A GIS-based tool for the estimation of impacts of volcanic ash dispersal on European air traffic

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***Abstract*—Impacts of volcanic ash on air traffic have been reconsidered in the aftermath of the 2010 eruption of Eyjafjallajökull volcano (Iceland), which caused great impacts to the European air traffic network. We present a GIS-based methodology to estimate the impacts of tephra dispersal from explosive volcanic eruptions aimed at improving air traffic management in case of ash-contaminated airspace. We use the 2010 Eyjafjallajökull eruption as a case study with two main objectives: to introduce the methodology and to perform *a posteriori* analysis of the 2010 aviation breakdown. Modelling results of atmospheric tephra dispersal over Europe build upon a reanalysis dataset of meteorological and volcanological parameters. Given that there is still no consensus on thresholds of ash concentration that is critical for flight safety, the methodology takes into account several ash concentration values. Results are hourly tables and maps containing information on potentially affected airports and routes at different Flight Levels (FLs). This allows estimating impacts at a high temporal frequency. We also compute daily-accumulated impacts for each FL. We compare our results with the 2010 impacts. Furthermore, advantages and disadvantages of this methodology are discussed and compared with similar existing tools. Finally, we underline possible improvements of the methodology and describe further work.**

I. INTRODUCTION

Tephra dispersal is a common phenomenon during explosive volcanic eruptions and can affect downwind areas at regional to global scales. It is well recognized since the first serious jet engine aircraft encounter with ash in the 80s [9] that ash contamination of airspace can cause short to long-term disruptions to airports and aircraft. The knowledge in this field has been systematized during the last decades [9], [8], [23], [21], but the sistemic impacts were underestimated until the Eyjafjallajökull eruption [3], which lasted 4 weeks between April and May 2010 and caused the largest civil aviation breakdown after World War II. It is estimated that this event provoked 2.6 billion US$ losses in Europe and impacted regional and global economy [29] highlighting the high vulnerability of European air traffic network, particularly to long-lasting volcanic eruptions [3].

The 2010 Eyjafjallajökull eruption triggered a change of procedures in the volcanic ash events in Europe. In fact, the procedures in effect in 2010 were put in discussion [3]. The precautionary "zero tolerance" paradigm [23] showed its limitations for an effective management of the European airspace. During the eruption, the closure of airspace in presence of low concentrations of ash was strongly criticized. On 19th May 2010, the European Aviation Crisis Coordination Cell (EACCC) was established, with the aim to improve preparedness, enhance current procedures and ensure cooperation for an integrated risk management [26]. One of the changes was the introduction of the ash concentration charts, based on quantitative thresholds. The zones of lower concentration would not be closed to air traffic, but the operations are subject to the Safety Risk Assessment [3], [7].

In May 2010, the International Civil Aviation Organization (ICAO) established the International Volcanic Ash Task Force (IVATF). The IVATF comprises experts from different fields and identified the stakeholders' needs for the effective management of civil aviation during explosive volcanic eruptions. One of the most critical issues was recognized to be the estimation of ash concentration tolerance of turbines and the definition of ash concentration thresholds [24]. Quantitative thresholds were first suggested by UK MET Office, accepted by EACCC [7] and then modified by the ICAO International Volcanic Ash Task Force [26]. There is still no consensus on the critical values [3] and, although several tests are being performed by manufacturers [12], this remains an open issue.

At present, there are only a few examples of air traffic management procedures linked closely with volcanic ash monitoring systems. Probably, the most advanced system for managing air traffic operations in presence of volcanic ash is the one implemented at the "Istituto Nazionale di Geofisica e Vulcanologia" (INGV) in Catania, Italy [31]. Seismic and plume monitoring are combined with ash dispersal models for different eruptive scenarios to provide dispersal forecasts every 12 hours. The system helps in managing airspace closure in case of ash contamination from Etna volcano. During the 2010 aviation breakout, local response strategies were developed, some being very effective in the mitigation of impacts. For example, the Icelandic company Icelandair managed to move some aircraft from Keflavik (Iceland) to Glasgow (UK), lowering the impacts of ash contamination and maintaining their routes to North America opened [34]. During the 2011 eruption of Cordón Caulle (Chile) [16], [1], Aerolinas Argentinas and LAN Chile declared that a large percentage of economic losses were caused by their fleet being blocked at Bariloche airport, closed for months [2]. This issue could have been better managed with a timely action allowing part of the fleet to be moved elsewhere.

