A Probabilistic Storm Avoidance Concept for En-Route Flight

Antonio Franco, Alfonso Valenzuela,
and Damián Rivas
Department of Aerospace Engineering
ETSI, Universidad de Sevilla
Seville, Spain
{antfranco, avalenzuela, drivas}@us.es

Daniel Sacher and Jürgen Lang
MeteoSolutions GmbH
Darmstadt, Germany
{daniel.sacher, juergen.lang}
@meteosolutions.de

Thomas Hauf
Institute of Meteorology and
Climatology
Leibniz Universität Hannover
Hannover, Germany
hauf@muk.uni-hannover.de

Abstract— **In this paper a probabilistic weather avoidance concept is presented, which integrates new meteorological capabilities in the storm avoidance process, namely, probabilistic nowcasts. These new meteorological products provide not only a forecast of the storm evolution, but also information about the uncertainty of the convective cells. In this concept, the required input is a probabilistic nowcast and a risk level, which is an adjustable parameter intended to define the avoidance strategy. The output is a unique avoidance trajectory that takes into account the uncertainty of the convective cells, obtained for the given risk level. Simulation results show that the safety and the workload of pilots and air traffic controllers are improved, although with a small loss of flight efficiency, compared to today's practice. This new weather avoidance concept will be used in a follow-up project, with the goal of developing a Medium-Term Storm Avoidance tool intended to enhance air traffic control efficiency.**

***Keywords*— meteorological uncertainty; probabilistic storm avoidance; short-term trajectory planning.**

I. INTRODUCTION

Weather can significantly affect aircraft operations. In particular, thunderstorms and the additional associated phenomena (i.e. hail, severe icing, and severe turbulence) present serious hazards to aviation [1]. Furthermore, the individual storm cells comprising the storm field change with time and their evolution is very difficult to predict; some grow strongly, others decay, new ones appear, some merge and some split. The apparent motion of the storm field is not deterministic but has a stochastic component in it.

The major risk mitigation measure for thunderstorm hazards is thunderstorm avoidance. During the flight planning stage, aircraft operators have the opportunity of planning the routes to avoid areas of predicted storm activity. Once airborne, pilots are responsible of in-flight avoidance. For this purpose, aircraft are equipped with weather radars, which provide an indication of the intensity of the upcoming convective weather [2]. The tactical diversions required to minimize the risk of encountering severe turbulence increase the flight time and, therefore, the fuel consumption, thus negatively impacting flight efficiency and the environment. Additionally, the flight crew workload increases significantly in a weather avoidance scenario, not just because of the decision-making associated with weather avoidance but also because of turbulence, management of in-flight icing, and increased communications.

In convective scenarios, the workload of air traffic controllers also rises significantly, mainly because the air traffic becomes irregular and difficult to anticipate and there is less available airspace for conflict resolution. This increase in controllers' workload translates into a reduction of the airspace capacity. If the traffic demand exceeds the capacity, flow management regulations may be applied, such as re-routings or regulated take-off times, which cause further delays and inefficiencies.

In this paper we present a concept for *probabilistic storm avoidance* (PSA), that is the development of avoidance routes that take into account the information available about the uncertainty of the storm cells. These routes are called *probabilistic storm avoidance routes* in this work.

The development of the PSA concept requires the integration of new meteorological capabilities in the storm avoidance process, namely, ground-based probabilistic forecasts of the storm evolution, referred to as probabilistic nowcasts. These forecasts obtain the storm information from a cluster of ground-based weather radars (meteorological radar composite data), which has a larger coverage area than on-board weather radars. Using the composite radar data, it is possible to stochastically extrapolate the development of storms for the upcoming hour. The meteorological information consists mainly of forecasts of individual storm cells, their positions, extents, intensities, and cloud heights. Nowcasts are released every 5 or 10 minutes, and each release provides the meteorological information for equally spaced sampling times.

Thanks to the integration of these new meteorological capabilities, we expect that the PSA concept will enable the anticipation of the avoidance maneuvers, resulting in more predictable and safer deviations that decrease the subsequent tactical interventions. Since the information is available on ground, air traffic controllers could use these enhanced resources to better organize the traffic, and thus they could be involved with a more active role in the storm avoidance process.

To properly limit the scope of this work, we consider the en-route phase, with constant altitude flights and time evolving meteorology. The storm cells are modeled in 2D because, in practice, the storm avoidance is typically 2D (storm cells are rarely flown over because it is deemed to be too risky). (Nonetheless, extension to a 3D model would be straightforward, using the radar echo top information provided by the nowcasts.)

The methodology to generate the probabilistic storm avoidance routes relies on the use of a deterministic storm avoidance tool. In this work we use DIVMET [3], which was developed at the Leibniz Universität Hannover and is now a property of MeteoSolutions GmbH. DIVMET was also used in SESAR's TBO-Met project [4], which addressed the tactical prediction of en-route sector demand using an ensemble-based stochastic methodology, which takes into account the stochastic evolution of the convective cells obtained from nowcasts.

