Analysis of vulnerability of ATM to weather phenomena

Vittorio Di Vito¹, Edoardo Bucchignani¹, Roberto Valentino Montaquila¹, Giovanni Cerasuolo¹, Myriam Montesarchio¹, Alessandra Lucia Zollo¹, Davide Cinquegrana¹

¹CIRA, Italian Aerospace Research Centre, Via Maiorise snc, 81043 Capua (CE), Italy
E-mail: v.divito@cira.it, m.montesarchio@cira.it

Abstract. Weather conditions and Air Traffic Management (ATM) operations are strongly related, due to the relevant influence that the observed and forecasted weather conditions into assigned airspace have on the operational conditions that are therefore possible for such airspace. In the framework of the SESAR JU funded project CREATE (Innovative operations and climate and weather models to improve ATM resilience and reduce impacts), therefore, a dedicated study has been carried out in order to investigate the relation between weather and ATM. Such study both investigated the consequences that adverse weather conditions can have on ATM and, on the other side, addressed the currently and future available tools that can support ATM in the prediction and management of weather conditions from the aeronautical operations point of view. In this paper, the results of such literature study are outlined. More in details, in the paper first the main outcomes of the study are summarized, in terms of identification of the most relevant weather phenomena that affect the ATM operations, indication of their main impacts on them in terms of operational disruptions and, finally, identification of the associated level of severity. In particular, the above indicated aspects are addressed by taking into specific consideration the enroute and the TMA (Terminal Manoeuvring Area) flight phases and, for each of them, the main affecting weather phenomena and the main affected operations are identified. Then, in the paper the results of the study are summarized about the identification of the most relevant meteo tools that are expressed by state-of-the-art technologies to support the ATM operations in order to properly take into account the weather conditions in a precise and timely manner. This study addresses both the review of available and perspective tools for weather reporting and of the available and perspective numerical models supporting ATM in terms of weather models and air quality models.

1. Introduction
Weather phenomena such as low clouds, fog, rain, lightning, and thunderstorms may affect the visibility around airports or safe operability of aircraft, which can cause delays or disruptions in flight schedules. The severity and frequency of these weather phenomena may increase due to the changing climate. To improve ATM operations’ weather resilience in a changing climate (and, vice versa, to mitigate the effects of aviation on greenhouse gases and on air pollution), dedicated study of the relationship between environment and aviation, focusing on all ATM aspects, has been funded by SESAR JU through the Exploratory Research project CREATE (Innovative Operations and Climate and Weather Models to Improve ATM Resilience and Reduce Impacts) [1]. The project started in 2020 and is carried out by a consortium including: University of Naples “Parthenope”, CIRA, ISSNOVA, Universitat Politècnica de Catalunya, NLR, ARIANET, FMI.
The CREATE project aims achieving the following main objectives: assess the environmental and climate impacts of ATM operations, and find a solution to improve the resilience of ATM operations to adverse weather events [2].

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In the frame of the project, a study has been carried out aimed to:

- individuate the most relevant weather phenomena that affect the ATM operations, their main impacts in terms of operational disruptions and the associated level of severity;
- individuate the most relevant state-of-the-art meteo tools available to support ATM operations in order to properly take into account the weather conditions in a precise and timely manner.

The aim of this paper is to outline the main results of this study [3], whose outputs constitute the inputs for the subsequent project activities devoted to:

- the design of meteo tools able to detect and provide info about weather phenomena;
- the design of the tactical trajectory management tools for enroute and TMA [4].

More in details, in the following of this paper the main outcomes of the study about identification of vulnerability of ATM with respect to weather phenomena and about identification of main impacting weather phenomena and main impacted ATM performance areas are reported in section 2. Then, in section 3, the most relevant results about the identification of state-of-the-art technologies to support the ATM operations, in order to properly take into account the weather conditions in a precise and timely manner, are outlined. In section 4, finally, some concluding remarks are summarized.