These examples underline the need for methodologies and systems to support mitigation strategies, and many times reiterated request for a higher degree of freedom in the decision-making and management during these events by the airlines. During the 2010 Task force meeting [26], the idea that airlines should be able to decide whether to fly or not in an airspace for which is forecasted to have volcanic ash was expressed. This procedure was then implemented during the 2011 Volcanic Ash Exercise (VOLCEX) [20], an exercise that is performed once or twice yearly in the ICAO European and Northern Atlantic Region with the objective of improving the response to volcanic eruptions and volcanic ash contamination. At present, specific strategies may be applied by any airline, after having presented and approved a Safety Risk Assessment (SRA) [4], [13].

Here we present a methodology for a preliminary estimation of ash dispersal impacts on civil aviation. Ash dispersal maps and air traffic data are combined to estimate expected impacts in form of maps, plots and tables. The methodology is implemented within a Geographical Information System (GIS) that allows effective data management, visualization and post-processing of results [28]. This is the first time that a GIS-based tool is used to assess impacts of ash on civil aviation. The only comparable tool is EVITA (European crisis Visualization Interactive Tool for ATFCM), a map-based tool developed in 2010 by EUROCONTROL and used during the last three VOLCEX exercises and the Grimsvötn eruption in 2011 [3], [4], [32]. EVITA acts as a web-based tool and provides graphical visualization of VAAC's ash charts, produced every 6 hours. Moreover, it is linked with the EUROCONTROL's flight plan database and allows the visualisation of the impacted flights in both horizontal and vertical planes. The advantage of our methodology is that it allows estimating hourly impacts by analysing every time step of the ash dispersal forecast. We apply the methodology to the 2010 Eyjafjallajökull case-study and discuss the implications of results for European air traffic management.

II. TEPHRA DISPERSAL MODELLING

The 2010 Eyjafjallajökull eruption has been modeled using different Tephra Transport and Dispersal Models (TTDMs) [16], including those running at the London and Toulouse Volcanic Ash Advisory Centers (VAACs), responsible for issuing volcanic ash advisories in Europe [22]. For example, Folch et al. [17] simulated 10 days of the eruption (from 14^{th} to 24^{th} April 2010) using the FALL3D model [10], [18]. The meteorological dataset was the ECMWF (European Center for Medium-range Weather Forecasts) Era-Interim reanalysis, produced for a computational grid having horizontal resolution of 0.25^{o}. The volcanological inputs relied on hourly-averaged radar observations of plume height [17] and characterization of the ejected material [6], [11]. It should be noted that, because *a posteriori* simulations use better-constrained (defined) meteorological and volcanological model inputs, it comes at no surprise that outcomes from reanalysis simulations can be different from those of forecasts.

Results from TTDMs are a necessary input for subsequent impact assessment, but transferring results to the decision-makers is not straightforward. In fact, numerical models produce a large amount of information, usually stored in compact binary formats. Here we automatically generate digital ash concentration maps for each time step and vertical level considered. There are several tools that support post-processing of modelling results, e.g GRASS GIS [28]. Given that we combine ash concentration maps with air traffic data at selected Flight Levels (FLs), model results are extracted the vertical level closest to each FL. On the other hand, because ash concentration thresholds are still undefined, we contemplate three different values associated to no-ash, 0.2, and 2 mg/m^3 concentration respectively. This approach has been already adopted by recent hazard assessments from tephra dispersal [19], [30], [33].