This work is under the scope of the thematic challenge *Efficient provision and use of meteorological information in ATM* of SESAR's Engage Knowledge Transfer Network, which has the objective of integrating suitable meteorological information into ATM stakeholders' planning and decision-making processes through the development of user-support tools.

II. METEOROLOGICAL INPUT

The probabilistic storm avoidance tool presented in this paper requires a probabilistic nowcast as input; in particular, we consider an *ensemble nowcast*. Such an advanced product is under development by the meteorological agencies, but, to the best of our knowledge, is not available yet. Hence, a statistical procedure has been developed in this work, which takes a deterministic nowcast as input and provides a probabilistic nowcast that follows an ensemble-based approach.

A. *Deterministic nowcast*

Nowcast models for convective weather phenomena usually use radar or satellite data, some in combination with wind data. Some nowcasts identify storms as objects in the current radar image at the prediction time T_P, extracting polygonal areas that exceed a certain reflectivity level in the radar data (e.g. 37dBZ is a widely used threshold to identify storms). In this case, the motion of any storm is determined by analyzing successive radar images up to T_P and serves as the base for further extrapolation to the sampling times $T_P + \Delta t, T_P + 2\Delta t, \ldots, T_P + (M-1)\Delta t$, with $T_F = (M-1)\Delta t$ being the nowcast lead time. This approach is called cell tracking and is suitable for identifying and tracking severe convective storms [5]. Following this approach, the nowcast can be seen as a set of M frames (one frame per nowcast sampling time, including the prediction time), and each one is composed of a set of storm cells characterized by their geometry and location.

Some other nowcast models process the complete radar reflectivity image, and extrapolate the whole radar image to the sampling times already defined ($T_P + k\Delta t$, with $k = 1, \ldots, M-1$). In this case, the nowcast does not identify storms, but it is a set of M frames (one frame per nowcast sampling time, including the prediction time), each one being composed of a radar image. In this case, a pre-processing has to be applied to extract polygons of thunderstorm cells from the raster data. This extraction relies on the principle that each raster element with a radar reflectivity greater than a suitable threshold belongs to an area of heavy rainfall and most likely to a thunderstorm cell. Then, by grouping these raster elements, contours of storm cells are obtained. The radar reflectivity is measured in decibels relative to Z (dBZ), which is the unit used in weather radars, and a common threshold for heavy rainfall is 35 dBZ.

In this work, the NowCastMIX-Aviation (NCM-A) is considered as the deterministic nowcast. NCM-A is a product of the Germany's National Meteorological Service (Deutscher Wetterdienst, DWD) that offers radar reflectivities in dBZ as short-term forecasts and covers a large area of Central Europe. The NCM-A data comes as raster data in GRIB file format with a spatial resolution of 1x1km. Each file contains 13 GRIB messages, one message for the observation and 12 messages of forecasts up to one hour in 5-minute time resolution; in other words, the nowcast sampling interval considered is $\Delta t = 5$ min, and the nowcast lead time is $T_F = 60$ min, so that it has 13 frames ($M = 13$). The update cycle of NCM-A data is 5 minutes as well; that is, a new set of 13 frames is released every 5 minutes. The polygons of thunderstorm cells are obtained from the raster considering a radar reflectivity threshold of 37dBZ.

B. *Ensemble of nowcasts*

To develop a probabilistic nowcast, we assume that the main source of uncertainty is the location of the individual storm cells. Hence, we apply a similar procedure as the one used in TBO-Met project [4], which generates each nowcast ensemble member by randomly perturbing the position of the storm cells predicted by the deterministic nowcast. The displacement errors of any storm cell at any nowcast sampling time are taken as independent Gaussian random variables. The standard deviations increase with the forecast sampling time and are consistent with the empirical laws by Sauer et al. [6]. Both space and temporal correlations of displacement errors are neglected. Following this procedure, each ensemble member contains the same pieces of information as the deterministic nowcast, namely, a set of M frames (one frame per nowcast sampling time), and each frame is composed of a set of storm cells characterized by their geometry and their location.

In this work the polygons of heavy rainfall obtained from the NCM-A data are perturbed in location to produce a synthetic ensemble of nowcasts of 100 ensemble members.

III. PSA CONCEPT

In this section we describe the probabilistic storm avoidance tool developed to implement the PSA concept. As already indicated, this tool relies on the use of DIVMET, and it is called DIVMET-P. The required input for DIVMET-P is composed of a reference trajectory, the wind and temperature fields, a probabilistic nowcast (providing information about the uncertainty of the convective cells), and a risk level, which is an adjustable parameter intended to define the avoidance strategy. The output is a probabilistic avoidance trajectory, which is a unique trajectory obtained for a given risk level. A high-level conceptual description of DIVMET-P is sketched in Fig. 1.