2. Vulnerability of the Air Traffic Management system to weather phenomena

Severe weather conditions can disrupt ATM operations, both in enroute and in TMA. The International Air Transport Association (IATA) identifies weather events as the first threat contributing to aircraft accidents and, according to the NTSB (National Transportation Safety Board) based statistics, about 30% of accidents is related to weather conditions, as for instance emphasized by the following figures (Figure 1, Figure 2, Figure 3) and considerations:

- Small non-commercial airplanes: highest number of weather-related accidents (88% of all accidents for the period 2000-2011);
- Commercial jet aircraft: over 70% of weather-related accidents for the period 2000-2011 was related to turbulence.

![Figure 1. Breakdown of Weather-related Accident Citations 2003–2007 [5]](image1)

![Figure 2. Small aircraft weather as cause/factor during all accidents for 2000-2011 [6]](image2)
Extreme weather events can have different impacts on operational procedures, infrastructure and working conditions of the air system and these in turn involve different operational reaction patterns, as indicated in the following Figure 4.

**Figure 3.** Commercial jet aircraft weather related cause/factors for 2000-2011 [7]

![Weather Impact](image)

**Figure 4.** Weather events, impact on the aviation system and operational reaction patterns [8]

The analysis of the operations, enroute and in TMA, has been carried out taking into consideration the main applicable performance areas and indicators defined in the “SESAR performance framework”, which encompasses both the performance management process and the application of the relevant performance framework concepts of Key Performance Areas (KPAs) and related Key Performance Indicators (KPIs) for the purpose of assessing performance and tracking achievement of targets. The SESAR Performance Framework addresses the following Key Performance Areas: Safety, Security, Environment, Capacity, Predictability and Punctuality, Cost Efficiency, Flexibility, Access and Equity, Human Performance, Civil Military Cooperation and Coordination, Cost Benefits Analysis. In the CREATE project study here considered, nevertheless, the Security, Access and Equity, Civil Military Cooperation and Coordination KPAs were out of the scope, because issues such as security, equity and civil military cooperation do not affect the correlation between ATM and weather phenomena. For example, the hijacking of an aircraft is part of security, i.e. an accident not attributable to weather phenomena, but to human decisions.

Based on the results of the study and expected, the main weather phenomena affecting ATM are: Ice, Air turbulence, Hail damage, Lightning strike, Volcanic ash, Strong low level/surface winds, Tornadoes,
Thunderstorms and heavy showers, Fog, rain and snow. The study carried out in the CREATE project, nevertheless, aimed to implement an original and innovative approach, consisting in the evaluation of the severity of impact of the indicated weather phenomena on the ATM assuming a severity classification similar to the one adopted by EUROCAE through its Hazards Classification methodology, as indicated in the following Table 1.

The main outcomes of such study are summarized in the following Table 2 and Table 3, with reference to enroute and TMA operations, respectively, where a score has been assigned, based on proper evaluation performed in the study, to the impact that the weather phenomena have on KPAs, considering the criteria described in the EUROCAE Hazards Classification (Table 1). More in details, Table 2 (referred to enroute operations) and Table 3 (referred to TMA operations) have been elaborated based on detailed analysis of literature and/or projects documents and the assigned scores are to be interpreted according to EUROCAE Hazards Classification outlined in Table 1, ranging from 1 (indicating the highest severity) to 5 (indicating the lowest severity).

As it can be noticed, not all relevant weather phenomena can be associated, in terms of existing impact, to all operations, because enroute operations are not affected by issues related to strong low level and surface winds or to tornadoes.