III. DATA MANAGEMENT

We use two types of air traffic data: spatial data in the form of GIS maps and air traffic data in the form of database tables. Spatial data is processed and visualized by two common GIS software: GRASS GIS [28] and QGIS (www.qgis.org), both open source. Air traffic data is managed and analyzed using tailored python codes (www.python.org). Queries are performed in Structured Query Language (SQL).

A. *Spatial data*

Spatial data is constituted by GIS maps containing the main European airports and route trajectories, provided by EUROCONTROL. For simplification, we consider only airports located in the European area and routes that connect the selected European airports. We use air traffic data for 14^{th} 2010, corresponding to the eruption onset. In total, the input database for the impact assessment methodology contains 1264 airports and 22494 flights. Airports and flights are identified in both spatial database and tables by unique identification (ID) codes [14].

B. *Air traffic data tables*

We used air traffic data from the EUROCONTROL Demand Data Repository (DDR), in particular from the M1SO6 database that contains the last filed flight plans for all flights in the European airspace [14]. Air traffic on Wednesday 14^{th} April 2010 was normal, with a total of 28157 flights, while on 15^{th} and 16^{th} of April the number of flights dramatically decreased due to the applied restrictions in Northern Europe (I). On 17^{th} and 18^{th} April, the European air traffic continued to decrease. From 17^{th} April, the European air traffic saw a dramatic breakdown that lasted until the 21^{st} of April. The rating of the day in the monthly rank (column "Position" in Table I) underlines the evolution of the crisis, showing that the days 17^{th} and 18^{th} had the lowest air traffic values in April 2010.

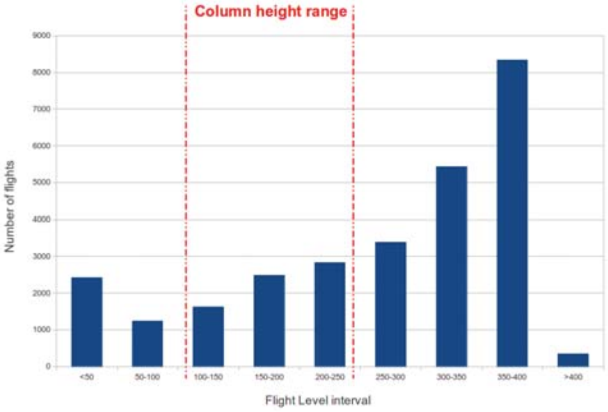

Fig. 1. Flight level statistics for European flights for 14^{th} April 2010. The histogram shows the numbers of flights (identified by an unique Flight ID) having the cruise altitude in each FL interval. Dashed lines show the range of eruptive column height [17]

The day 14^{th} April, used in our analysis, is one of the top-10 days for April 2010, and therefore can be a representative day for April air traffic in Europe. Assuming that air traffic patterns on week days in the same period are similar, air traffic data for 14^{th} April 2010 is used to estimate the impacts on air traffic for the 15^{th} and 16^{th} April. Having discarded extra-European flights, we take into account the 22494 flights contained in the spatial database. Air traffic data consists of flight profiles that are stored as 4D trajectories composed of a sequence of segments, each having start and end time, length and Flight Level (FL) (see [14] for details). An analysis of 14^{th} April air traffic was performed in order to identify the strategic FLs. For each flight, all the trajectory segments are extracted, and the most frequent value of FL in the en-route flight phase is determined. For very short flights, when no value appears to be the most frequent, we take the maximum FL value.

As the en-route phase is characterized by the relatively constant altitude, we take the extracted most frequent (or maximum for short flights) FL value as a constant en-route FL in our methodology. Fig. 1 shows the distribution of estimated en-route altitudes grouped by FL intervals for 14^{th} April 2010 air traffic data. This plot underlines the importance of FLs in the range 300-400, that together account for approximately 50% of the total flights. Given that we do not expect to have critical ash concentration at upper FLs [17], we include FLs 150, 200 and 250, that were strongly impacted during Eyjafjallajökull eruption, and together account for approximately 20% of total flights. The flight levels considered are therefore FL150, FL200, FL250.

TABLE I
NUMBER OF FLIGHTS DURING APRIL 2010 AND MONTHLY RANK OF THE DAY.