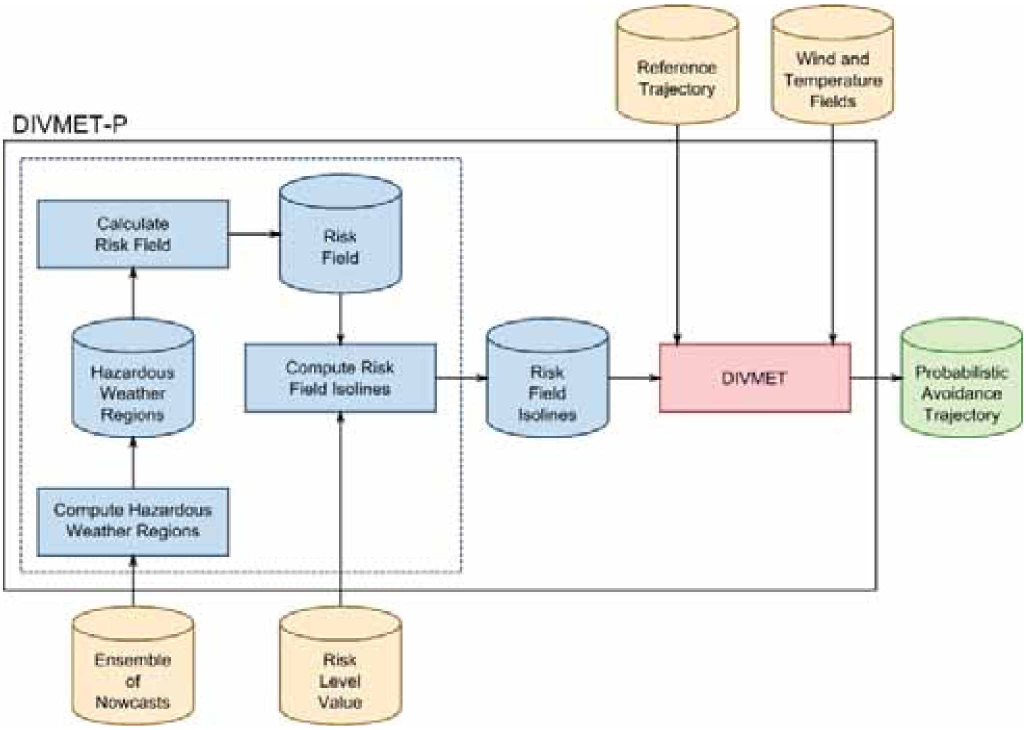

Figure 1. DIVMET-P block diagram

DIVMET-P performs the following four steps. First, it computes the *hazardous weather regions* by extending every storm cell with a safety margin, which is done for each ensemble member of the probabilistic nowcast. Appropriate filtering is applied to merge intersecting regions and remove regions inside other regions.

Then, DIVMET-P computes the probability that a given location be affected by adverse weather at a given nowcast sampling time, which is called *risk* in the context of this project. The spatial risk distribution obtained is referred to as ***risk field***. To obtain the risk field for each nowcast sampling time, an airspace tessellation is assumed so that it is divided into tiles, which are defined by a given grid. Then, the risk field at a given grid tile and nowcast sampling time is computed as the percentage of ensemble members forecasting that grid tile being covered by a hazardous weather region. For instance, a 40% risk at a given grid tile and for a nowcast sampling time means that this tile is covered by a hazardous weather region in 40% of the ensemble members of the probabilistic nowcast at that nowcast sampling time.

Afterwards, DIVMET-P proceeds to obtain the risk field isolines that correspond to the given risk level value. The risk level is a user-selectable parameter introduced in DIVMET-P to control the modelling of the no-fly regions so as to capture the different avoidance strategies that can be adopted when facing uncertain weather hazards. The risk level is taken as the maximum admissible risk in the avoidance strategy; hence, it ranges from 0% (accounting for the most conservative avoidance strategy) to 100% (accounting for the riskiest avoidance strategy). Therefore, the areas where the risk field is higher than or equal to the specified risk level are to be taken as no-fly regions, and the boundaries of these areas are defined by the risk field isolines that correspond to the selected risk level. Note that there is one risk field per nowcast sampling time; accordingly, DIVMET-P computes a possibly different set of no-fly regions for each nowcast sampling time, leading to a time-evolving description of the no-fly regions. Indeed, although the uncertainty increases along time, the time evolution of the no-fly regions strongly depends on the risk level value considered to compute them. For high risk level values, the no-fly regions tend to shrink along time, whereas they tend to grow along time for low risk level values.

Finally, once the set of no-fly regions has been obtained from the given probabilistic nowcast and the specified risk level, the deterministic avoidance tool (DIVMET) is applied to obtain the corresponding avoidance route, which circumvents the no-fly regions and reattaches to the given reference trajectory. This probabilistic avoidance route is a unique planned route to avoid the storm cells for the given risk level. Again, as an example, the avoidance route for risk level 40% is such that the probability that each point of the route be inside a storm cell is equal or lower than 40 %. It is important to remark that DIVMET-P also provides an estimation of the flight times along the route.

