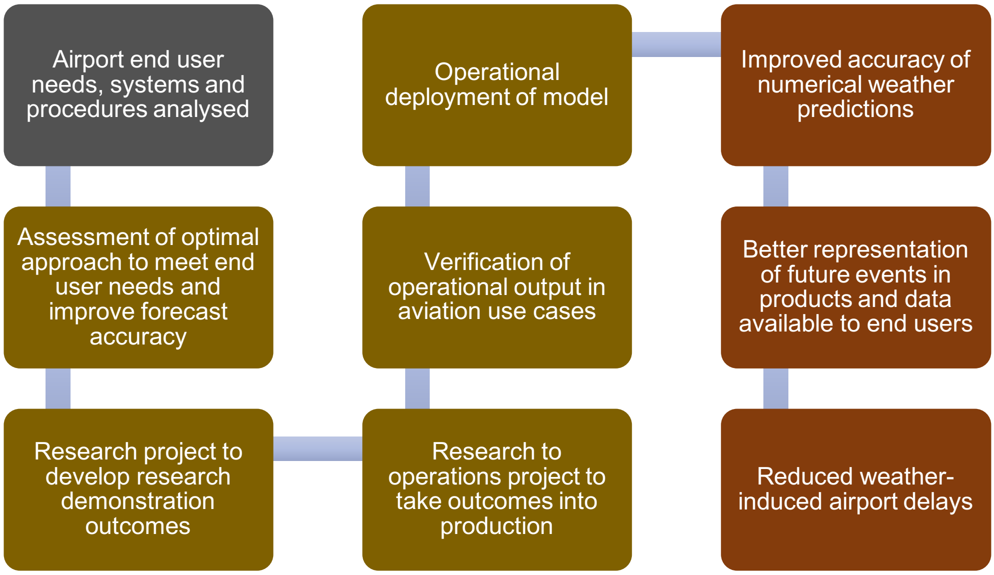

Figure 25: Schematic representation of the required steps leading to improved temporal and spatial resolution in numerical weather models used for aviation weather forecasting. Brown shading indicates meteorological development milestones and red shading the added value for end users.

Research and development of especially temporally higher resolution nowcasting models could be carried out as an international collaboration to reduce the cost and duration of such a project. Projects should also be based on existing solid research findings to justify the selected approach. Particular importance should be given to the verification of operational model output against limited area and global models in aviation-specific cases to demonstrate suitability for aviation purposes. Many models do not directly output some important parameters to aviation end users, such as precipitation type or visibility. These are usually post-processed using various methods. The post-processing output should also be carefully evaluated and verified against operational aviation weather observations to ensure the quality and consistency of the produced information. Extensive post-processing should be avoided since it will make the ongoing development of the model more difficult as the methods must be also updated and output verified following each update.

7.8 Improving forecasts of High Altitude Ice Crystal concentrations

The effect of ice crystal icing on aircraft turbine engines potentially leading to the risk of sudden loss of engine thrust in very cold air has been known for decades[56]. The ice crystals in question are generated by deep convective cells which in turn are prevalent especially in the tropics. The ice crystals are difficult to observe as they are often not visible to the eye and do not appear in the onboard weather radar due to extremely low reflectivity. Convective cells breaking across the tropopause and areas downwind of the overshoot are typical areas to encounter high concentrations of ice crystals. Since the very small ice crystals do not adhere to the airframe, they are not detected by the conventional ice detectors onboard most modern aircraft. While no internationally agreed standard exists to provide warnings to airspace users on high altitude ice crystals, such provisions are being discussed and for now the best avoidance strategy is to avoid large convective systems with adequate safe distance using the onboard weather radar. The convective systems producing the ice crystals also produce turbulence, lightning and regular icing and as such should already be avoided for these reasons. The extension of ice crystals downwind from convective systems could be taken into account in any forecast or warning product as a safety precaution.

From a meteorological standpoint, the research challenge is on the correct identification of deep convection leading to overshooting tops capable of producing ice crystals at high altitudes from available remote sensing information and the subsequent nowcasting and forecasting of the evolution of the systems. Ground-breaking work has been achieved in a major High Altitude Ice Crystal (**HAIC**) research project[57] led by Airbus in collaboration with several meteorological service providers and industry to better understand the phenomena and develop nowcasting capabilities. The methods developed and deployed to identify severe turbulence areas from weather satellite data are essentially what can be used to also identify areas where ice crystal concentrations are likely to be high. Since the provision of global significant weather charts currently lies with World Area Forecast Centres, and to ensure global consistency and interoperability, warning on ice crystal concentrations could be assigned to WAFCs. In addition, WAFCs already monitor turbulence and major convective systems with a global reach and the addition of ice crystal warnings should not pose a large additional burden insofar as the methodology for the detection, forecasting and warning of ice crystals is

[56] http://www.skybrary.aero/index.php/High_Level_Ice_Crystal_Icing (link tested 30 Nov. 17)
[57] http://www.haic.eu/ (link tested 30 Nov. 17)

proven and accepted internationally. The challenges are similar to those of determining acceptable levels of volcanic ash ingestion by the turbine engines

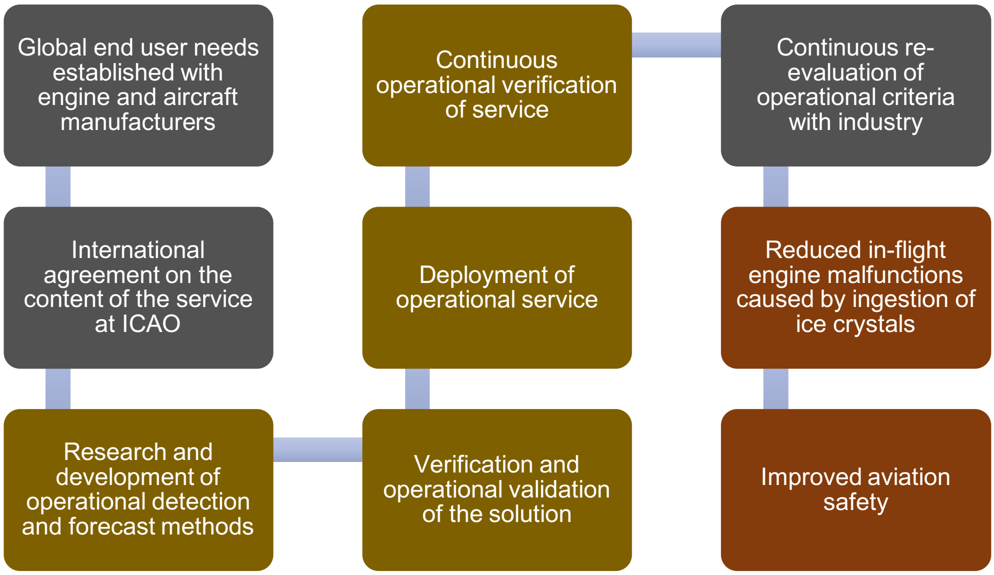

Figure 26: Schematic representation of the required steps leading to improved forecast and warning of high altitude ice crystal risk. Brown shading indicates meteorological development milestones and red shading the added value for end users.

The proposed process provided in Figure 26 aims to outline key performance areas related to the operational implementation of such a service. Continuous dialogue with the engine and aircraft manufacturing industry and close monitoring of any incident involving ice crystals is key to ensuring the service does not generate a significant bias and thus continues to add value.

7.9 Harmonisation and collaboration between MET service providers

A global strategy and roadmap to encompass meteorological service provision can be only founded on the defined needs and requirements of the main air transport industries and therefore a high-level dialogue needs to take place where the airline and ATM representatives form a definitive roadmap together with the meteorological service providers based on the existing service capability, trends in the air transport industry and technological developments. The objective of the global strategy should be to further improve aviation safety by ensuring that the air transport sector has at its disposal the best quality of meteorological information possible tailored for each specific need at global, regional and local levels. A mutually agreed roadmap should ensure that any developments are what the end users require to improve safety (see Figure 27).

The objectives and visions need to be translated into a global action plan and strategy following the detailed definition of end user needs and requirements. This development should be co-led by ICAO and WMO and should build on the existing Global Air Navigation Plan (GANP) and ASBU methodology. Currently the focus of these Block Upgrades has been almost solely on the World Area Forecast System (WAFS) development and the SWIM architecture without any clear guidance as to where the entire community of meteorological service providers should focus their development in order to improve aviation safety. The global vision needs to include a position on what the most important research questions are and where the integration of meteorological information to decision support systems is most needed.

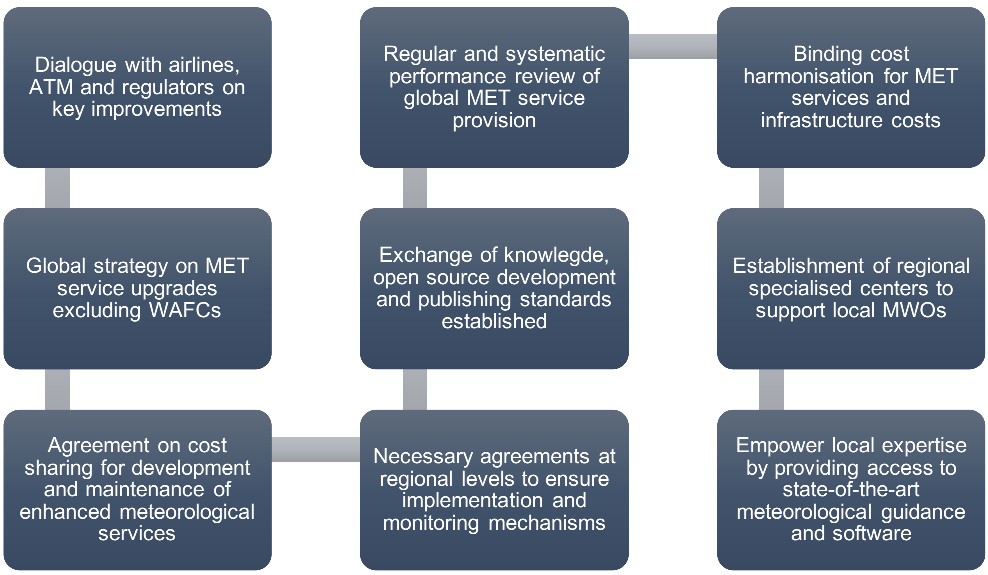

Figure 27: Schematic representation of the required steps leading to improved global meteorological service provision.

