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Discussions

A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes – Part 2: Vulnerability and impact

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Abstract

We perform a multi-scale impact assessment of tephra fallout and dispersal from explosive volcanic activity in Iceland. A companion paper (Biass et al., 2014) introduces a multi-scale probabilistic assessment of tephra hazard from 4 Icelandic volcanoes (Hekla, Askja, Eyjafjallajökull and Katla) and presents probabilistic hazard maps for tephra accumulation in Iceland and tephra dispersal across Europe. Here, we present the subsequent vulnerability and impact assessment, that accounts the relevance of single features at national and European levels and considers several vulnerability indicators for tephra dispersal and deposition. At national scale, we focus on physical, systemic and economic vulnerability of Iceland to tephra fallout, whereas at European scale we focus on the systemic vulnerability of the air traffic system to tephra dispersal. Results include vulnerability maps for Iceland and European airspace and allow identifying the expected impacts of the different eruptive scenarios considered. Results at national scale show that tephra accumulation from the considered eruptive scenarios can disrupt main electricity network, in particular in case of eruption at Askja volcano. Results also show that if eruptive scenarios occurred at Hekla, Askja and Katla volcanoes, many power plants would be affected, causing a substantial systemic impact due to their importance for the Icelandic economy. Moreover, the considered scenarios at Askja and Katla could produce substantial impact on agricultural activities (crops and pastures). At European scale, tephra dispersal from explosive volcanic activity at Askja and Katla volcanoes is likely to produce substantial impacts at European level and, in particular, at Keflavik and London Flight Information Regions (FIRs), but also at FIRs above France, Germany and Scandinavia, in particular for long-lasting activity at Katla volcano. Explosive activity at Hekla volcano is likely to produce high impacts at Keflavik FIR and London FIRS, but in case of higher magnitude scenario, can impact also France FIRs. Results could support land use and emergency planning at national level and risk management strategies of the European air traffic

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system. Although we focus on Iceland, the proposed methodology could be applied to other active volcanic areas, enhancing the long-term tephra risk management.

1 Introduction

Tephra dispersal and deposition during explosive volcanic eruptions can produce impacts at different scales, from local to continental. Compared to other volcanic hazards, tephra fallout is unlikely to cause casualties but, nonetheless, it often produces high systemic and socio-economic impacts (e.g. Wardman et al., 2012; Biass et al., 2012). On the other hand, the presence of volcanic ash in the atmosphere disrupts aerial navigation and may cause additional socio-economic impacts at larger scales, from regional to continental, depending on the eruption intensity and duration, ash properties and atmospheric circulation. For these reasons it is necessary to include tephra dispersal and deposition in any risk assessment of active volcanoes characterized by explosive activity.

Iceland is amongst the most active volcanic areas in the word, hosting more than 30 volcanic systems displaying different eruptive styles and a wide range of volcanic products (Thordarson and Larsen, 2007). In a companion paper, Biass et al. (2014) present a probabilistic tephra hazard assessment from 4 Icelandic volcanoes (Hekla, Askja, Katla and Eyjafjallajökull), selected for showing recent activity, different levels of historical record, and a variety of eruptive styles and activities. In this manuscript we present the associated vulnerability and impact assessment in order to support more effective mitigation strategies in Iceland and Europe.

Volcanic risk evaluation builds upon three factors: hazard, exposure and vulnerability (e.g., De la Cruz Reyna and Tilling, 2008). Exposure is a key element in risk assessment, since it “encompasses all elements, processes, and subjects that might be affected by a hazardous event. Consequently, exposure is the presence of social, economic, environmental or cultural assets in areas that may be impacted by a hazard” (Birkmann, 2013, p. 305). Thus, the identification of exposed targets largely depends

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on their location in respect to the impacted area for the considered hazard and to the type of hazard at stake. Finally, it is worth noting that exposure, although crucial for an effective risk assessment, does not account for the variability of response of people, infrastructure, goods or ecosystems to the hazardous event: such response depends on their susceptibility to be harmed or, in other terms, on their vulnerability.