Day	Flights	Position
13	27550	12
14	28157	9
15	20528	25
16	11596	27
17	5296	29
18	5291	30
19	9504	28
20	13261	26
21	22159	22
22	27241	14

IV. METHODOLOGY

For each hour, the area with critical ash concentration is overlaid with the air traffic features (airports, routes) and the disruptions are quantified. A GRASS script performs, for each hour, three main operations: data extraction, overlap of hazard (ash concentration) and air traffic data, and production of results in form of tables. All extractions are performed using SQL queries embedded into GRASS scripts.

A. *Disrupted airports*

The disrupted airports are identified by overlapping the critical hourly ash concentration map and the digital map of European airports. Impacted airports are the ones overlaid by the ash cloud at the FLs 050, 100 and 150, where take-off and landing operations occur.

Airports are stored as points in the GIS database, but we create a circular buffer of user-defined radius surrounding each airport, in order to account for its spatial extension. For each time step, we produce a table containing the characteristics of the airport (ID code, position). The unique ID code can be used to connect this table to other databases and support specific analyses.

B. *Impacted flights*

Disrupted flights are identified by overlapping the critical ash concentration map and the digital map of routes, for each hour and at each FL considered. The procedure is performed in 5 steps that are repeated for each FL and concentration thresholds:

1) We extract the flights scheduled in the given hourly interval. An automated SQL query selects all flights passing at ± 3000 feet from the FL for which the ash concentration is calculated. We allow an overlap of 1000 feet between adjacent FLs, that is, some routes are extracted two times, for upper and lower FLs. Although this could lead to a slight overestimation of impacts, this procedure allows accounting for the vertical uncertainties on cloud location, related to the modelling output.
2) We overlap selected flights at FL ± 3000 ft and ash concentration chart, identifying the ones that may be impacted.
3) For the intersected flights, we extract the waypoints and the corresponding segments scheduled for the time step.

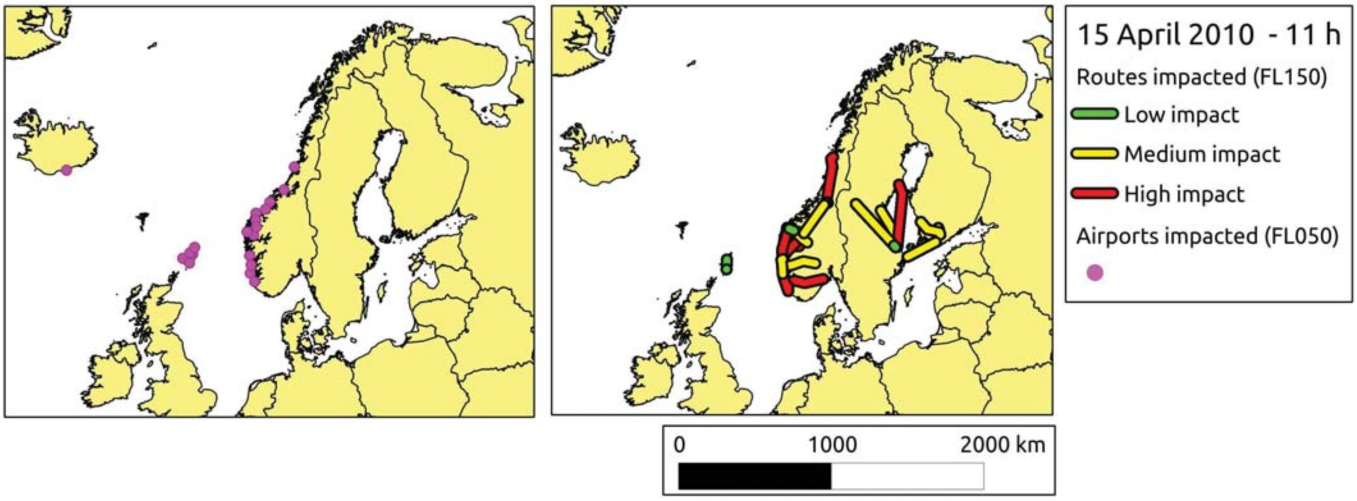

Fig. 2. Visualization of hourly impacts on European air traffic. The script exports graphical output in shp format, that can be visualized by any GIS system. The example shows airports impacted at FL050 (left) and routes impacted at FL150 (right), for 15^{th} April, from 11:00 UTC to 12:00 UTC at FL150. Impacted routes are visualized with green, yellow and red color, respectively for low, medium and high impact. Note that few flights were present at FL150, which is coherent with FL statistics (Fig. 1).