Once a clear roadmap, action plan and strategy have been developed, the funding for the investments should be resolved. Throughout this thesis, funding mechanisms for the research and development of meteorological services have been either regular research funding via proposals in general calls, directed funding by an executive agency to resolve a specific issue, co-funding for a common project, investments proposed by the meteorological service providers and paid by the end users via charges or tailored projects for commercial customers. The funding originates either from the taxpayers via national governments or from passengers via en-route and terminal charges, where the latter is the preferred option to ensure the developments are accountable, transparent and driven by user needs. Meteorological service providers designate a widely varying share of meteorological infrastructure (observation, numerical weather prediction and remote sensing) costs to aviation due to the lack of explicit guidance and oversight and thus meteorological service costs are not comparable from one country to another. This should also be addressed and global guidelines given to the community in order to facilitate an equal operational environment for meteorological service providers.

The countries that do not recover the costs of meteorological services to airspace users risk the meteorological service becoming outdated and affecting negatively to the development of safety objectives. The WMO has carried out a global survey of cost recovery and meteorological service provision showing that there remains a large number of countries where cost recovery is not implemented. A transparent business plan with investments and clear Key Performance Indicators (KPIs) agreed mutually with regulators and end users enables a long-term and sustainable development of meteorological services. A clear regulation should be established on the allocation of meteorological infrastructure cost, role of public funding versus airspace users and between en-route and terminal costs to aviation. At the same time, funding for the World Area Forecast Centers (WAFC), Volcanic Ash Advisory Centers (VAAC), Tropical Cyclone Advisory Centers (TCAC) and Space Weather Prediction Centers should be revised. SWIM-services should also be extended to be cost recovered via a globally uniform mechanism.

This thesis has established the fact that the research and development of meteorological services to aviation is not evenly distributed, operating under a global strategy or adequately funded. A key element in the successful contribution towards improving the safety objectives is to ensure that funding is available also to smaller service providers in a globally balanced way. For this purpose, a global meteorological service for aviation development fund needs to be set up under the joint mandate of WMO and ICAO with revenue collected from airspace charges and landing fees. This fund would award projects in specific thematic areas on topics aligned with a global strategy agreed with the end users. All project outcomes would be published as open data and all software as open source within the aviation community. Projects should address gaps at local, regional and global level and should promote cross-border cooperation and sharing of resources.

The monitoring of performance needs to be streamlined and user focused at a regional level. This could be achieved by holding annual stakeholder review meetings where regional total meteorological service costs are presented and discussed and user feedback received on the most important investments at a regional level. A bi-annual global stakeholder workshop between ICAO, WMO, IATA and CANSO with regional representation should complement the regional level to provide a global consensus on the meteorological service cost and future investments into research and development. Transparency into planned and ongoing development activities with open access publishing standards of research results of meteorological applications will speed up development significantly. When considering the global, regional and local level mechanisms for funding research and development actions, open sharing of research results should be a key priority. Publication of developed algorithms, post-processing methods, software and research findings as open source will benefit all of the involved parties and therefore should become the norm.

Some meteorological service providers struggle with fulfilling the mandate of providing Meteorological Watch Office (**MWO**) services such as SIGMETs. This may be due to conflict, natural disaster, critical lack of resources or some other reason. In such cases, as has been proposed during the conjoint ICAO-WMO MET Divisional Meeting in 2014, another MWO in the region could (and should) fill in the gap and provide the critical safety function on behalf of the underperforming MWO. Such Regional Hazardous Weather Advisory Centers (**RHWAC**) would issue SIGMETs on behalf of other MWOs and provide the critical service that airspace users have paid for. The RHWAC concept can also be extended on a voluntary basis between willing service providers to improve cost efficiency, harmonise service provision across Flight Information Region (**FIR**) boundaries and provide backup for service interruptions.

8 CONCLUDING REMARKS

This work presents a comprehensive overview of the impacts of weather on air transport, where the science is progressing and who the actors are. Some proposals for the future are also provided to spark ideas among the readers. The subject is complex, international, political and scientific. Meteorological services should be developed from a safety perspective drawing from the advances in technology and science in close collaboration between all of the global players. Information must be shared and innovations fostered between the scientists and developers. The ideas presented in Chapter 7 provide seeds for those involved in cultivating meteorological information to air transport.

The role of the meteorological service providers is heavily focussed on operational forecasting with only a small fraction of the total amount going to research and development activities. There is a clear need for a global aeronautical meteorological development agenda and improved interaction with the major research funding agencies. Current interaction between researchers working on aeronautical meteorological research and development activities is limited to meteorological societies' meetings such as the American Meteorological Society Aviation, Range, and Airspace Meteorology conference (ARAM) held biannually and the European Meteorological Society conference on applied meteorology (ECAM) also held biannually without a specific conference. A global scientific event such as the WMO Aeronautical Meteorology Scientific Conference held from 6 to 10 November 2017 in Toulouse, France for the second time ever since 1968 is strongly endorsed to be continued regularly.

Aeronautical meteorological research is a field too small for duplicating effort to continue to make gains in forecast skill and improve air transport safety and efficiency. Collaboration, cooperation, data sharing and joint research activities should be fostered to pool the best talent to work on the challenges remaining in ceiling and visibility, turbulence, icing, high wind and convection, properly integrating the information into decision support systems leading to better operations.

REFERENCES

1. Adamson, H. P., 1990: Method for producing a warning of the existence of low-level wind shear and aircraft borne system for performing same. US Patent US4965572 A.
2. Albers, S. C., J. A. McGinley, D. L. Birkenheuer, and J. R. Smart, 1996: The Local Analysis and Prediction System (LAPS): Analyses of Clouds, Precipitation, and Temperature. Weather and Forecasting, 11, 273-287.
3. Alcott, T. I., and W. J. Steenburgh, 2013: Orographic Influences on a Great Salt Lake–Effect Snowstorm. Monthly Weather Review, 141, 2432-2450.
4. Allan, S. S., S. G. Gaddy, and J. E. Evans, 2001: Delay Causality and Reduction at the New York City Airports Using Terminal Weather Information Systems. Project Report.
5. Allen, R. A., 1969: Operational Evaluation of a Ceiling and Visibility Prediction Technique. Project Report.
6. Amendola, A., and G. Mingione, 2001: On the problem of icing for modern civil aircraft. Air & Space Europe, 3, 214-217.
7. AMS, 2012: State of the Weather and Climate Enterprise 2012 Summer Community Meeting, National Weather Center at The University of Oklahoma, AMS Commission on the Weather and Climate Enterprise, 34.
8. Antonescu, B., and S. Burcea, 2010: A Cloud-to-Ground Lightning Climatology for Romania. Monthly Weather Review, 138, 579-591.
9. Baldwin, M., R. Treadon, and S. Contorno, 1994: Precipitation type prediction using a decision tree approach with NMCs mesoscale eta model. 10th Conference On Numerical Weather Prediction, AMS, 30-31.
10. Barbaresco, F., P. Juge, M. Klein, Y. Ricci, J. Y. Schneider, and J. F. Moneuse, 2011: Optimising runway throughput through wake vortex detection, prediction and decision support tools. 2011 Tyrrhenian International Workshop on Digital Communications - Enhanced Surveillance of Aircraft and Vehicles, 27-32.
11. Bauer, P., A. Thorpe, and G. Brunet, 2015: The quiet revolution of numerical weather prediction. Nature, 525, 47-55.