The risk level is expected to have an important effect on the resulting avoidance route. The choice of a high risk level is equivalent to deciding to deviate very little from the reference trajectory, what in principle could seem to be beneficial, but would require to face the eventual incursions into storm cells tactically, which is neither efficient nor safe. Conversely, choosing a small enough risk level would allow to prevent the avoidance trajectory from zigzagging around the hazardous regions and from getting into narrow corridors between pairs of them. However, on one hand, a small risk level would reduce the airspace permeability and, thus, would increase the interactions with other trajectories and, on the other hand, it would lead to proactively solving contingencies that might not even happen, increasing the deviation from the reference trajectory. Therefore, by properly choosing the risk level (for some intermediate values) one can obtain safer and more efficient intermediate solutions between underreacting and overreacting to the weather hazard information.

IV. ILLUSTRATIVE EXAMPLE

In this section an illustrative example is presented, which shows the potential of the PSA concept to facilitate an enhanced storm-avoidance process. In this application, several probabilistic avoidance routes are computed for a given flight. The corresponding reference route is originally planned at constant course from an initial waypoint at 42.2260° N, 009.3642° E, to a final waypoint at 46.8390° N, 001.1576° E; the initial time (which coincides with the prediction time, T_P) is 14:00, 22nd June 2017. This reference route lies within the NCM-A coverage area.

The NCM-A deterministic nowcast corresponding to that prediction time has been pre-processed to obtain the polygons of thunderstorm cells at each nowcast sampling time. These are depicted in Fig. 2 in blue for the observation at the nowcast prediction time and in red for the subsequent sampling times. Note that the figure only covers an area close to the considered flight, whose reference route is also shown.

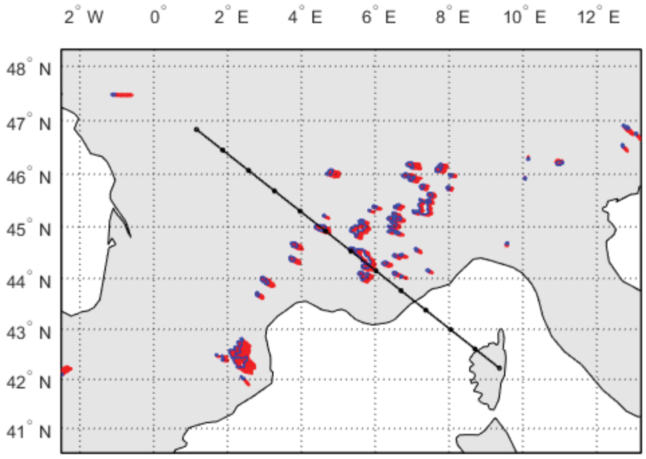

Figure 2. Thunderstorm cells nowcasted at 14:00, 22/06/2017, and reference route of the flight considered. Observation at T_P (blue), future extrapolations (red), and reference route (black).

Then, the ensemble of nowcasts is generated according to the procedure explained before. The polygons describing the individual storm cells at $T_P + 20$ min for all the ensemble members are depicted in Fig. 3 (recall that a total of 100 members are generated), whereas those corresponding to the 50th ensemble member are depicted in Fig. 4. A close comparison of both pictures gives a clear impression of the uncertainty in the location of the storm cells at that forecast sampling time.

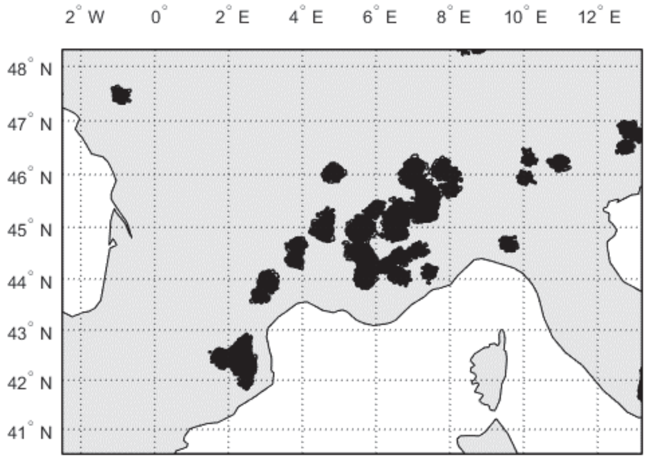

Figure 3. Joint picture of all the nowcast ensemble members at $T_P + 20$ min.