TABLE II
QUALITATIVE IMPACT CLASSIFICATION DEFINED FOR IMPACTED ROUTES, BASED ON THE PERCENTAGE OF ROUTE DISRUPTED.

Lenght disrupted x(%)	Impact	Impact rating	Strategy
x <10%	Low	1	Small deviation
10% <x <80%	Medium	2	Change FL
x >80%	High	3	Not flying

4) We select the segments that are intersected by ash cloud.
5) For each time step, we produce a table containing the characteristics of the whole flight (length, duration). We then calculate the disrupted length and consequently the percentage of the route that is impacted by ash.

Based on the impacted length, we distinguish three qualitative levels of impact: low (disrupted portion lower than 10%), medium (disrupted portion between 10% and 80%), and high (disrupted portion greater than 80%) (Table II). Criteria of 10% and 80% have been chosen according to our personal opinions and considerations, and can be changed. This criterion can be associated also with a limitation on impacted length in km, in order to include long distance and intercontinental flights. Finally, hypothesizing a constant speed of the aircraft, we estimate the exposure time.

V. RESULTS

We produced two hourly tables containing information on impacted airports and routes. As an example, Table III contains length and duration of disrupted flights, and the percentage of length impacted by ash cloud, value used to estimate the qualitative impact level. Results correspond to the 15^{th} April, from 11:00 UTC to 12:00 UTC at FL150. Having calculated the percentage length impacted by ash cloud, the corresponding impact level is assigned.

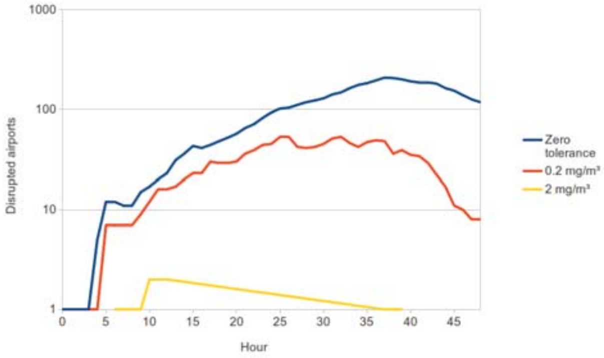

Fig. 3. Hourly impacts on airports for 15^{th} and 16^{th} April 2010 (48 hours) at FL050. The plot shows the number of impacted airports for the critical ash concentration threshold considered (zero tolerance, 0.2 and 2 mg/m^3). Note that the Y-Axis has logarithmic scale.

For every hour, we also produce a graphical output of the expected impacts. For example, Fig. 2 shows the impacts on airports (left) and routes (right) for 15^{th} April, from 11:00 to 12:00 UTC at FL050 for airports and FL150 for routes. Finally, we produce plots to summarize the impacts for the whole day or period. Fig. 3 summarizes impacts on airports, collecting all hourly information generated by the automated impact assessment methodology. We estimate the number of impacted airports for 15^{th} and 16^{th} April at FL050, relevant for take-off and landing operations, for the three critical thresholds of ash concentration considered. There is a peak in the number of impacted airports, considering the FL050, corresponding to

TABLE III
HOURLY IMPACTED ROUTES FOR 15th APRIL, 11:00 TO 12:00 UTC. TABLE CONTAINS THE UNIQUE ROUTE ID, TOTAL AND DISRUPTED ("DIS") LENGTH AND DURATION (IN KM AND MINUTES, RESPECTIVELY), PERCENTAGE OF DISRUPTED LENGTH AND THE QUALITATIVE IMPACT RATING ASSOCIATED TO EACH FLIGHT (TABLE II)