12. Bech, J., N. Pineda, T. Rigo, and M. Aran, 2013: Remote sensing analysis of a Mediterranean thundersnow and low-altitude heavy snowfall event. Atmospheric Research, 123, 305-322.
13. Benjamin, S. G., and Coauthors, 2016: A North American Hourly Assimilation and Model Forecast Cycle: The Rapid Refresh. Monthly Weather Review, 144, 1669-1694.
14. Bentley, M. L., and J. A. Stallins, 2005: Climatology of cloud-to-ground lightning in Georgia, USA, 1992-2003. International Journal of Climatology, 25, 1979-1996.
15. Bergot, T., 2007: Quality Assessment of the Cobel-Isba Numerical Forecast System of Fog and Low Clouds. Pure Applied Geophysics, 164, 1265-1282.
16. ——, 2013: Small-scale structure of radiation fog: a large-eddy simulation study. Quarterly Journal of the Royal Meteorological Society, 139, 1099-1112.
17. Bergot, T., J. Escobar, and V. Masson, 2015: Effect of small-scale surface heterogeneities and buildings on radiation fog: Large-eddy simulation study at Paris–Charles de Gaulle airport. Quarterly Journal of the Royal Meteorological Society, 141, 285-298.
18. Bernstein, B. C., and C. Le Bot, 2009: An inferred climatology of icing conditions aloft, including supercooled large drops. part II: Europe, Asia, and the Globe. Journal of Applied Meteorology and Climatology, 48, 1503-1526.
19. Bernstein, B. C., C. A. Wolff, and F. McDonough, 2007: An inferred climatology of icing conditions aloft, including supercooled large drops. Part I: Canada and the continental United States. Journal of Applied Meteorology and Climatology, 46, 1857-1878.
20. Bernstein, B. C., T. A. Omeron, F. McDonough, and M. K. Politovich, 1997: The Relationship between Aircraft Icing and Synoptic-Scale Weather Conditions. Weather and Forecasting, 12, 742-762.
21. Bernstein, B. C., T. A. Omeron, M. K. Politovich, and F. McDonough, 1998: Surface weather features associated with freezing precipitation and severe in-flight aircraft icing. Atmospheric Research, 46, 57-73.
22. Bernstein, B. C., and Coauthors, 2005: Current Icing Potential: Algorithm Description and Comparison with Aircraft Observations. Journal of Applied Meteorology, 44, 969-986.
23. Bocchieri, J. R., H. R. Glahn, and F. T. Globokar, 1973: An Application of Model Output Statistics to the Prediction of Ceiling and Visibility. Project Report.

24. Bocchieri, J. R., R. L. Crisci, H. R. Glahn, F. Lewis, and F. T. Globokar, 1974: Recent Developments in Automated Prediction of Ceiling and Visibility. Journal of Applied Meteorology, 13, 277-288.
25. Bosart, L. F., 1981: The Presidents' Day Snowstorm of 18–19 February 1979: A Subsynoptic-Scale Event. Monthly Weather Review, 109, 1542-1566.
26. Bott, A., and T. Trautmann, 2002: PAFOG—a new efficient forecast model of radiation fog and low-level stratiform clouds. Atmospheric Research, 64, 191-203.
27. Bourgouin, P., 2000: A Method to Determine Precipitation Types. Weather and Forecasting, 15, 583-592.
28. Boutle, I. A., A. Finnenkoetter, A. P. Lock, and H. Wells, 2016: The London Model: forecasting fog at 333 m resolution. Quarterly Journal of the Royal Meteorological Society, 142, 360-371.
29. Bovalo, C., C. Barthe, and N. Begue, 2012: A lightning climatology of the South-West Indian Ocean. Natural Hazards and Earth System Sciences, 12, 2659-2670.
30. Bradford, M., 2000: Scanning the Skies: A History of Tornado Forecasting. University of Oklahoma Press.
31. Bringi, V. N., and V. Chandrasekar, 2001: Polarimetric Doppler Weather Radar: Principles and Applications. Cambridge University Press.
32. Browning, K. A., 1983: Air motion and precipitation growth in a major snowstorm. Quarterly Journal of the Royal Meteorological Society, 109, 225-242.
33. Burghardt, B. J., C. Evans, and P. J. Roebber, 2014: Assessing the Predictability of Convection Initiation in the High Plains Using an Object-Based Approach. Weather and Forecasting, 29, 403-418.
34. Caine, S., T. P. Lane, P. T. May, C. Jakob, S. T. Siems, M. J. Manton, and J. Pinto, 2013: Statistical Assessment of Tropical Convection-Permitting Model Simulations Using a Cell-Tracking Algorithm. Monthly Weather Review, 141, 557-581.
35. Carriere, J. M., C. Lainard, C. Le Bot, and F. Robart, 2000: A climatological study of surface freezing precipitation in Europe. Meteorological Applications, 7, 229-238.
36. Cecil, D. J., D. E. Buechler, and R. J. Blakeslee, 2014: Gridded lightning climatology from TRMM-LIS and OTD: Dataset description. Atmospheric Research, 135, 404-414.
37. Chan, P. W., and K. K. Hon, 2016: Performance of super high resolution numerical weather prediction model in forecasting

terrain-disrupted airflow at the Hong Kong International Airport: case studies. Meteorological Applications, 23, 101-114

38. Changnon, S. A., 2003: Urban modification of freezing-rain events. Journal of Applied Meteorology, 42, 863-870.
39. Changnon, S. A., and D. Changnon, 2005: Snowstorm catastrophes in the United States. Global Environmental Change Part B: Environmental Hazards, 6, 158-166.
40. Chen, J., Y. Wang, L. Li, B. Zhao, F. Chen, Y. Li, and Y. Cui, 2013: A unified verification system for operational models from Regional Meteorological Centres of China Meteorological Administration. Meteorological Applications, 20, 140-149.
41. Chmielecki, R. M., and A. E. Raftery, 2011: Probabilistic Visibility Forecasting Using Bayesian Model Averaging. Monthly Weather Review, 139, 1626-1636.
42. Clark, D. A., 1995: Characterizing the causes of low ceiling and visibility at US airports. 6th Conf. on Aviation Weather Systems, 325-330.
43. Clark, D. A., 2006: Terminal ceiling and visibility product development for northeast airports. Proc. 14th Conf. on Aviation, Range, and Aerospace Meteorology, AMS.
44. Clodman, S., and W. Chisholm, 1996: Lightning flash climatology in the southern Great Lakes region. Atmosphere and Ocean, 34, 345-377.
45. Coleman, H., and J. Marwitz, 2002: Thermodynamic and kinematic structure of a snowband and freezing rain event during STORM-FEST. Weather and Forecasting, 17, 27-46.
46. Crowe, B. A., and D. W. Miller, 1999: Thr Benefits of Using NEXRAD Veritcally Integrated Liquid Water as an Aviation Weather Product. 8th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Society.
47. Crowe, C., P. Market, B. Pettegrew, C. Melick, and J. Podzimek, 2006: An investigation of thundersnow and deep snow accumulations. Geophys Res Lett, 33, n/a-n/a.
48. Cummins, K. L., and M. J. Murphy, 2009: An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, With an In-Depth Look at the US NLDN. IEEE Trans. Electromagn. Compat., 51, 499-518.
49. Czys, R. R., R. W. Scott, K. C. Tang, R. W. Przybylinski, and M. E. Sabones, 1996: A Physically Based, Nondimensional Parameter for

Discriminating between Locations of Freezing Rain and Ice Pellets. Weather and Forecasting, 11, 591-598.
50. Davis, C., B. Brown, and R. Bullock, 2006: Object-Based Verification of Precipitation Forecasts. Part II: Application to Convective Rain Systems. Monthly Weather Review, 134, 1785-1795.
51. de Leege, A. M. P., M. M. van Paassen, and M. Mulder, 2012: Using Automatic Dependent Surveillance-Broadcast for Meteorological Monitoring. J Aircraft, 50, 249-261.
52. De Troch, R., R. Hamdi, H. Van de Vyver, J. F. Geleyn, and P. Termonia, 2013: Multiscale Performance of the ALARO-0 Model for Simulating Extreme Summer Precipitation Climatology in Belgium. J Climate, 26, 8895-8915.
53. de Villiers, M. P., and D. White, 2014: Near-surface winds and wind shear at four airports during the 'St Jude's day storm'. Weather, 69, 288-294.
54. Deierling, W., W. A. Petersen, J. Latham, S. Ellis, and H. J. Christian, 2008: The relationship between lightning activity and ice fluxes in thunderstorms. Journal of Geophysical Research, 113.
55. DeLaura, R., 2012: Route Availability Planning Tool. Project Report.
56. Deng, D., S. Gao, X. Du, and W. Wu, 2012: A diagnostic study of freezing rain over Guizhou, China, in January 2011. Quarterly Journal of the Royal Meteorological Society, 138, 1233-1244.
57. Dixon, M., and G. Wiener, 1993: TITAN: Thunderstorm Identification, Tracking, Analysis, and Nowcasting—A Radar-based Methodology. J Atmos Ocean Tech, 10, 785-797.
58. Doswell, C. A., S. J. Weiss, and R. H. Johns, 1993: Tornado Forecasting: a Review. The Tornado: Its Structure, Dynamics, Prediction, and Hazards, American Geophysical Union, 557-571.
59. Dupont, J.-C., M. Haeffelin, A. Protat, D. Bouniol, N. Boyouk, and Y. Morille, 2012: Stratus–Fog Formation and Dissipation: A 6-Day Case Study. Boundary-Layer Meteorology, 143, 207-225.
60. Dutta, D., and S. Chaudhuri, 2015: Nowcasting visibility during wintertime fog over the airport of a metropolis of India: decision tree algorithm and artificial neural network approach. Nat Hazards, 75, 1349-1368.
61. ECMWF, 2016: Part III: Dynamics and Numerical Procedures. IFS Documentation CY43R1, ECMWF.
62. Enno, S. E., 2011: A climatology of cloud-to-ground lightning over Estonia, 2005-2009. Atmospheric Research, 100, 310-317.