Vulnerability can be defined as the potential of exposed targets to be directly or indirectly damaged by a given hazard. Definitions, conceptual frameworks and methodologies for analyzing and assessing vulnerability are very heterogeneous, although "there is a clear recognition of the importance of place-based studies in examining vulnerability" (Cutter, 2013, p. 1089). In the last decade, vulnerability has been largely recognized as a multi-dimensional concept, comprising different aspects (physical, systemic, social, economic, environmental, institutional, etc.), constantly interacting in time and space (Birkmann, 2006; Galderisi et al., 2008; UNISDR, 2009; Menoni et al., 2011). In particular, the concept of systemic vulnerability is spreading in the scientific literature and refers to the fragilities arising as a consequence of interdependencies among elements and systems within a given territory, which can reduce its overall functioning in face of a hazardous event (Rashed and Weeks, 2003; Menoni, 2005; Galderisi et al., 2008; Pascale et al., 2010; Ensure, 2011). Territorial systems are characterized by a dense network of physical and functional interdependencies (Paton and Johnston, 2006; Hellstrom, 2007) and the potential impact of a hazard on a given element may reverberate on others, physically or functionally connected to the former. The concept of systemic vulnerability has been applied in several areas of natural hazards such as floods, earthquakes, tsunamis, etc. (e.g. Minciardi et al., 2005; Pascale et al., 2010) but, in volcanology, this concept has been introduced only recently (e.g. Galderisi et al., 2013). Systemic vulnerability has a particular relevance in the case of tephra fallout, which may produce much higher secondary than primary impacts, that is, the physical failure of an element may also impact other connected activities and infrastructures (Biass et al., 2012). For example, the failure of the electrical network can cause cascading effects on several productive activities, such as manufacturing, power generation, agriculture, or tourism. On the other hand, tephra dispersal and deposition largely affect transportation networks, which are crucial for accessibility to urban areas and emergency facilities. Finally, social and economic aspects of vulnerability have been deepened in scientific literature since the Nineties, but an unequivocal definition of both social and economic vulnerabilities and of their mutual relationships is still missing (Parker et al., 2009; Tapsell et al., 2010).

Iceland is considered a well-prepared and highly resilient country, but the traditional risk management strategies of the Icelandic civil protection have traditionally focused on the short-term reaction rather than on the long-term land use planning (Jóhannesdóttir and Gísladóttir, 2010). As a consequence, there is a lack of specific studies on vulnerability of the Icelandic territory to tephra deposition, although tephra fallout is a relatively frequent phenomenon in Iceland. Here we perform a vulnerability assessment taking into account that, according to the analysis of past events (Biass et al., 2014), agriculture, transportation and energy sectors are the most vulnerable to tephra accumulation. To this aim, we define exposed targets, estimate vulnerability for each considered target and evaluate the expected impacts for all the eruptive scenarios defined in the previous hazard assessment (Biass et al., 2014). At national scale, we focus on systemic and economic dimensions of vulnerability. Physical vulnerability of buildings is not considered because, according to the hazard analysis of Biass et al. (2014), expected tephra accumulations are unlikely to cause significant damage to buildings for the volcanoes and activity scenarios considered (proximal areas around the selected volcanoes are mostly inhabited). Moreover, our analysis is performed at a national scale (the whole Island), while physical vulnerability assessments require detailed on-site surveys, for example on building stock, which are usually performed at local scale. However, we consider physical vulnerability of the electricity network because its failure can trigger relevant impacts on the whole society. We also focus on the potential for temporary or permanent loss of economic activities, relevant to the maintenance of the level of welfare of population.

The disruption of flights caused by the 2010 Eyjafjallajökull event was economically significant for both Europe and Iceland (Sammonds et al., 2010; Oxford Economics, 2010; Alexander, 2013). Using the last 10 years of the ERA-Interim reanalysis dataset, Biass et al. (2014) conclude that the probability of having upper troposphere winds blowing towards central and northern Europe is 6–8 %, a value consistent with the 6 % found by Sammonds et al. (2010). Given the 2010 experience, these probabilities suggest that assessing the vulnerability of the European air traffic system to Icelandic ash dispersal is relevant for the management of volcanic risk in civil aviation, particularly since no vulnerability assessment of any air traffic system specifically focused on volcanic ash hazard exists. Wegner and Marsh (2007) and Wilkinson et al. (2011) underlined some relevant aspects of the European air traffic network and showed that it is a scale-free network highly vulnerable to the disruption of the main hubs. Based on this finding, we develop the first assessment of vulnerability of the European airspace to tephra dispersal. The analysis is based on the systemic approach and aims to identify the critical features for the system, that is, the elements that can produce the highest systemic impacts on the whole European air traffic system in case of failure. As we did at National scale, we identify the distribution and the features of the exposed targets and define vulnerability indicators in order to evaluate the expected impact for the different eruptive scenarios considered in the hazard assessment (Biass et al., 2014).

This manuscript is arranged as follows. Section 2 overviews the eruptive scenarios for the selected volcanoes and the findings from the hazard assessment of Biass et al. (2014). Section 3 presents the vulnerability and impact assessment to tephra fallout at National scale and Sect. 4 the vulnerability and impact assessment to tephra dispersal at European scale. Section 5 discusses the advantages and disadvantages of the proposed methodology and the future research developments required to improve it. Finally, Sect. 6 concludes with a summary.