Flight ID	Time tot (min)	Length tot (km)	Length dis (km)	Time dis (min)	Length dis (%)	Impact
135200495	33	247	221	29	89	3
135200372	34	268	252	32	94	3
135195266	268	974	172	47	18	2
135199465	57	582	343	34	59	2
135199991	38	436	334	29	77	2
135200164	48	545	327	28	60	2
135199526	40	425	280	26	66	2
135200166	68	782	257	22	33	2
135197704	141	656	139	30	22	2
135199822	66	697	74	7	11	2
135199382	73	605	65	8	11	2
135197704	141	646	54	12	8	1
135199866	36	251	17	2	7	1

approximately 15:00 UTC of 16th April 2010.

Fig. 4 shows the hourly impacted routes for 15th and 16th April. Results have been produced for the critical thresholds at the considered FL (150, 200 and 250 from top to bottom). This figure allows visualizing the temporal evolution of impacts during the peak days of the emergency. Maximum impacts correspond to 16th April, 04.00 pm and 15th April, 13:00 and 07:00 UTC, respectively for FLs 150, 200 and 250. Highest disruptions are estimated at FL150 and FL200, while at FL250 only few flights would be highly impacted according to the analysis.

During the 2010 crisis, a high percentage of European flights were cancelled, as documented in the EUROCONTROL's Monthly Network Operations report for April 2010 [15], and the levels of European air traffic dramatically decreased due to the partial closure of European airspace (Table I). We compare the number of cancelled routes on 15th and 16th April 2010 [15] and the expected impacts resulting from our analysis for the zero tolerance criterion (Table IV). Table IV shows a high difference in the number of cancelled routes.

VI. DISCUSSION

The ultimate aim of this work is to support the decision-making process, taking the highest advantage of the modelling output and transferring the relevant information to decision-makers. The final decision on whether to fly or not is not addressed in this document, but we aim to support this decision with the highest amount of information available.

TABLE IV
COMPARISON OF TOTAL NUMBER OF CANCELLED ROUTES ON 15th-16th APRIL 2010 AND ESTIMATED NUMBER OF IMPACTED ROUTES IN THIS STUDY.

Day	2010	This study
15th April	7736	170
16th April	16938	208

First, the methodology presented here takes into account the developments done by the modelling community. Given that Eyjafjallajökull eruption has been carefully studied and input parameters are relatively well constrained, modelling is expected to give reliable outputs. Moreover, although ash charts are provided by VAACs every 6 to 12 hours, modelling results can have a higher temporal resolution, *e.g.* on the order of 0.5-2 hours. A higher temporal resolution allows to transfer information to the stakeholders in a more dynamic way. In fact, by estimating impacts at each time-step (one hour in our study), the improvements achieved in the estimation of ash concentration could be transferred to the decision-makers with the highest possible temporal and spatial resolution. This is particularly true with the implementation of new cutting-edge techniques such as data-assimilation, which is a suitable and not-so-far-fetched achievement for the scientific community [16]. These techniques could increase the accuracy of results [5], [17].

Results for the Eyjafjallajökull case-study can be useful for two main reasons: evaluation of what occurred during 2010 eruption with an hourly-based analysis, and possible integration of this methodology within current strategies. Results produced for each time step (Table III) would provide a more dynamic and timely information basis for managing disruptions than is the case with 6-hour forecasts. The calculation of length of disrupted segments and elapsed travel time through ash cloud is of particular interest. In fact, if critical ash ingestion rate is defined, these parameters may be integrated in the impact assessment methodology. It should be stressed that this comparison performed in Table IV is biased by the fact that, in 2010, results of the forecast were different from the ones used in this study. Moreover, it has been stated that many flight cancellations were not directly caused by the presence of ash, but were the consequence of the airspace closures (based on the forecasted ash presence). For these reasons, although the 2010 aviation breakdown has been widely studied in recent years, it is not straightforward to compare what occurred with *a posteriori* analysis. However, this comparison underlines the order of magnitude of differences between the 2010 impacts and the ones expected today. The aim of this comparison is not to criticize the air traffic management during 2010 but to underline the enormous opportunities for improvement in this field.