63. EUROCONTROL, 2004: Report on Aeronautical MET Costs. Report, 114 pp.
64. ——, 2016: U.S. - Europe continental comparison 2006-2014 of ANS cost-efficiency trends. Report, 34 pp.
65. Evans, J. E., 2001: Tactical weather decision support to complement “strategic” traffic flow management for convective weather. 4th USA/Europe Air Traffic Management R&D Seminar.
66. Evans, J. E., and E. R. Ducot, 2006: Corridor integrated weather system. Lincoln Laboratory Journal, 16, 59.
67. FAA, 2005: General Aviation Pilot’s Guide to Preflight Weather Planning, Weather Self-Briefings, and Weather Decision Making. D. o. Commerce, Ed., FAA, 36.
68. ——, 2016: FAA Budget Estimates for Fiscal Year 2017. U.S. Department of Transportation, 795.
69. FAA, and EUROCONTROL, 2013: Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe. Report, 106 pp.
70. Freebairn, J. W., and J. W. Zillman, 2002: Economic benefits of meteorological services. Meteorological Applications, 9, 33-44.
71. Frei, T., 2010: Economic and social benefits of meteorology and climatology in Switzerland. Meteorological Applications, 17, 39-44.
72. Fuchs, W., and K. P. Schickel, 1995: Aircraft icing in visual meterological conditions below low stratus clouds. Atmospheric Research, 36, 339-345.
73. Fulton, C., and Coauthors, 2017: Cylindrical Polarimetric Phased Array Radar: Beamforming and Calibration for Weather Applications. IEEE Transactions on Geoscience and Remote Sensing, 55, 2827-2841.
74. Gerz, T., and Coauthors, 2009: The Wake Vortex Prediction and Monitoring System WSVBS Part II: Performance and ATC Integration at Frankfurt Airport. Air Traffic Control Quarterly, 17, 323-346.
75. Gill, P. G., 2014: Objective verification of World Area Forecast Centre clear air turbulence forecasts. Meteorological Applications, 21, 3-11.
76. Gill, P. G., and P. Buchanan, 2014: An ensemble based turbulence forecasting system. Meteorological Applications, 21, 12-19.
77. Glahn, B., A. D. Schnapp, and J.-S. Im, 2015: THE LAMP AND HRRR CEILING HEIGHT AND VISIBILITY MELD.

78. Glahn, B., A. D. Schnapp, J. E. Ghirardelli, and J.-S. Im, 2017: A LAMP–HRRR MELD for Improved Aviation Guidance. Weather and Forecasting, 32, 391-405.
79. Glahn, H. R., and D. A. Lowry, 1972: The Use of Model Output Statistics (MOS) in Objective Weather Forecasting. Journal of Applied Meteorology, 11, 1203-1211.
80. Goff, R. C., 1980: The Low-Level Wind Shear Alert System (LLWSAS).
81. Golding, B. W., 1998: Nimrod: a system for generating automated very short range forecasts. Meteorological Applications, 5, 1-16.
82. Gremillion, M. S., and R. E. Orville, 1999: Thunderstorm Characteristics of Cloud-to-Ground Lightning at the Kennedy Space Center, Florida: A Study of Lightning Initiation Signatures as Indicated by the WSR-88D. Weather and Forecasting, 14, 640-649.
83. Gultepe, I., J. A. Milbrandt, and B. Zhou, 2017: Marine Fog: A Review on Microphysics and Visibility Prediction. Marine Fog: Challenges and Advancements in Observations, Modeling, and Forecasting, Springer, 345-394.
84. Gultepe, I., and Coauthors, 2014: Ice Fog in Arctic During FRAM–Ice Fog Project: Aviation and Nowcasting Applications. Bulletin of the American Meteorological Society, 95, 211-226.
85. Gultepe, I., and Coauthors, 2007: Fog Research: A Review of Past Achievements and Future Perspectives. Pure Applied Geophysics, 164, 1121-1159.
86. Haan, S. d., and A. Stoffelen, 2012: Assimilation of High-Resolution Mode-S Wind and Temperature Observations in a Regional NWP Model for Nowcasting Applications. Weather and Forecasting, 27, 918-937.
87. Haeffelin, M., and Coauthors, 2010: PARISFOG: Shedding New Light on Fog Physical Processes. Bulletin of the American Meteorological Society, 91, 767-783.
88. Hagelin, S., L. Auger, P. Brovelli, and O. Dupont, 2014: Nowcasting with the AROME Model: First Results from the High-Resolution AROME Airport. Weather and Forecasting, 29, 773-787
89. Hallowell, R., and Coauthors, 1999: The terminal convective weather forecast demonstration at the DFW international airport. American Meteorological Society 79th Annual Meeting, Dallas, TX.
90. Hansen, B., 2007: A Fuzzy Logic–Based Analog Forecasting System for Ceiling and Visibility. Weather and Forecasting, 22, 1319-1330.

91. Hautala, R. e. a., 2008: Benefits of meteorological services in South Eastern Europe Vol. 109, VTT Technical Research Centre of Finland 100 pp.
92. Herzegh, P., G. Wiener, R. Bateman, J. Cowie, and J. Black, 2015: Data Fusion Enables Better Recognition of Ceiling and Visibility Hazards in Aviation. Bulletin of the American Meteorological Society, 96, 526-532.
93. Herzegh, P. H., 2006: Development of FAA National Ceiling and Visibility products: Challenges, strategies and progress. 12th Conference on Aviation Range and Aerospace Meteorology.
94. Herzegh, P. H., R. L. Bankert, B. K. Hansen, M. Tryhane, and G. Wiener, 2004: Recent progress in the development of automated analysis and forecast products for ceiling and visibility conditions. Proceedings of the 20th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography and Hydrology.
95. Hiemstra, C. A., G. E. Liston, R. A. P. Sr., D. L. Birkenheuer, and S. C. Albers, 2006: Comparing Local Analysis and Prediction System (LAPS) Assimilations with Independent Observations. Weather and Forecasting, 21, 1024-1040.
96. Hodanish, S., D. Sharp, W. Collins, C. Paxton, and R. E. Orville, 1997: A 10-yr monthly lightning climatology of Florida: 1986-95. Weather and Forecasting, 12, 439-448.
97. Huffman, G. J., and G. A. Norman, 1988: The Supercooled Warm Rain Process and the Specification of Freezing Precipitation. Monthly Weather Review, 116, 2172-2182.
98. Hunter, G., 2010: Probabilistic forecasting of airport capacity. 29th Digital Avionics Systems Conference, 2.A.3-1-2.A.3-8.
99. IATA, 2016: Economic Performance of the Airline Industry. End-year report, 6 pp.
100. ICAO, 2016a: 2016–2030 Global Air Navigation Plan. 2016 ed., International Civil Aviation Organization (ICAO), 142.
101. ——, 2016b: Annex 3 — Meteorological Service for International Air Navigation. Nineteenth edition 2016 ed., ICAO, 208.
102. JCAB, 2010: Long-term Vision for the Future Air Traffic Systems - Changes to Intelligent Air Traffic Systems. Japan Civil Aviation Bureau.
103. Jeck, R. K., 2011: Spatial and Microphysical Characteristics of Low-Ceiling, Temperature-Inverted Clouds in Warm Overrunning and

Freezing-Rain Conditions: A Case Study. Journal of Applied Meteorology and Climatology, 50, 2062-2072.
104. Jiang, H., and Coauthors, 2015: Real-Time Applications of the Variational Version of the Local Analysis and Prediction System (vLAPS). Bulletin of the American Meteorological Society, 96, 2045-2057.
105. Kaltenboeck, R. R., A., 2016: A freezing rain storm explored with a C-band polarimetric weather radar using the QVP methodology. Meteorologische Zeitschrift.
106. Keller, T. L., S. B. Trier, W. D. Hall, R. D. Sharman, M. Xu, and Y. Liu, 2015: Lee Waves Associated with a Commercial Jetliner Accident at Denver International Airport. Journal of Applied Meteorology and Climatology, 54, 1373-1392.
107. Kicinger, R., J.-T. Chen, M. Steiner, and J. Pinto, 2016: Airport Capacity Prediction with Explicit Consideration of Weather Forecast Uncertainty. Journal of Air Transportation, 24, 18-28.
108. Kicinger, R., C. Cross, T. Myers, J. Krozel, C. Mauro, and D. Kierstead, 2011: Probabilistic Airport Capacity Prediction Incorporating the Impact of Terminal Weather. AIAA Guidance, Navigation, and Control Conference, 6691.
109. Kim, J.-H., H.-Y. Chun, R. D. Sharman, and T. L. Keller, 2011: Evaluations of Upper-Level Turbulence Diagnostics Performance Using the Graphical Turbulence Guidance (GTG) System and Pilot Reports (PIREPs) over East Asia. Journal of Applied Meteorology and Climatology, 50, 1936-1951.
110. Kim, J.-H., H.-Y. Chun, R. D. Sharman, and S. B. Trier, 2014: The Role of Vertical Shear on Aviation Turbulence within Cirrus Bands of a Simulated Western Pacific Cyclone. Monthly Weather Review, 142, 2794-2813.
111. Kim, J.-H., W. N. Chan, B. Sridhar, and R. D. Sharman, 2015: Combined Winds and Turbulence Prediction System for Automated Air-Traffic Management Applications. Journal of Applied Meteorology and Climatology, 54, 766-784.
112. Kim, J.-H., W. N. Chan, B. Sridhar, R. D. Sharman, P. D. Williams, and M. Strahan, 2016: Impact of the North Atlantic Oscillation on Transatlantic Flight Routes and Clear-Air Turbulence. Journal of Applied Meteorology and Climatology, 55, 763-771.
113. Kim, S.-H., and H.-Y. Chun, 2016: Aviation turbulence encounters detected from aircraft observations: spatiotemporal characteristics