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2 Eruptive scenarios and results from the hazard assessment

A companion paper (Biass et al., 2014) presents a multi-scale probabilistic tephra hazard assessment for different eruptive scenarios of four highly active Icelandic volcanoes (Hekla, Askja, Katla and Eyjafjallajökull; Fig. 1). This hazard assessment considers both national-scale fallout and European-scale dispersal for different scenarios based on the eruptive record (Table 1). Each scenario was modeled assuming a statistical set of inputs using TEPHRA (Bonadonna et al., 2005) and FALL3D (Costa et al., 2006; Folch et al., 2009) models for tephra fallout and dispersal respectively. Results of the hazard assessment at the national scale are probabilistic hazard maps for ground tephra accumulation. Probabilistic hazard maps were computed for tephra load thresholds of 1, 10, and 100 $kg\,m^{-2}$, which correspond, approximately, to 0.1, 1, and 10 cm of accumulation at ground. At a European scale, results are probabilistic hazard maps (giving the probability of "disruption") for ash mass concentration thresholds of 2 and 2×10^{-3} $mg\,m^{-3}$. The second value (corresponding to a negligible mass concentration) was considered in order to estimate the impact in case of a zero-ash tolerance criterion. Moreover, Biass et al. (2014) also provide maps of disruption mean persistence (Sulpizio et al., 2012) and arrival times for the 2 $mg\,m^{-3}$ concentration threshold. The main findings from the hazard assessment are:

- A 10 year recurrence rate eruption of Hekla (i.e., Hekla ERS 2000-type) only produces significant tephra accumulation close to the vent and in the southern part of Iceland. Ash concentration has a low probability (< 1 %) to exceed the threshold of 2 $mg\,m^{-3}$ at any FL in the UK airspace.

- A 100 year recurrence rate eruption of Hekla (i.e., Hekla ERS 1947-type) produces substantial tephra accumulation in the Southeastern part of Iceland. However, far-range ash concentrations still have low probabilities (< 5 %) of affecting the UK airspace with concentrations above the 2 $mg\,m^{-3}$ threshold at any FL.

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- A moderate long-lasting basaltic eruption of Katla (i.e., Katla LLERS with tephra production during 1–4 days) is likely to produce substantial tephra deposition in Southern Iceland. Ash dispersal has a substantial probability of reaching northern Europe, UK (8–15 %) and central Europe (∼ 5 %) with concentrations exceeding 2 $mg\,m^{-3}$ at any FL.

- An eruption of Askja similar to that of 1875 (i.e., Askja OES 1875-type) is likely to produce massive tephra deposition in eastern Iceland. Ash dispersal has a substantial probability of reaching northern Europe, UK (8–15 %) and central Europe (∼ 5 %) with concentrations exceeding 2 $mg\,m^{-3}$ at any FL.

- An eruption of Eyjafjallajökull similar to 2010 (i.e., Eyjafjallajökull LLOES 2010-type) is likely to produce moderate tephra accumulation south of the volcanic edifice around the town of Vìk. For computational reason, probabilistic approaches to assess the airborne concentration resulting from such a long eruption were not applied.

Finally, in order to compare the relative impact of the different scenarios, one historical eruption was selected for each volcano for which ash dispersal and atmospheric concentrations were assessed using the same wind conditions of Eyjafjallajökull 2010 eruption. The selected eruptions include Hekla 1947, Katla 1918, Eyjafjallajökull 2010, and Askja 1875. The conclusion was that, all eruptions would be likely to disrupt the European air traffic, with the most important perturbations caused by Katla 1918 and Hekla 1947. Results underline that particle grainsize distributions and eruption duration play a key role, even more than the erupted volume.

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3 National-scale vulnerability and impacts

3.1 Exposed targets

In order to assess vulnerability and estimate potential impacts of tephra fallout in Iceland, one needs first to identify the "social, economic, environmental or cultural assets in areas that may be impacted by a hazard" (Birkmann, 2013, p. 305). The main exposed targets have been identified based on the scientific literature on tephra fallout impacts. In detail, the exposed targets that we consider are:

1. *Population*: Iceland has 320 000 inhabitants of which 120 000 live in Reykjavik, the capital. About 60 % of the total population lives in the so-called Greater Reykjavik (Supplement Table S1). Recent trends (Byggdastofnun, 2012) show that population is growing around the capital and in the eastern part of the country, were tephra fallout has high probabilities of occurrence for some of the eruption scenarios considered (Biass et al., 2014). The central part of the island is mostly inhabited. Approximately one quarter of the population has reduced mobility: in fact, a 15 % of inhabitants are under 10 years old and a 9 % are over 70 (Statice, 2012). This segment of population is potentially more exposed to suffer respiratory difficulties due to the presence of suspended PM_{10} (Baxter et al., 1983; Horwell and Baxter, 2006). In addition, all population is exposed to indirect impacts due to failure of services (water and electricity supply, transportation, access to health cares). Data on population for each municipality and percentage of exposed people are available in the Supplement Table S2.