Results of *a posteriori* numerical modelling performed by Folch et al. [17] show that at FLs 300, 350 and 400 there was no critical concentration of 2 or 0.2 mg/m^3. If follows that changing altitudes to the upper FLs would have been possible, at least for the aircraft with the necessary technical characteristics. For this reason, the strategy of changing FL seems suitable for long-lasting eruptions with low eruptive columns, for the flights that are able to take-off (climb/descent is not impeded by ash presence).

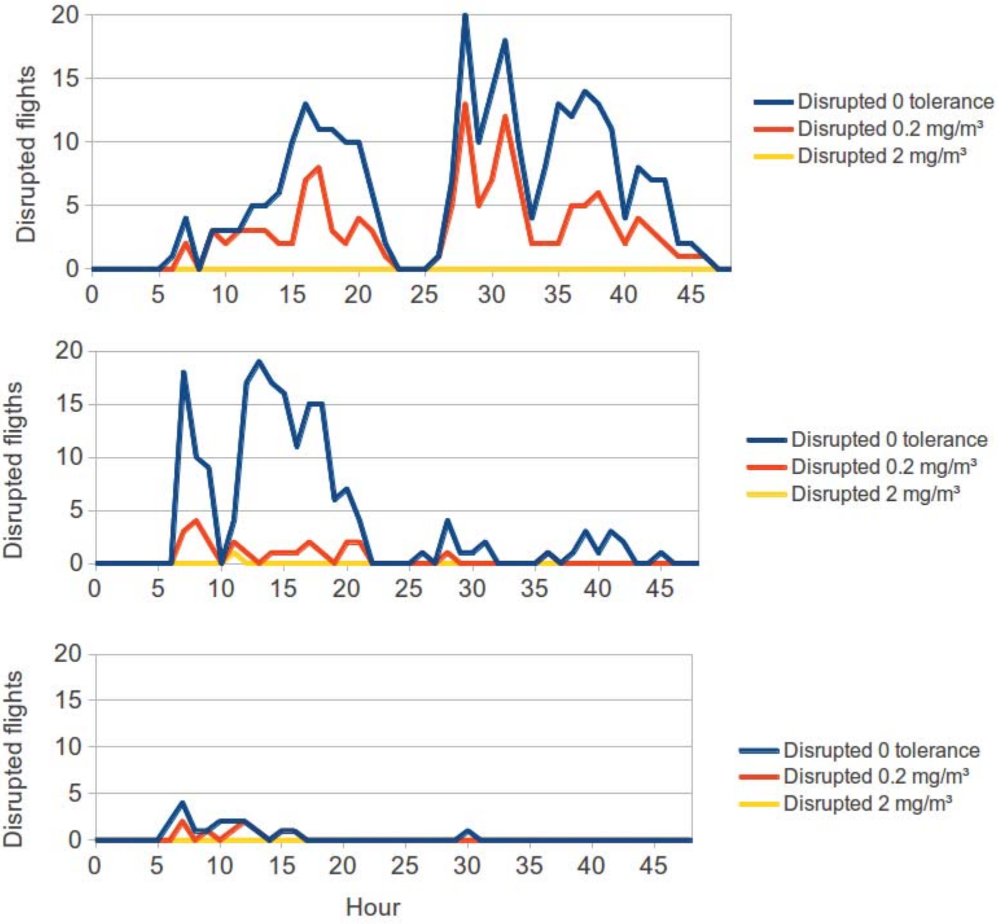

Fig. 4. Hourly impacts for 15^{th} and 16^{th} April 2010 for FL 150, 200 and 250 (from top to bottom). The plot shows the number of impacted routes for the critical ash concentration threshold in case of zero tolerance (blue) and for the thresholds of 0.2 and 2 mg/m^3 (red and yellow, respectively)

One important difference between the impact assessment methodology presented here and the one implemented within EVITA is that EVITA shows the effects for every 6 hours, while our methodology allows the estimation of impacts at every time step of the ash dispersal forecast. In addition, the operational automated forecast can be produced every few hours (depending on the resolution of the domain and the complexity of the eruptive scenario, but indicatively every 2-3 hours). This would allow to update the expected impacts with higher temporal frequency.