and application to Korean Aviation Turbulence Guidance. Meteorological Applications, 23, 594-604.
114. Klein, A., 2010: Airport delay prediction using weather-impacted traffic index (WITI) model. 29th Digital Avionics Systems Conference, 2.B.1-1-2.B.1-13.
115. Klein, A., S. Kavoussi, and R. S. Lee, 2009: Weather forecast accuracy: study of impact on airport capacity and estimation of avoidable costs. Eighth USA/Europe Air Traffic Management Research and Development Seminar.
116. Klingle-Wilson, D., and J. Evans, 2005: Description of the Corridor Integrated Weather System (CIWS) Weather Products. Project Report ATC-317, MIT Lincoln Laboratory, Lexington, MA.
117. Knightley, P., 2016: Forecasting Severe Weather in the United Kingdom and Ireland. Extreme Weather, John Wiley & Sons, Ltd, 235-246.
118. Kober, K., G. C. Craig, C. Keil, and A. Dörnbrack, 2012: Blending a probabilistic nowcasting method with a high-resolution numerical weather prediction ensemble for convective precipitation forecasts. Quarterly Journal of the Royal Meteorological Society, 138, 755-768.
119. Konopka, J., and H. Fischer, 2005: The wake vortex warning system at Frankfurt airport. 24th Digital Avionics Systems Conference, 3.A.6-31-14 Vol. 31.
120. Kopeć, J. M., K. Kwiatkowski, S. de Haan, and S. P. Malinowski, 2016: Retrieving atmospheric turbulence information from regular commercial aircraft using Mode-S and ADS-B. Atmos. Meas. Tech., 9, 2253-2265.
121. Koračin, D., C. E. Dorman, J. M. Lewis, J. G. Hudson, E. M. Wilcox, and A. Torregrosa, 2014: Marine fog: A review. Atmospheric Research, 143, 142-175.
122. Krozel, J., J. S. B. Mitchell, V. Polishchuk, and J. Prete, 2007: Maximum Flow Rates for Capacity Estimation in Level Flight with Convective Weather Constraints. Air Traffic Control Quarterly, 15, 209-238.
123. Kumjian, M. R., and W. Deierling, 2015: Analysis of Thundersnow Storms over Northern Colorado. Weather and Forecasting, 30, 1469-1490.
124. Kuo, K. S., K. Shrestha, A. Lin, and R. Ramachandran, 2016: Snowstorm climatology derived from NASA MERRA reanalysis as an example for event-based virtual collections. 2016 IEEE

International Geoscience and Remote Sensing Symposium (IGARSS), 2177-2180.

125. Kwong, K. M., J. N. K. Liu, P. W. Chan, and R. Lee, 2008: Using LIDAR doppler velocity data and chaotic oscillatory-based neural network for the forecast of meso-scale wind field. 2008 IEEE Congress on Evolutionary Computation (IEEE World Congress on Computational Intelligence), 2012-2019.
126. Lackmann, G. M., 2001: Analysis of a Surprise Western New York Snowstorm. Weather and Forecasting, 16, 99-116.
127. Lazo, J. K., R. E. Morss, and J. L. Demuth, 2009: 300 Billion Served. Bulletin of the American Meteorological Society, 90, 785-798.
128. Leyton, S. M., and J. M. Fritsch, 2003: Short-Term Probabilistic Forecasts of Ceiling and Visibility Utilizing High-Density Surface Weather Observations. Weather and Forecasting, 891.
129. ——, 2004: The Impact of High-Frequency Surface Weather Observations on Short-Term Probabilistic Forecasts of Ceiling and Visibility. Journal of Applied Meteorology, 43, 145-156.
130. Li, L., and J. P. Clarke, 2010: Airport configuration planning with uncertain weather and noise abatement procedures. 29th Digital Avionics Systems Conference, 2.B.5-1-2.B.5-9.
131. Liao, Z., and Y. Zhang, 2013: Concurrent variation between the East Asian subtropical jet and polar front jet during persistent snowstorm period in 2008 winter over southern China. Journal of Geophysical Research: Atmospheres, 118, 6360-6373.
132. Lynch, F. T., and A. Khodadoust, 2001: Effects of ice accretions on aircraft aerodynamics. Progress in Aerospace Sciences, 37, 669-767.
133. Lynn, B. H., Y. Yair, C. Price, G. Kelman, and A. J. Clark, 2012: Predicting Cloud-to-Ground and Intracloud Lightning in Weather Forecast Models. Weather and Forecasting, 27, 1470-1488.
134. Mäkelä, A., S.-E. Enno, and J. Haapalainen, 2014: Nordic Lightning Information System: Thunderstorm climate of Northern Europe for the period 2002–2011. Atmospheric Research, 139, 46-61.
135. Mäkelä, A., E. Saltikoff, J. Julkunen, I. Juga, E. Gregow, and S. Niemelä, 2013: Cold-Season Thunderstorms in Finland and Their Effect on Aviation Safety. Bulletin of the American Meteorological Society, 94, 847-858.
136. Market, P. S., C. E. Halcomb, and R. L. Ebert, 2002: A Climatology of Thundersnow Events over the Contiguous United States. Weather and Forecasting, 17, 1290-1295.

137. Marwitz, J., M. Politovich, B. Bernstein, F. Ralph, P. Neiman, R. Ashenden, and J. Bresch, 1997: Meteorological conditions associated with the ATR72 aircraft accident near Roselawn, Indiana, on 31 October 1994. Bulletin of the American Meteorological Society, 78, 41-52.
138. Marzban, C., S. Leyton, and B. Colman, 2007: Ceiling and Visibility Forecasts via Neural Networks. Weather and Forecasting, 22, 466-479.
139. Mass, C., 2012: Nowcasting: The Promise of New Technologies of Communication, Modeling, and Observation. Bulletin of the American Meteorological Society, 93, 797-809.
140. Matsushita, H., and F. Nishio, 2008: A Simple Method of Discriminating between Occurrences of Freezing Rain and Ice Pellets in the Kanto Plain, Japan. J Meteorol Soc Jpn, 86, 633-648.
141. McCann, D. W., 2005: NNICE – a neural network aircraft icing algorithm. Environmental Modelling & Software, 20, 1335-1342.
142. McCaul, E. W., S. J. Goodman, K. M. LaCasse, and D. J. Cecil, 2009: Forecasting Lightning Threat Using Cloud-Resolving Model Simulations. Weather and Forecasting, 24, 709-729.
143. McCaul, E. W., J. L. Case, S. R. Dembek, F. Kong, S. J. Goodman, and S. J. Weiss, 2012: The WRF Lightning Forecast Algorithm: Recent Updates and Results from Convective Ensemble Forecasts.
144. Melody, J. W., T. Başar, W. R. Perkins, and P. G. Voulgaris, 2000: Parameter identification for inflight detection and characterization of aircraft icing. Control Engineering Practice, 8, 985-1001.
145. Menut, L., S. Mailler, J.-C. Dupont, M. Haeffelin, and T. Elias, 2013: Predictability of the Meteorological Conditions Favourable to Radiative Fog Formation During the 2011 ParisFog Campaign. Boundary-Layer Meteorology, 150, 277-297.
146. Miller, S. D., and Coauthors, 2014: Estimating Three-Dimensional Cloud Structure via Statistically Blended Satellite Observations. Journal of Applied Meteorology and Climatology, 53, 437-455.
147. Mills, G. A., and S. Pendlebury, 2003: Processes leading to a severe wind-shear incident at Hobart Airport. Australian Meteorological Magazine, 52, 171.
148. Mirza, A. K., S. P. Ballard, S. L. Dance, P. Maisey, G. G. Rooney, and E. K. Stone, 2016: Comparison of aircraft-derived observations with in situ research aircraft measurements. Quarterly Journal of the Royal Meteorological Society, 142, 2949-2967.

149. Novak, D. R., C. Bailey, K. Brill, M. Eckert, D. Petersen, R. Rausch, and M. Schichtel, 2011: Human improvement to numerical weather prediction at the Hydrometeorological Prediction Center. 91th Annual AMS Meeting, AMS 24th Conference on Weather and Forecasting/20th Conference on Numerical Weather Prediction.
150. Pasini, A., V. Pelino, and S. Potestà, 2001: A neural network model for visibility nowcasting from surface observations: Results and sensitivity to physical input variables. Journal of Geophysical Research: Atmospheres, 106, 14951-14959.
151. Pearson, J. M., and R. D. Sharman, 2017: Prediction of Energy Dissipation Rates for Aviation Turbulence. Part II: Nowcasting Convective and Nonconvective Turbulence. Journal of Applied Meteorology and Climatology, 56, 339-351.
152. Pejovic, T., V. Williams, R. Noland, and R. Toumi, 2009: Factors Affecting the Frequency and Severity of Airport Weather Delays and the Implications of Climate Change for Future Delays. Transportation Research Record: Journal of the Transportation Research Board, 2139, 97-106.
153. Philip, A., T. Bergot, Y. Bouteloup, and F. Bouyssel, 2016: The Impact of Vertical Resolution on Fog Forecasting in the Kilometric-Scale Model AROME: A Case Study and Statistics. Weather and Forecasting, 31, 1655-1671.
154. Pinto, J., W. Dupree, S. Weygandt, M. Wolfson, S. Benjamin, and M. Steiner, 2010: Advances in the consolidated storm prediction for aviation (CoSPA).
155. Pinto, J. O., J. A. Grim, and M. Steiner, 2015: Assessment of the High-Resolution Rapid Refresh model's ability to predict mesoscale convective systems using object-based evaluation. Weather and Forecasting, 30, 892-913.
156. Poelman, D. R., W. Schulz, G. Diendorfer, and M. Bernardi, 2016: The European lightning location system EUCLID – Part 2: Observations. Nat. Hazards Earth Syst. Sci., 16, 607-616.
157. Prater, E. T., and A. A. Borho, 1992: Doppler Radar Wind and Reflectivity Signatures with Overrunning and Freezing-Rain Episodes - Preliminary-Results. Journal of Applied Meteorology, 31, 1350-1358.
158. Qaddouri, A., and V. Lee, 2011: The Canadian Global Environmental Multiscale model on the Yin-Yang grid system. Quarterly Journal of the Royal Meteorological Society, 137, 1913-1926.