### Table 1. EUROCAE Hazards Classification [9]

| Hazard Class | 1 (most severe) | 2 | 3 | 4 | 5 (least severe) |
|--------------|-----------------|---|---|---|-----------------|
| **Effect on Operations** | Normal with hull loss. Total loss of flight control, mid-air collision, flight into terrain or high-speed surface movement collision. | Large reduction in safety margins or aircraft functional capabilities. | Significant reduction in safety margins or aircraft functional capabilities. | Slight reduction in safety margins or aircraft functional capabilities. | No effect on operational capabilities or safety. |
| **Effect on Occupants** | Multiple fatalities. | Serious or fatal injury a small number of passengers or cabin crew. | Physical distress, possibly including injuries. | Physical discomfort. | Inconvenience. |
| **Effect on Air Crew** | Fatalities or incapacitation | Physical distress or excessive workload impairs ability to perform tasks. | Physical discomfort, possibility including injuries or significant increase in workload | Slight increase in workload. | No effect on flight crew. |
| **Effect on Air Traffic Service** | Total loss of separation. | Large reduction in separation or a total loss of air traffic control for a significant time. | Significant reduction in separation or significant reduction in air traffic control capability. | Slight reduction in separation or slight reduction in air traffic control capability. | Slight increase in air traffic controller workload. |

### Table 2. Weather phenomena impact on enroute operations [3]

| KPAs | Ice | Air turbulence | Hail damage | Lightning strike | Volcanic Ash | Strong low level/surface winds | Tornadoes | Low cloud | Thunderstorms | Heavy showers | Fog | Rain | Snow |
|------|-----|----------------|-------------|-----------------|-------------|-----------------------------|-----------|----------|---------------|---------------|-----|------|------|
| Safety | 1   | 2              | 3           | 4               | 2           | N.A.                        | N.A.      | 4        | 5             |               |     |      |      |
| Environment | 2  | 3              | 3           | 3               | 1           | N.A.                        | N.A.      | 4        | 4             |               |     |      |      |
| Capacity | 2   | 3              | 4           | 4               | 1           | N.A.                        | N.A.      | 5        | 5             |               |     |      |      |
| Predictability and Punctuality | 2 | 3              | 3           | 4               | 1           | N.A.                        | N.A.      | 5        | 5             |               |     |      |      |
| Cost Efficiency | 1  | 3              | 3           | 3               | 1           | N.A.                        | N.A.      | 5        | 5             |               |     |      |      |
| Flexibility | 1   | 3              | 1           | 3               | 1           | N.A.                        | N.A.      | 5        | 5             |               |     |      |      |
| Human Performance | 1  | 1              | 3           | 3               | 1           | N.A.                        | N.A.      | 4        | 4             |               |     |      |      |
| Cost Benefits Analysis | 1   | 3              | 3           | 4               | 2           | N.A.                        | N.A.      | 5        | 5             |               |     |      |      |
Table 3. Weather phenomena impact on TMA operations [3]

| KPAs                      | Ice | Air turbulence | Hail damage | Lightning strike | Volcanic Ash | Strong low level/surface winds | Tornadoes | Low cloud thunderstorms heavy showers | Fog Rain Snow |
|---------------------------|-----|----------------|-------------|------------------|--------------|-------------------------------|-----------|--------------------------------------|---------------|
| Safety                    | 1   | 1              | 2           | 3                | 1            | 1                             | 1         | 3                                    | 4             |
| Environment               | 2   | 2              | 2           | 4                | 1            | 2                             | 1         | 3                                    | 3             |
| Capacity                  | 3   | 2              | 3           | 5                | 1            | 2                             | 1         | 4                                    | 4             |
| Predictability and Punctuality | 3   | 2              | 3           | 5                | 1            | 1                             | 1         | 4                                    | 4             |
| Cost Efficiency           | 1   | 3              | 2           | 4                | 1            | 1                             | 1         | 4                                    | 4             |
| Flexibility               | 2   | 2              | 2           | 4                | 1            | 1                             | 1         | 4                                    | 4             |
| Human Performance         | 2   | 2              | 2           | 4                | 1            | 1                             | 1         | 3                                    | 3             |
| Cost Benefits Analysis    | 1   | 3              | 2           | 5                | 2            | 2                             | 1         | 4                                    | 4             |

The study carried out in the project, then, identified the main affected KPAs for both enroute and TMA operations, as summarized in Table 4. Based on the analysis of such table, it can be derived that:
- for enroute operations, the most impacted KPA is Human Performance, while the most resilient KPA is Capacity (unless extreme events occur);
- for TMA operations, the most impacted KPA is Safety, while Capacity obtains the best average score.