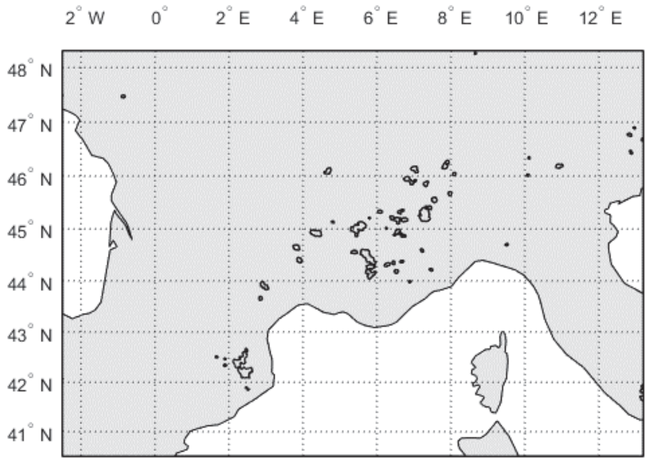

Figure 4. Ensemble member #50 at $T_P + 20$ min.

Once the enhanced meteorological input is available, the first step in DIVMET-P is the computation of the hazardous weather regions, as explained above. This gives a set of polygons for each nowcast ensemble member at each nowcast sampling time. The hazardous weather regions at $T_P + 20$ min, for the 50th ensemble member, and for a 10 NM safety margin are depicted in Fig. 5 (in yellow) along with the corresponding individual storm cells (in black). The clustering effect is clearly visible in this image.

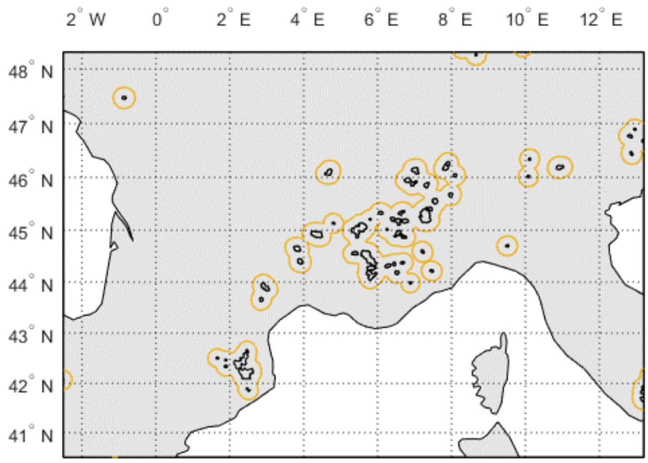

Figure 5. Hazardous weather regions (yellow) for a 10 NM safety margin. Ensemble member #50 at $T_P + 20$ min.

The next computation performed by DIVMET-P is the determination of the risk field associated to the hazardous weather regions, for a given safety margin. Fig. 6 shows the risk field at $T_P + 20$ min for a 10 NM safety margin. Then, the risk field isolines are computed for a given risk level value. In this example, results are presented for some risk level values (10%, 50%, and 90%) in Fig. 7.

Finally, DIVMET is applied to obtain the corresponding avoidance route, which circumvents the no-fly regions and reattaches to the given reference trajectory. The probabilistic avoidance trajectories corresponding to two different risk level values (50% and 90%) are given in Figs. 8 and 9, respectively (also, for reference, the isolines at $T_P + 20$ min are depicted). These figures show the expected effect that the magnitude of the diversion decreases with growing risk level value.

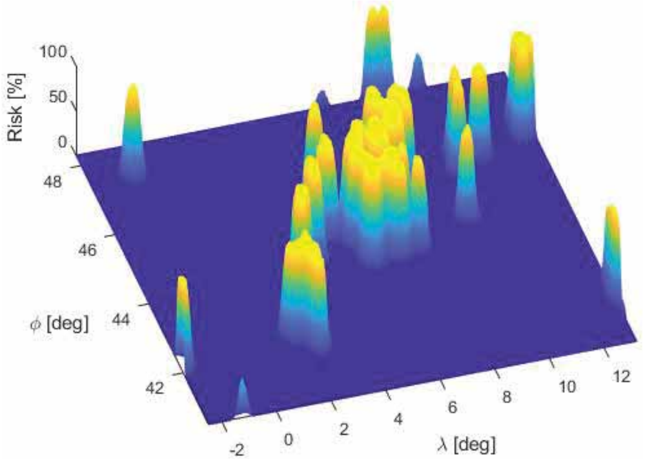

Figure 6. Risk field at $T_P + 20$ min for a 10 NM safety margin.

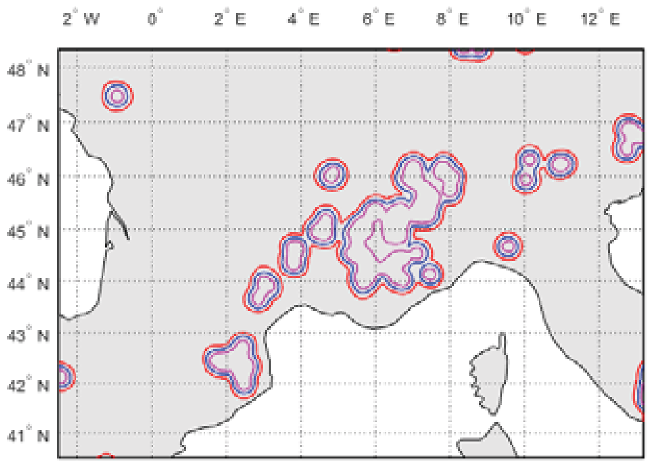

Figure 7. Risk field isolines at $T_P + 20$ min. Risk level values 10% (red), 50% (blue), and 90% (magenta).