159. Raghavan, S., 2003: Radar Meteorology. Vol. 27, Springer Science+Business Media, B.V.
160. Ramer, J., 1993: An empirical technique for diagnosing precipitation type from model output. Fifth Int. Conf. on Aviation Weather Systems, Vienna, MA, American Meteorological Society, 227-230.
161. Rasmussen, R., and Coauthors, 2001: Weather Support to Deicing Decision Making (WSDDM): A Winter Weather Nowcasting System. Bulletin of the American Meteorological Society, 82, 579-595.
162. Rasmussen, R., and Coauthors, 1992: Winter Icing and Storms Project (WISP). Bulletin of the American Meteorological Society, 73, 951-974.
163. Rasmussen, R. M., I. Geresdi, G. Thompson, K. Manning, and E. Karplus, 2002: Freezing drizzle formation in stably stratified layer clouds: The role of radiative cooling of cloud droplets, cloud condensation nuclei, and ice initiation. J Atmos Sci, 59, 837-860.
164. Rauber, R. M., L. S. Olthoff, M. K. Ramamurthy, and K. E. Kunkel, 2000: The relative importance of warm rain and melting processes in freezing precipitation events. Journal of Applied Meteorology, 39, 1185-1195.
165. ——, 2001a: Further investigation of a physically based, nondimensional parameter for discriminating between locations of freezing rain and ice pellets. Weather and Forecasting, 16, 185-191.
166. Rauber, R. M., L. S. Olthoff, M. K. Ramamurthy, D. Miller, and K. E. Kunkel, 2001b: A synoptic weather pattern and sounding-based climatology of freezing precipitation in the United States east of the Rocky Mountains. Journal of Applied Meteorology, 40, 1724-1747.
167. Rauber, R. M., and Coauthors, 2017: Finescale Structure of a Snowstorm over the Northeastern United States: A First Look at High-Resolution HIAPER Cloud Radar Observations. Bulletin of the American Meteorological Society, 98, 253-269.
168. Reynolds, D. W., D. A. Clark, F. W. Wilson, and L. Cook, 2012: Forecast-Based Decision Support for San Francisco International Airport: A NextGen Prototype System That Improves Operations during Summer Stratus Season. Bulletin of the American Meteorological Society, 93, 1503-1518.
169. Rickard, G. J., R. W. Lunnon, and J. Tenenbaum, 2001: The Met Office upper air winds: Prediction and verification in the context of commercial aviation data. Meteorological Applications, 8, 351-360.

170. Robbins, C. C., and J. V. Cortinas, 2002: Local and synoptic environments associated with freezing rain in the contiguous United States. Weather and Forecasting, 17, 47-65.
171. Roquelaure, S., and T. Bergot, 2009: Contributions from a Local Ensemble Prediction System (LEPS) for Improving Fog and Low Cloud Forecasts at Airports. Weather and Forecasting, 24, 39-52.
172. Roquelaure, S., R. Tardif, S. Remy, and T. Bergot, 2009: Skill of a Ceiling and Visibility Local Ensemble Prediction System (LEPS) according to Fog-Type Prediction at Paris-Charles de Gaulle Airport. Weather and Forecasting, 24, 1511-1523.
173. Rusu, L. I., W. Rahayu, T. Torabi, F. Puersch, W. Coronado, A. T. Harris, and K. Reed, 2012: Moving towards a collaborative decision support system for aeronautical data. Journal of Intelligent Manufacturing, 23, 2085-2100.
174. Ruzanski, E., and V. Chandrasekar, 2012: Improved Liquid Water Equivalent Nowcasting Using the Weather Support to Deicing Decision Making System. J Atmos Ocean Tech, 29, 407-416.
175. Ruzanski, E., V. Chandrasekar, and Y. Wang, 2011: The CASA Nowcasting System. J Atmos Ocean Tech, 28, 640-655.
176. Sand, W. R., W. A. Cooper, M. K. Politovich, and D. L. Veal, 1984: Icing Conditions Encountered by a Research Aircraft. J Clim Appl Meteorol, 23, 1427-1440.
177. Sanders, F., and L. F. Bosart, 1985: Mesoscale Structure in the Megalopolitan Snowstorm of 11–12 February 1983. Part I: Frontogenetical Forcing and Symmetric Instability. J Atmos Sci, 42, 1050-1061.
178. Sauer, M., T. Hauf, L. Sakiew, P. W. Chan, S.-M. Tse, and P. Hupe, 2016: On the identification of weather avoidance routes in the terminal maneuvering area of Hong Kong International Airport. Journal of Zhejiang University SCIENCE A, 17, 171-185.
179. Scheufele, K., K. Kober, G. C. Craig, and C. Keil, 2014: Combining probabilistic precipitation forecasts from a nowcasting technique with a time-lagged ensemble. Meteorological Applications, 21, 230-240.
180. Schroeder, J. J., D. A. R. Kristovich, and M. R. Hjelmfelt, 2006: Boundary Layer and Microphysical Influences of Natural Cloud Seeding on a Lake-Effect Snowstorm. Monthly Weather Review, 134, 1842-1858.

181. Schultz, D. M., 1999: Lake-Effect Snowstorms in Northern Utah and Western New York with and without Lightning. Weather and Forecasting, 14, 1023-1031.
182. Schultz, D. M., and R. J. Vavrek, 2009: An overview of thundersnow. Weather, 64, 274-277.
183. Schultz, P., and M. K. Politovich, 1992: Toward the Improvement of Aircraft-Icing Forecasts for the Continental United States. Weather and Forecasting, 7, 491-500.
184. Schumann, U., and R. Sharman, 2014: Aircraft Wake-Vortex Encounter Analysis for Upper Levels. Journal of Aircraft, 52, 1277-1285
185. Serke, D. J., M. C. King, R. Hansen, and A. L. Reehorst, 2016: Analysis of 2015 Winter In-Flight Icing Case Studies with Ground-Based Remote Sensing Systems Compared to In-Situ SLW Sondes.
186. Sharda, R., D. Delen, E. Turban, J. Aronson, and T. P. Liang, 2014: Businesss Intelligence and Analytics: Systems for Decision Support-(Required). 10 ed. Pearson.
187. Sharman, R., C. Tebaldi, G. Wiener, and J. Wolff, 2006: An Integrated Approach to Mid- and Upper-Level Turbulence Forecasting. Weather and Forecasting, 21, 268-287.
188. Sharman, R. D., and T. Lane, 2016: Aviation Turbulence: Processes, Detection, Prediction. Springer International Publishing.
189. Sharman, R. D., and J. M. Pearson, 2017: Prediction of Energy Dissipation Rates for Aviation Turbulence. Part I: Forecasting Nonconvective Turbulence. Journal of Applied Meteorology and Climatology, 56, 317-337.
190. Sharman, R. D., L. B. Cornman, G. Meymaris, J. Pearson, and T. Farrar, 2014: Description and Derived Climatologies of Automated In Situ Eddy-Dissipation-Rate Reports of Atmospheric Turbulence. Journal of Applied Meteorology and Climatology, 53, 1416-1432.
191. Sherwood, S. C., V. T. J. Phillips, and J. S. Wettlaufer, 2006: Small ice crystals and the climatology of lightning. Geophys Res Lett, 33.
192. Shin, J., and B. Berkowitz, 1994: Prediction of ice shapes and their effect on airfoil drag. J Aircraft, 31, 263-270.
193. Slangen, A. B. A., and M. J. Schmeits, 2009: Probabilistic forecasts of winter thunderstorms around Amsterdam Airport Schiphol. Advances in Science and Research, 3, 39.
194. Smith, D. A., L. Sherry, and G. Donohue, 2008: Decision support tool for predicting aircraft arrival rates, Ground Delay Programs,

and airport delays from weather forecasts. Proc. of International Conference on Research in Air Transportation, Citeseer.

195. Sondij, J., 2015: Aeronautical Meteorological Service Provision - Governance and business models. WMO RA VI European Conference on Meteorology for Aviation (ECMA-2015), WMO.

196. Spiegler, D., 2007: COMMUNITY: The Private Sector In Meteorology - An Update. Bulletin of the American Meteorological Society, 88, 1272-1275.

197. Sprague Jr, R. H., 1980: A framework for the development of decision support systems. MIS quarterly, 1-26.

198. Steenburgh, W. J., and D. J. Onton, 2001: Multiscale Analysis of the 7 December 1998 Great Salt Lake–Effect Snowstorm. Monthly Weather Review, 129, 1296-1317.

199. Stensrud, D. J., and Coauthors, 2009: Convective-scale warn on forecast: A vision for 2020. Bull. Am. Meteorol. Soc, 90.

200. Stensrud, D. J., and Coauthors, 2013: Progress and challenges with Warn-on-Forecast. Atmospheric Research, 123, 2-16.

201. Stewart, R. E., and P. King, 1987: Freezing Precipitation in Winter Storms. Monthly Weather Review, 115, 1270-1280.

202. Stoelinga, M. T., and T. T. Warner, 1999: Nonhydrostatic, Mesobeta-Scale Model Simulations of Cloud Ceiling and Visibility for an East Coast Winter Precipitation Event. Journal of Applied Meteorology, 38, 385-404.