Table 4. Mean impact of all meteo hazards (as overall) on the ATM related KPAs [3]

| KPAs                        | En-route operations | TMA operations |
|-----------------------------|---------------------|----------------|
| Safety                      | 3.0                 | 1.9            |
| Environment                 | 2.9                 | 2.2            |
| Capacity                    | 3.4                 | 2.8            |
| Predictability and Punctuality | 3.3              | 2.7            |
| Cost Efficiency             | 3.0                 | 2.3            |
| Flexibility                 | 2.7                 | 2.3            |
| Human Performance           | 2.4                 | 2.1            |
| Cost Benefits Analysis      | 3.3                 | 2.7            |

In terms of identification of main affecting weather phenomena, finally, the results of the study carried out in the project are summarized in the following Table 5, which allows emphasizing that:
- formation of ice and volcanic eruptions can have a serious impact both on the enroute and on the TMA operations;
- tornadoes and low-level winds can have a strong impact on the TMA operations;
- rains and thunderstorms are generally well tolerated in the enroute phase.

Table 5. Mean impact of specific meteo hazards on the ATM operations [3]

|                    | Ice | Air turbulence | Hail damage | Lightning strike | Volcanic Ash | Strong low level/surface winds | Tornadoes | Low cloud thunderstorms heavy showers | Fog Rain Snow |
|--------------------|-----|----------------|-------------|------------------|--------------|-------------------------------|-----------|--------------------------------------|---------------|
| En-route operations| 1.4 | 2.6            | 2.9         | 3.5              | 1.3          | N.A.                          | N.A       | 4.6                                  | 4.8            |
| TMA operations     | 1.9 | 2.1            | 2.3         | 4.3              | 1.1          | 1.4                           | 1.0       | 3.6                                  | 3.8            |
3. Meteo tools supporting Air Traffic Management

Monitoring and forecasting of weather conditions occurring over an airport or along a flight route are crucial aspects in aviation operations, and are aimed to ensure the safety and efficiency of operations. The aviation community receives information about weather conditions in different ways:

- **Weather reports**: they contain observations and forecasts for selected locations and areas, following specific standard regulated from the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO). The most frequently used report to support aviation are: METAR (Meteorological Aviation Routine Weather Report) SPECI (Aviation Special Weather Report); PIREP (Pilot Weather Reports); SIGWX (Significant Weather Forecasts); TAF Terminal Aerodrome Forecasts); AIRMETs and SIGMETs.

- **Systems**: during the last years, newer developments in internet-based weather services, and especially the innovations driven by the usage of mobile devices and GPS navigation systems, were pioneering the introduction of primarily graphical and interactive accessible weather information for aeronautical users. Currently, several systems are available, operationally used or under development, devoted to integrate different meteorological information (observed and forecasted). Examples of systems are:
  1. AWDSS (Aviation Weather Decision Support System) - It is devoted to support airport operations related to aviation. It integrates weather data coming from different sources in order to provide warnings of weather hazards, providing end-user interface for operational meteorologists and air traffic controllers.
  2. ITWS (Integrated Terminal Weather System) - It is an ATM tool devoted to terminal air traffic managers and controllers, providing current and near-term forecasts of weather conditions. The aim is to reduce flight delays and improve safety of flight in adverse weather conditions, also reducing the terminal controller workload.
  3. 4DwxCube MET-GATE - It is a virtual repository of information produced by multiple meteo service and made available to ATM stakeholders via its SWIM compliant MET-GATE. It consolidates all the information, in such a way that the users can extract the details relevant to their situation.
  4. SESAR IMET project - Research project aimed to develop probabilistic trajectory prediction (PTP) and quantify the uncertainty in trajectory parameters due to weather conditions. Its approach can be used for flight planning applications in ATM systems.