Both EVITA and the methodology presented here improve graphical outputs, compared with the initial tabular formats strongly criticized by several stakeholders [25], [27], [4]. In the case of EVITA, the graphical aspect received positive feedback during the VOLCEX exercises [4]. Our hourly maps are readable by GIS and Google Earth, which helps to better visualise results. Moreover, it supports the production of animations of the evolution of impacts. The use of these formats could also enhance the interoperability between different stakeholders and ultimately the communication and information management.

The methodology presented here is a first academic attempt to support civil aviation management in cases of ash-contaminated airspace. We are aware that this topic is very complex, and that we need to introduce improvements in order to produce a methodology that is flexible, adaptable and efficient. Table V synthesizes the main limitations and advantages of the methodology, as well as the possible improvements. On one hand, the impact assessment methodology relies on strong assumptions that greatly simplify the real processes, and is not operational yet. On the other hand, the main advantage of this methodology is that it links ash dispersal modelling and civil aviation management by providing the hourly results from the modelling output, which has a great practical value for decision makers, especially for the airlines, during the volcanic ash event. Further advantage is that this methodology can potentially be interfaced with results coming from any ash dispersal model, and is therefore model-independent.

TABLE V
MAIN LIMITATIONS AND ADVANTAGES OF THE METHODOLOGY. POSSIBLE IMPROVEMENTS ARE UNDERLINED FOR FUTURE WORK.

Limitations	Advantages	Improvements
Strong assumptions	Link science and management	Economic aspect
Not operational	Synhtesis	Become operational
	Hourly analysis	Include probabilistic forecast
	Model-independent	

We identify three main roads for the future development of the presented methodology: including the economic analysis, interfacing this methodology with a probabilistic ash dispersal forecast, and integrating the methodology into a broader operational framework. First, the combined analysis of our results and the economic impact estimated for the 2010 crisis could help clarifying the process of propagation of impacts from civil aviation to society. Although the definition of economic impacts of civil aviation breakdowns is extremely difficult due to the multitude of variables involved, an effort should be made to include it in a broader multi-disciplinary methodology. Second, this methodology could have as input a probabilistic forecast, that is, a forecast constructed of many forecasts produced by varying the eruptive scenario. The ensemble of these forecasts would produce a probabilistic output, allowing to account for the uncertainties related to the modelling process. The probabilistic approach would strongly support new impact assessment methodologies.

Third, the GIS-based methodology presented here could also be integrated in the existing risk management strategies for civil aviation management such as VOLCEX exercises and SRAs. The implementation of the impact assessment methodology presented here, far from being straightforward, could enable the stakeholders to define operational strategies within their long-term plans, that would need to be supported by the input data (operational ash dispersal forecast and air traffic). Furthermore, the design of the reliable and user-friendly decision-support tool would greatly improve the usefulness of the methodology to the end users. Our contribution could therefore improve the current risk management strategies by supporting the decision-making process, in order to increase preparedness and eventually minimize losses.

VII. CONCLUSIONS

This work presents the first example of GIS-based ash dispersal impact assessment especially designed for civil aviation purposes. The impact assessment methodology presented here is a valid result in itself, and may be applied to other case-studies or implemented in a broader short-term risk management operational strategy. Specific results presented for Eyjafjallajökull 2010 eruption allow to perform *a posteriori* analysis of impacts and identify the critical issues to solve. Finally, this is a first attempt of filling a gap between ash dispersal modelling and civil aviation management, allowing to use the full potential of the model outcomes, and to produce practical results that can support an effective management of civil aviation during explosive volcanic eruptions.

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