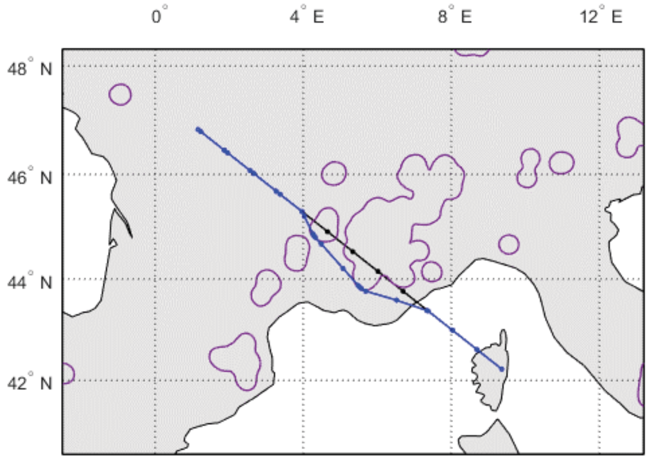

Figure 8. Probabilistic avoidance route for a 50% risk level value. Reference trajectory (black), avoidance trajectory (blue), and risk isolines at $T_P + 20$ min (purple).

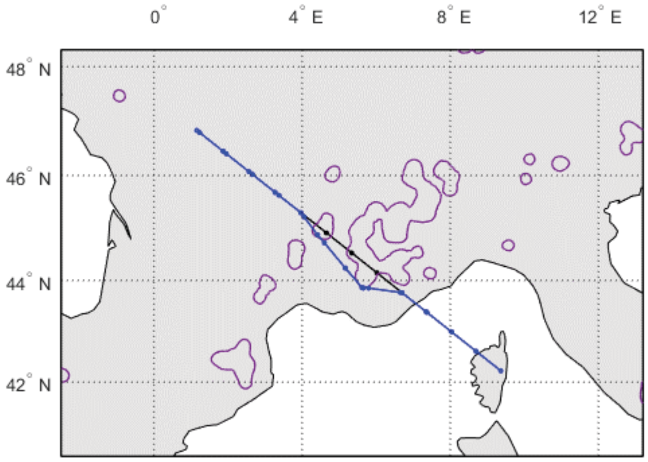

Figure 9. Probabilistic avoidance route for a 90% risk level value. Reference trajectory (black), avoidance trajectory (blue), and risk isolines at $T_P + 20$ min (purple).

V. CONCEPT ASSESSMENT

The objective of the concept assessment is twofold. First, to study the effects of the risk level on the probabilistic weather avoidance routes. Second, to evaluate the costs and benefits resulting from the aircraft following these avoidance routes. This evaluation focuses on the following performance areas: flight efficiency, safety, and workload.

The assessment is based on fast-time simulations of a given scenario, which corresponds to a real storm situation and comprises a set of synthetic flights that pass through the region affected by the storm. Since the scope of this project is the en-route phase, all flights are operated at constant altitude and speed.

In this study, for each flight, one has the following trajectories:

- Reference trajectory: Planned trajectory that the aircraft agreed to fly without taking the storm into account.
- Probabilistic avoidance trajectory: Planned route generated by using DIVMET-P and the probabilistic nowcasts, and its corresponding flight times, which avoids the no-fly regions obtained for a selected risk level value and reattaches to the reference trajectory.
- Executed reference trajectory: Trajectory flown by the aircraft when it executes the reference trajectory and faces the actual weather realizations. In this trajectory, the aircraft may tactically deviate to circumvent the realized storm cells.
- Executed avoidance trajectory: Trajectory flown by the aircraft when it executes the probabilistic avoidance trajectory and faces the actual weather realizations. As in the previous one, the aircraft may tactically deviate to circumvent the realized storm cells.

The simulation process is as follows. The scenario starts at a given time; at that time, the positions of all the aircraft, their reference trajectories, and the probabilistic nowcast are known. First, various probabilistic avoidance trajectories are generated for each aircraft by DIVMET-P, each one for a different risk level value. Then, the execution of each avoidance trajectory is simulated using the deterministic DIVMET and the actual weather realizations (see subsection *A* below). The executed reference trajectories are also simulated by DIVMET; they represent today's practice, where the flights follow the reference trajectories and the storms are just tactically faced. Once all the simulations are performed, the obtained paths and flight times are analyzed.

The following subsections describe 1) the meteorological data, 2) the simulation scenario, 3) the assessment indicators, and 4) the assessment results.