203. Stone, E. K., and M. Kitchen, 2015: Introducing an Approach for Extracting Temperature from Aircraft GNSS and Pressure Altitude Reports in ADS-B Messages. J Atmos Ocean Tech, 32, 736-743.

204. Stone, E. K., and G. Pearce, 2016: A Network of Mode-S Receivers for Routine Acquisition of Aircraft-Derived Meteorological Data. J Atmos Ocean Tech, 33, 757-768.

205. Sun, J., and Coauthors, 2014: Use of NWP for Nowcasting Convective Precipitation: Recent Progress and Challenges. Bulletin of the American Meteorological Society, 95, 409-426.

206. Sweeney, C. P., P. Lynch, and P. Nolan, 2013: Reducing errors of wind speed forecasts by an optimal combination of post-processing methods. Meteorological Applications, 20, 32-40.

207. Tang, Y. M., R. Capon, R. Forbes, and P. Clark, 2009: Fog prediction using a very high resolution numerical weather prediction model forced with a single profile. Meteorological Applications, 16, 129-141.

208. Temme, A., and Coauthors, 2014: Guidebook for Enhancing Resilience of European Air Traffic in Extreme Weather Events. Project Report.
209. Terradellas, E., and D. Cano, 2007: Implementation of a Single-Column Model for Fog and Low Cloud Forecasting at Central-Spanish Airports. Fog and Boundary Layer Clouds: Fog Visibility and Forecasting, I. Gultepe, Ed., Birkhäuser Basel, 1327-1345.
210. Traveria, M., A. Escribano, and P. Palomo, 2010: Statistical wind forecast for Reus airport. Meteorological Applications, 17, 485-495.
211. Trier, S. B., and R. D. Sharman, 2016: Mechanisms Influencing Cirrus Banding and Aviation Turbulence near a Convectively Enhanced Upper-Level Jet Stream. Monthly Weather Review, 144, 3003-3027.
212. Tuba, Z., and Z. Bottyán, 2017: Fuzzy logic-based analogue forecasting and hybrid modelling of horizontal visibility. Meteorol Atmos Phys, 1-13.
213. Tudor, M., S. Ivatek-Šahdan, A. Stanešić, K. Horvath, and A. Bajić, 2013: Forecasting weather in Croatia using ALADIN numerical weather prediction model. Climate Change and Regional/Local Responses, InTech.
214. UK Met Office, 2007: The Public Weather Service's contribution to the UK economy
215. Umek, L., and A. Gohm, 2016: Lake and Orographic Effects on a Snowstorm at Lake Constance. Monthly Weather Review, 144, 4687-4707.
216. van der Velde, I. R., G. J. Steeneveld, B. G. J. Wichers Schreur, and A. A. M. Holtslag, 2010: Modeling and Forecasting the Onset and Duration of Severe Radiation Fog under Frost Conditions. Monthly Weather Review, 138, 4237-4253.
217. Vislocky, R. L., and J. M. Fritsch, 1997: An Automated, Observations-Based System for Short-Term Prediction of Ceiling and Visibility. Weather and Forecasting, 12, 31-43.
218. Von Gruenigen, S., S. Willemse and T. Frei, 2014: Economic Value of Meteorological Services to Switzerland's Airlines. Weather, Climate and Society, 6, 264-272.
219. Wang, Y., 2011: Prediction of weather impacted airport capacity using ensemble learning. 2011 IEEE/AIAA 30th Digital Avionics Systems Conference, 2D6-1-2D6-11.

220. Wang, Y. X., M. Wei, Z. h. Wang, S. Zhang, and L. X. Liu, 2017: Novel Scanning Strategy for Future Spaceborne Doppler Weather Radar With Application to Tropical Cyclones. Ieee J-Stars, PP, 1-9.
221. Weisman, M. L., W. C. Skamarock, and J. B. Klemp, 1997: The Resolution Dependence of Explicitly Modeled Convective Systems. Monthly Weather Review, 125, 527-548.
222. Wieringa, J., 1980: Representativeness of Wind Observations at Airports. Bulletin of the American Meteorological Society, 61, 962-971.
223. Wilkinson, J. M., H. Wells, P. R. Field, and P. Agnew, 2013: Investigation and prediction of helicopter-triggered lightning over the North Sea. Meteorological Applications, 20, 94-106.
224. Williams, J. K., 2014: Using random forests to diagnose aviation turbulence. Machine Learning, 95, 51-70.
225. Williams, P. D. and M. M. Joshi, 2013: Intensification of winter transatlantic aviation turbulence in response to climate change. Nature Climate Change, 3, 644-648.
226. Williams, P. D., 2016: Transatlantic flight times and climate change. Environmental Research Letters, 11, 8.
227. ——, 2017: Increased Light, Moderate, and Severe Clear-Air Turbulence in Response to Climate Change. Advances in Atmospheric Sciences, 34, 576-586.
228. Wilson, J. W., Y. Feng, M. Chen, and R. D. Roberts, 2010: Nowcasting Challenges during the Beijing Olympics: Successes, Failures, and Implications for Future Nowcasting Systems. Weather and Forecasting, 25, 1691-1714.
229. Wilson, J. W., N. A. Crook, C. K. Mueller, J. Sun, and M. Dixon, 1998: Nowcasting Thunderstorms: A Status Report. Bulletin of the American Meteorological Society, 79, 2079-2099.
230. WMO, 2014: Guide to Meteorological Instruments and Methods of Observation: (CIMO guide). 2014 ed., C. f. I. a. M. o. Observation, Ed., WMO.
231. Wolff, C., F. McDonough, M. Politovich, and G. Cunning, 2009: Forecast Icing Product: Recent Upgrades and Improvements. 1st AIAA Atmospheric and Space Environments Conference, American Institute of Aeronautics and Astronautics.
232. Wolfson, M. M., W. J. Dupree, R. M. Rasmussen, M. Steiner, S. G. Benjamin, and S. S. Weygandt, 2008: Consolidated storm prediction for aviation (CoSPA). 2008 Integrated Communications, Navigation and Surveillance Conference, 1-19.

233. Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS) – A multi-scale nonhydrostatic atmospheric simulation and prediction model. Part I: Model dynamics and verification. Meteorol Atmos Phys, 75, 161-193.
234. Xue, M., D. Wang, J. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. Meteorol Atmos Phys, 82, 139-170.
235. Zerr, R. J., 1997: Freezing rain: An observational and theoretical study. Journal of Applied Meteorology, 36, 1647-1661.
236. Zhang, F., C. Snyder, and R. Rotunno, 2002: Mesoscale Predictability of the "Surprise" Snowstorm of 24–25 January 2000. Monthly Weather Review, 130, 1617-1632.
237. Zhang, X., H. Wang, X.-Y. Huang, F. Gao, and N. A. Jacobs, 2015: Using Adjoint-Based Forecast Sensitivity Method to Evaluate TAMDAR Data Impacts on Regional Forecasts. Advances in Meteorology, 2015, 13.
238. Zhang, Y., Y. Liu, and T. Nipen, 2016: Evaluation of the Impacts of Assimilating the TAMDAR Data on 12 to 4 km Grid WRF-Based RTFDDA Simulations over the CONUS. Advances in Meteorology, 2016, 13.
239. Zhou, B., and J. Du, 2010: Fog Prediction from a Multimodel Mesoscale Ensemble Prediction System. Weather and Forecasting, 25, 303-322.

APPENDIX 1

National Meteorological and Hydrological Institutes of the world with an indication of activities in aeronautical meteorological research. Information collected from the WMO Country Profile Database (CPDB) available at: https://www.wmo.int/cpdb/. Y = Yes, U = Unknown & N = No.

Country	NMHS	Research (Y/U/N)	Aeronautical Research (Y/U/N)	Aviation MET Service provider (Y/N)
Afghanistan	Afghanistan Meteorological Authority (AMA)	U	N	Y
Albania	The Hydrometeorological Institute	Y	N	Y
Algeria	Office National de la Meteorologie	Y	U	Y
Angola	Instituto Nacional de Hidrometeorologia e Geofísica	U	N	N
Antigua and Barbuda	Antigua and Barbuda Meteorological Services (ABMS)	U	N	Y
Argentina	Servicio Meteorológico Nacional	Y	U	Y
Czech Republic	Czech Hydrometeorological Institute	Y	U	Y
Côte d'Ivoire	SODEXAM (Societe d'Exploitation et de Developpement Aeroportuaire, Aeronautique et Meteorologique)	U	U	Y
Democratic People's Republic of Korea	State Hydrometeorological Administration(SHMA)	U	U	Y
Democratic Republic of the Congo	Agence Nationale de Meteorologie et de Teledetection par Satellite "METTELSAT"	N	N	Y
Denmark	Danish Meteorological Institute	Y	Y	Y
Djibouti	Service de la Météorologie	N	N	N
Dominica	Dominica Meteorological Services	U	N	N
Dominican Republic	Oficina Nacional de Meteorologiá	U	N	N
Ecuador	Instituto Nacional de Meteorología e Hidrología - INAMHI (INAMHI)	Y	U	Y
Egypt	The Egyptian Meteorological Authority	U	U	Y
El Salvador	Gerencia de Meteorología. Management of Meteorology (MARN)	U	N	N
Eritrea	Civil Aviation Authority	N	N	Y
Estonia	Estonian Environment Agency (ESTEA)	Y	N	Y