- **Numerical models**: The importance of accurate weather forecast to support aviation is widely recognized: Numerical Weather Prediction (NWP) models take current weather observations as input through a process defined data assimilation, aimed to produce initial conditions for the meteorological variables, from the oceans to the top of the atmosphere. In particular, Limited Area Models (LAMs) are widely used to obtain detailed information over the geographic area of interest. Several LAMs are available and are currently operationally used by the national meteorological forecast services:
  1. WRF - Weather Research and Forecasting model is a mesoscale NWP system, provided by National Center for Atmospheric Research (NCAR).
  2. COSMO - Limited-area non-hydrostatic model developed within the framework of the European Consortium for Small-scale MOnitoring.
  3. ALADIN - High-resolution limited-area hydrostatic and non-hydrostatic model developed under the leadership of Météo-France.
  4. RAMS - Regional Atmospheric Modelling System developed at Colorado State University for numerical simulations of atmospheric meteorology and other environmental phenomena.

Air quality models (AQMs) play a fundamental role in both the understanding of individual processes and the whole atmospheric system, moreover they represent an important tool in weather/climate modelling, as they are used to study the air pollution – climate feedbacks. They provide information on air quality on the basis of the emissions and of the atmospheric processes that lead to pollutant dispersion, transport, chemical conversion and removal from the atmosphere by deposition.
The most popular way of AQMs classification, based on the model structure, is the following:

1. Deterministic models: calculation of pollutant concentrations from emission inventory and meteorological variables according to the solutions of various equations;
2. Statistical Models: evaluation of concentrations from meteorological and traffic parameters after that an appropriate statistical relationship has been obtained empirically from measured concentrations;
3. Physical Models: a real process is simulated on a smaller scale in laboratory by a physical experiment.

Both NWPs and AQMs are nonlinear dynamical systems, in which the evolution depends on the initial conditions. The chaotic nature of the atmosphere and the involvement of nonlinear dynamics imply that small errors in estimating the initial state of the atmosphere grow rapidly with time. As regards NWPs, in the last decade a great effort has been focused on enhancing the prediction quality, mainly by developing skilful models addressing the uncertainty of initial conditions by better estimation techniques, and also on developing physical parameterization models that lead to improved predictive skill. From these considerations, it is clear that the improvement in the weather forecasting can be achieved by investigating the following challenging areas: improvement of initial conditions, optimization of parameterization schemes (e.g. convection), ensemble forecasting, high resolution to improve the forecast of extreme weather hazards, introduction of new urban parameterization and adoption of the ensemble modelling approach.

For what concerns AQMs, since the development of the first one a great progress occurred, but there are still gaps in the knowledge and understanding, mostly due to the spatial and temporal scales of the problem. AQMs address more challenging problems than NWPs, since the first ones must also diagnose and predict a wider range of variables, including trace gases and aerosols, along with the interactions between them. In few words, the following challenging areas for AQMs have been individuated: coupling between meteorological and chemical transport models, introduction of more physically and chemically realistic and computationally efficient algorithms, improvement of input parameters, improvement of the procedure for the uncertainty evaluation.

4. Conclusions
Within the CREATE project, weather phenomena with a great impact on enroute and TMA operations have been analysed, along with meteo tools supporting ATM. Meteorological hazards have been identified considering KPAs, as defined in the SESAR performance framework and by using EUROCAE Hazards Classification. Human Performance and Safety are the most affected KPAs for enroute and TMA operations respectively; Capacity is the most resilient for both (unless extreme events occur). Several perspectives of innovations for NWP and AQM have been individuated aimed to improve weather forecasting and air pollution simulation. The results of this work are supporting the project activities for the design of meteo tools aimed to provide weather data (e.g. Decision Support Tools) and the trajectory optimization at tactical level.

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