A. Meteorological data

The meteorological data has been described in Section II. The actual weather realizations are also obtained from NCM-A. They are given in the first message (weather observation) of consecutive NCM-A releases (every 5 minutes).

B. Simulation scenario

The scenario corresponds to a real heavy storm episode that took place over Germany on 29th June 2017. The starting time of this scenario is 20:30. The flights are generated so as to have a very demanding scenario: each reference trajectory is devised to interact with at least one forecasted storm cell. They are randomly generated according to the following criteria:

- The initial location and course of each flight are such that every aircraft is initially located at 20 minutes from the first encounter with a no-fly regions (20 minutes is the time horizon envisioned for the future Medium-Term Storm Avoidance tool introduced in section VII).
- The reference trajectories are flown at constant course and the airspeed is 230 m/s (approximately equivalent to Mach 0.78 at FL 360).
- The time to the final point is 60 minutes.
- All reference trajectories lie within the NCM-A coverage area.

A total of 988 flights have been generated, which are shown in Fig. 10, along with the NCM-A coverage area (included as a reference).

In order to analyze the effects of the risk level value, the probabilistic avoidance routes are generated for three different values of this parameter: 10%, 50%, and 90% (low, medium and high values). The safety margin considered in the assessment is 10 NM. Although DIVMET-P allows for the consideration of arbitrary wind and temperature fields, to ease the interpretation of the results, the international standard atmosphere with no wind is assumed for the simulations.

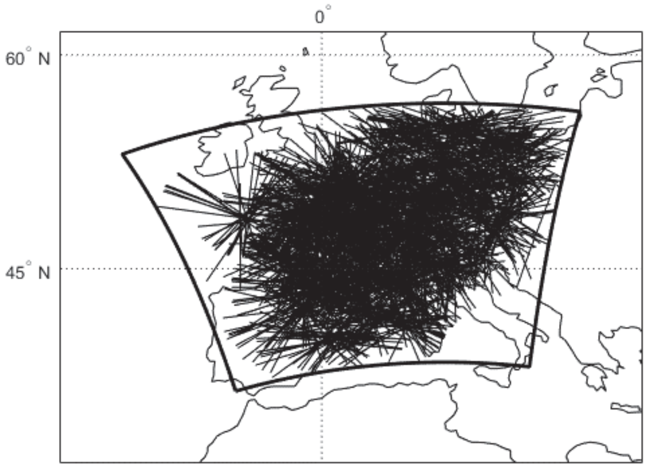

Figure 10. Reference trajectories.

C. Assessment indicators

In this assessment, we focus on the following three indicators for each risk level value:

- Percentage of avoidance trajectories different from the corresponding reference trajectories.

  An avoidance trajectory is considered to be different from a reference trajectory if it is laterally deviated more than 0.5 NM.

- Average number of tactical deviations per flight.

  An aircraft is tactically deviated from its planned trajectory (reference or avoidance trajectory) if the corresponding executed trajectory is deviated more than 0.5 NM from this planned trajectory. Multiple deviations may occur if, after the first deviation, the aircraft reattaches to the planned trajectory for at least 10 NM and then it deviates again. This indicator is related to: 1) the safety of the flights, because a pilot has to deviate tactically when the planned trajectory runs into a realized storm cell in order to avoid the associated hazardous phenomena, and 2) the workload of pilots and controllers, because in a tactical deviation the pilot is taking corrective actions that have to be coordinated with the air traffic controller.

- Difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories.

  The difference between these arrival times indicates whether the flights arrive earlier or later to their destinations than today's practice and, consequently, if they spend more or less fuel due to executing the avoidance trajectories. Therefore, it shows how the flight efficiency is affected. The measure of this indicator is given in terms of average and standard deviation.

D. Assessment results

In this section, all the simulations have been performed using the synthetic ensemble nowcast and the DIVMET-P tool already described.

1) Avoidance trajectories different from the corresponding reference trajectories

The percentage of avoidance trajectories different from the corresponding reference trajectories is shown in Table I. It can be seen that the percentage values are quite large in all cases; this is because all flights have been generated to encounter the storm, resulting in a very severe scenario. Also, it can be seen that these numbers decrease as the risk level increases; since the no-fly regions become smaller for larger values of the risk level, less flights are affected by the storm.

TABLE I. PERCENTAGE OF AVOIDANCE TRAJECTORIES DIFFERENT FROM THE CORRESPONDING REFERENCE TRAJECTORIES.

	Risk level		
	10%	50%	90%
Percentage	90.6	85.3	72.2

2) Tactical deviations per flight, and their magnitude

The average number of tactical deviations per flight is shown in Table II for aircraft following the avoidance and the reference routes. The number of deviations for high values of the risk level (90%) are very similar to today's practice, but they are smaller for medium and small risk level values (10% and 50%).

TABLE II. AVERAGE NUMBER OF TACTICAL DEVIATIONS PER FLIGHT.