Ethiopia	National Meteorological Agency (NMA)	U	N	Y
Fiji	Fiji Meteorological Service	N	N	Y
Finland	Finnish Meteorological Institute	Y	Y	Y
France	Météo-France	Y	Y	Y
French Polynesia	Direction Interrégionale pour la Polynésie francaise Meteo-France	Y	Y	Y
Gabon	Direction Generale de la Meteorologie	N	N	Y
Gambia	Department of Water Resources	U	N	Y
Georgia	Department of Hydrometeorology	U	N	N
Germany	Deutscher Wetterdienst	Y	Y	Y
Ghana	Ghana Meteorological Agency	U	N	Y
Greece	Hellenic National Meteorological Service	Y	U	Y
Guatemala	Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH)	U	N	Y
Guinea	Direction Nationale de la Météorologie Nationale Directorate of Meteorology	U	N	Y
Guinea-Bissau	Instituto Nacional de Meteorologia da Guiné-Bissau National Institute of Meteorology of Guinea-Bissau	U	N	Y
Guyana	Hydrometeorological Service	U	N	Y
Haiti	Centre national de météorologie	U	N	N
Honduras	Servicio Meteorológico Nacional de Honduras. National Weather Service of Honduras	U	N	Y
Hong Kong	Hong Kong Observatory (HKO)	Y	Y	Y
Hungary	Hungarian Meteorological Service (OMSZ)	Y	U	Y
Iceland	Icelandic Meteorological Office	Y	Y	Y
India	India Meteorological Department	Y	U	Y
Indonesia	Meteorological and Geophysical Agency	Y	U	Y
Iran	Islamic Repulic of Iran Meteorogical Organization (IRIMO)	Y	U	Y
Iraq	Iraqi Meteorological Organization and Seismology	U	N	Y
Ireland	The Irish Meteorological Service	Y	U	Y
Israel	Israel Meteorological Service	U	U	Y
Italy	Servizio Meteorologico	Y	Y	Y
Jamaica	Meteorological Service Division	N	N	Y
Japan	Japan Meteorological Agency	Y	Y	Y

Jordan	Jordan Meteorological Department	U	N	Y
Kazakhstan	Ministry of environment and wRepublican State Enterprise "Kazhydromet"	U	N	N
Kenya	Kenya Meteorological Department	Y	U	Y
Kiribati	Kiribati Meteorological Service	N	N	Y
Kuwait	Meteorological Department	U	N	Y
Kyrgyzstan	Agency on hydrometeorology under Ministry of emergency situations of the Kyrgyz Republic	U	N	Y
Lao	Department of Meteorology and Hydrology (DMH), Lao PDR	U	N	Y
Latvia	Latvian Environment, Geology and Meteorology Agency	Y	N	Y
Lebanon	Service Météorologique	U	N	N
Lesotho	Lesotho Meteorological Services	U	N	Y
Liberia	Liberia Meteorological Service	U	N	Y
Libya	National Meteorological Centre	U	N	Y
Lithuania	Lithuanian Hydrometeorological Service (LHMS)	U	N	Y
Luxembourg	Administration de l'Aéroport de Luxembourg	N	N	Y
Madagascar	Direction Générale de la Météorologie	U	N	N
Malawi	Department of Climate Change and Meteorological Services	N	N	Y
Malaysia	Malaysian Meteorological Department	U	U	Y
Maldives	Maldives Meteorological Service	N	N	Y
Mali	Agence Nationale de la Meteorologie (MALI-METEO)	U	N	Y
Malta	Meteorological Office	U	U	Y
Mauritania	Office National de la Météorologie	Y	N	Y
Mauritius	Mauritius Meteorological Services	U	N	Y
Mexico	Coordinación General del Servicio Meteorológico Nacional	Y	N	N
Micronesia, Federated States of	FSM Weather Station	N	N	Y
Monaco	Mission Permanente de la Principauté de Monaco	N	N	N
Mongolia	National Agency for Meteorology and Environment Monitoring of Mongolia	Y	N	Y
Montenegro	Hydrometeorological Institute of Montenegro	U	N	N
Morocco	Direction de la Météorologie Nationale	Y	U	Y

Mozambique	Instituto Nacional de Meteorologia	U	U	Y
Myanmar	Department of Meteorology and Hydrology	U	N	Y
Namibia	Namibia Meteorological Service	U	N	Y
Nepal	Department of Hydrology and meteorology	N	N	Y
Netherlands	Royal Netherlands Meteorological Institute (KNMI)	Y	Y	Y
New Caledonia	Météo-France Direction Interégionale en Nouvelle-Calédonie, Wallis et Futuna	Y	Y	Y
New Zealand	New Zealand National Meteorological Service	N	Y	Y
Nicaragua	Instituto Nicaraguense de Estudios Territoriales	U	N	Y
Niger	Direction de la Meteorologie nationale	U	N	Y
Nigeria	Nigerian Meteorological Agency	U	U	Y
Niue	Niue Meteorological Service	N	N	Y
Norway	Norwegian Meteorological Institute	Y	Y	Y
Oman	Director General of Meteorology	U	N	Y
Pakistan	Pakistan Meteorological Department	U	N	Y
Panama	Gerencia de Hidrometeorología	U	N	N
Papua New Guinea	Papua New Guinea Meteorological Service	U	N	Y
Paraguay	Dirección de Meteorología e Hidrología (DMH)	U	N	Y
Peru	Servicio Nacional de Meteorología e Hidrología del Perú	Y	N	N
Philippines	Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA)	Y	U	Y
Poland	Institute of Meteorology and Water Management	Y	U	Y
Portugal	Instituto Português do Mar e da Atmosfera (IPMA)	Y	U	Y
Qatar	Qatar Meteorology Department	U	U	Y
Republic of Korea	Korea Meteorological Administration	Y	Y	Y
Republic of Moldova	Serviciul Hidrometeorologic de Stat Moldova	U	N	N
Romania	National Meteorological Administration	Y	N	Y
Russian Federation	Russian Federal Service for Hydrometeorology and Environmental Monitoring	Y	Y	Y
Rwanda	Rwanda Meteorology Agency	Y	N	Y
Saint Lucia	Saint Lucia Meteorological Services (SLMS)	U	N	Y

Samoa	Samoa Meteorology Division	N	N	Y
Sao Tome and Principe	Instituto Nacional de Meteorologia	N	N	Y
Saudi Arabia	The General Authority of Meteorology and Environmenal Protection	U	N	N
Senegal	Direction de la Meteorologie, Meteorological Branch (ANACIM)	Y	U	Y
Serbia	Republic Hydrometeorological Service of Serbia	Y	U	Y
Seychelles	Service Meteorologiques Nationale des Seychelles (National Meteorological Services of Seychelles)	N	N	Y
Sierra Leone	Sierra Leone Meteorological Department	U	N	Y
Singapore	Meteorological Service Singapore (MSS)	Y	Y	Y
Slovakia	Slovak Hydrometeorological Institute (SHMU)	Y	U	Y
Slovenia	Slovenian Environment Agency (ARSO)	Y	U	Y
Solomon Islands	Solomon Islands Meteorological Service	N	N	Y
Somalia	Permanent Mission of Somalia	U	N	N
South Africa	South African Weather Service	Y	U	Y
Spain	Agencia Estatal de Meteorología (AEMET)	Y	Y	Y
Sri Lanka	Department of Meteorology	U	N	Y
Sudan	Sudan Meteorological Authority	U	N	N
Suriname	Meteorological Service	U	N	N
Swaziland	National Meteorological Service	U	N	Y
Sweden	Swedish Meteorological and Hydrological Institute	Y	Y	Y
Switzerland	MeteoSwiss	Y	Y	Y
Syrian Arab Republic	Ministry of Defence Meteorological Department	N	N	N
Tajikistan	State Administration for Hydrometeorlogy of the Republic of Tajikistan	Y	N	Y
Thailand	Thai Meteorological Department	Y	U	Y
The former Yugoslav Republic of Macedonia	Hydrometeorological Service (NHMS)	U	N	N
Timor-Leste	Dirrecão Nacional Meteorologia e Geofisica	U	N	N
Togo	Direction Generale de la Meteorologie	U	N	Y
Tonga	Tonga Meteorological Service	N	N	Y

Trinidad and Tobago	Trinidad and Tobago Meteorological Service	N	N	Y
Tunisia	Institut National de la Meteorologie	Y	N	Y
Turkey	Turkish State Meteorological Service	Y	U	Y
Turkmenistan	Administration of Hydrometeorology	U	N	N
Uganda	Uganda National Meteorological Authority	U	N	Y
Ukraine	Ukrainian Hydrometeorological Center	U	U	Y
United Arab Emirates	The National Center of Meteorology and Seismology (NCMS)	U	U	Y
United Kingdom of Great Britain and Northern Ireland	Met Office	Y	Y	Y
United Republic of Tanzania	Tanzania Meteorological Agency	Y	U	Y
United States of America	National Oceanic and Atmospheric Administration (NOAA)	Y	Y	Y
Uruguay	Instituto Uruguayo de Meteorologia (INUMET)	U	N	Y
Uzbekistan	Centre of Hydrometeorological Service of the Republic of Uzbekistan (Uzhydromet)	Y	N	Y
Vanuatu	Vanuatu Meteorological Services	N	N	Y
Venezuela	Instituto Nacional de Meteorologia e Hidrologia de la Republica Bolivariana de Venezuela (INAMEH)	U	N	N
Viet Nam	National Hydro-Meteorological Service of Viet Nam	Y	N	N
Yemen	Civil Aviation & Met Authority - Yemen meteorological Service	Y	N	Y
Zambia	Zambia Meteorological Department (ZMD)	U	N	Y
Zimbabwe	Meteorological Services Department	U	N	Y