	Risk level			Ref. traject.
	10%	50%	90%	
Average	0.67	0.87	1.02	0.99

Notice that, although the number of deviations is not improved for high risk level values, the results presented in Table III show that these deviations are smaller. The magnitude of the tactical deviations is measured as the difference between the arrival times of the executed trajectories and the arrival times of the corresponding planned trajectories (either the avoidance or the reference trajectories). A positive value means that the aircraft arrives later than planned and therefore the deviation is larger, and vice versa. In Table III it can be seen that following the reference trajectories leads to larger deviations: the results show larger values of average delay and dispersion (standard deviation). Following the avoidance route substantially reduces the magnitude of the tactical deviations, even for high risk level values; for example, for risk level 90% the average is cut by half, and the standard deviation is also strongly reduced. Smaller risk level values further reduce the magnitude of the tactical deviations.

TABLE III. DIFFERENCE BETWEEN THE ARRIVAL TIMES OF THE EXECUTED TRAJECTORIES AND THE ARRIVAL TIMES OF THE CORRESPONDING PLANNED TRAJECTORIES.

	Risk level			Ref. traject.
	10%	50%	90%	
Average [s]	14	29	38	79
Std. dev. [s]	61	77	81	116

In summary, by following the probabilistic avoidance routes, the safety of the flights and the workload of pilots and controllers can be improved: less tactical deviations are required and the remaining deviations are smaller, facilitating the work in the cockpit and the coordination with ATC.

3) Difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories

The difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories is shown in Table IV. Note that a positive difference means that the aircraft would arrive later to its destination if it executed the avoidance route (thus consuming more fuel), and vice versa. The average value shows that, for all risk levels, there is a penalty for executing the avoidance route; however, this penalty is small (less than 1 minute in 60-minute trajectories) and decreases as the risk level increases. The standard deviation indicates that this decrement is general for all flights. Therefore, the flight efficiency is not improved, but is only slightly penalized.

TABLE IV. DIFFERENCE BETWEEN THE ARRIVAL TIMES OF THE EXECUTED AVOIDANCE TRAJECTORIES AND THE ARRIVAL TIMES OF THE CORRESPONDING EXECUTED REFERENCE TRAJECTORIES.

	Risk level		
	10%	50%	90%
Average [s]	48	24	13
Standard deviation [s]	90	65	62

VI. CONCLUSIONS

This work has shown that the uncertainty which is present in the storm-avoidance process can be taken into account. Hence, the development of tools that integrate this type of uncertainty is shown to be viable. This integration would lead to having an improved situational awareness, which in turn would facilitate an anticipated and better-informed decision making. The expected benefits will come from the identification of more efficient and safer storm-avoidance strategies.

We have developed a probabilistic storm avoidance concept, based on the use of probabilistic weather nowcasts. This concept constitutes a clear contribution to advancing the state of the art in storm avoidance, which is presently based on deterministic nowcasting. Moreover, in today's practice, the deviations and delays caused by storms are not anticipated in the planned trajectories (the reference trajectories, which are not modified to face the storm) but they are tactically generated.

The probabilistic storm avoidance concept has crystallized into a probabilistic version of DIVMET, called DIVMET-P. This tool has allowed for the conduction of a concept assessment, which has provided a preliminary quantification of the costs and benefits resulting from aircraft following probabilistic storm avoidance trajectories. As a general conclusion, by considering the probabilistic avoidance trajectory instead of the reference trajectory, some of the inevitable weather-related deviations and delays are anticipated, leading to smaller subsequent tactical deviations and delays, at the cost of a slight increase in the executed time of arrival. Equivalently, the safety and the workload are improved at the cost of a small loss of flight efficiency.

Another relevant point is that further improvements are needed in the trajectory simulator to improve the acceptability by pilots and controllers: integration of common airlines policies to avoid storms, and inclusion of restrictions to prevent the flights from invading active airspace restrictions or adjacent sectors.

VII. NEXT STEPS

To bring current research to higher technology readiness levels (TRL), the following research action is planned: The development of a Medium-Term Storm Avoidance (MTSA) tool, for which the probabilistic storm avoidance concept developed in this work will be the key enabler. This tool would allow air traffic controllers to be involved with a more active role in the storm-avoidance process.

A. *MTSA tool concept*

The MTSA tool will detect and warn the controllers of those flights predicted to run into storm cells in the next 20 minutes, and will help controllers to determine an appropriate avoidance route for each flight. Once the controllers decide that an avoidance route fits the traffic situation, the pilots will be offered this route. The MTSA tool is intended to complement, not replace, the current practice in which pilots evade the storm using the on-board weather radar. If during the execution of the avoidance route the pilot notices that the aircraft runs into any storm cell, then the pilot will still be allowed to perform tactical diversions.

With the MTSA tool, the workload of tactical and planning tasks is expected to become more evenly balanced, enhancing sector team efficiency and providing a safer and better service to airspace users, and to reduce the trajectory uncertainty associated to storm avoidance.

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