2. *Emergency facilities, (e.g. hospitals, emergency shelters, police and fire stations):* the two main Icelandic hospitals are located in Reykjavik but other hospitals and local health centers, also considered in our analysis, exist in relevant towns such as Akureyri, Isafjordur, Nordfjordur and Selfoss. Police and fire stations are quite well distributed amongst the main towns. Finally, shelters are usually public buildings located in correspondence of areas of interest (monuments, touristic

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attractions) and towns but, for simplicity, we only consider schools as possible shelters.

3. *Mobility network (e.g. road network and mobility nodes such as ports and airports):* the road network is directly exposed to tephra fallout, which may disrupt traffic reducing the capacity of the population to reach critical facilities and, indirectly, affecting services and productive activities. In absence of railway in Iceland, the road network is extremely important for internal mobility. A main primary road circumvents Iceland along the coast. Disruption to mobility network, even if temporary can trigger relevant cascade effects. Ports are extremely important for the import-export activities in Iceland. In 2006, a total of 6 Mtons of freight passed through Icelandic ports, which mainly export marine products (25 %) and import/export “other goods” (49 and 51 % respectively) including textile and manufacturing goods (Statice, 2012). Finally, airports are also important mobility nodes. The main airport in Iceland is Keflavik, which accounts for more than 97 % and 99 % of international passengers and freight traffic (Isavia, 2012). Important airports for domestic routes are Reykjavik and Akureyri, accounting for approximately 25 and 50 % of domestic passengers and 47 and 20 % of freight (goods and mail), respectively (Isavia, 2012). Other smaller airports, including Egilsstadir, account for a 12.5 % of domestic traffic of passengers. The volume of the domestic air traffic is modest (around 800 000 passengers per year; Isavia, 2012) but, nonetheless, important for the national economy, given the absence of railway.

4. *Electricity network:* the electricity network is a critical infrastructure for economic activities and society in general. Electricity networks are very vulnerable to volcanic fallout (Wilson et al., 2009a, 2012), and consequences of a disruption of power generation and distribution are potentially dramatic. In Iceland, more than 80 % of the primary energy comes from renewable sources, hydroelectric (73 %) and geothermal plants (27 %) (Orkustofnun, 2012). More than 30 hydroelectric

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plants are sparse across the country, except in the southern area of the Vatnajökull ice cap (Icelandic national energy authority, 2012a), and up to 7 geothermal plants are located around the capital and in the northeast (Icelandic national energy authority, 2012b). Some of them are combined heat and power plants, which utilize geothermal water and steam.

5. *Economic activities*: main economic activities in Iceland are services and industry, which in 2011 employed a 75.7 and a 18.4 % of the working population respectively (Landshagir, 2012). The comparison between the capital region and other regions shows that in the capital region services share a higher percentage of employees while elsewhere industry dominates (Landshagir, 2012). In particular, aluminum smelters are strategic components of the Icelandic economy, constituting 37.6 % if the total Icelandic exports and placing the country in the top-20 aluminum-producing nations worldwide. In 2011, aluminum smelter accounted for approximately 73 % of the gross electricity consumption (Lanshagir, 2012).

6. *Agriculture*: the main agriculture activities are related to the production of wool and milk, which only account for a small percentage of the national GDP (Johánnesson, 2010). The distribution of the main agricultural areas (extracted from the Corine Land Cover raster map, see the Supllement Fig. S3) shows that a substantial part of the island is covered by snow and ice, and the few agricultural areas are barely visible and located in the proximities of main villages and coastal areas. Nevertheless, agriculture is important for local development, being the main economic resource for people living in small, aisled villages. Crops can suffer from short to long-term impacts due to tephra accumulation (Wilson et al., 2009b). Fluoride absorption can impact kettle due to its toxicity and, unless direct inhalation is not a big concern, its ingestion through plants and water can produce diseases (Dawson et al., 2010).

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7. *Water supplies*: Tephra fallout can disrupt water supply networks and water treatment plants (Stewart et al., 2006). In Iceland, the areas close to active volcanoes are not densely populated and the disruption of water supply in urban areas seems not a big issue. However, tephra fallout can contaminate ground and surface waters, which are in some cases used for domestic/agricultural use (about a 95 % of the national water consumption relies on high-quality groundwater and only a 5 % on surface water; Gunnarsdóttir, 2012). This is usually the case of aisled farms, where no official quality controls are performed and, consequently, are more exposed to this hazardous phenomenon. Moreover, farms can suffer the indirect impact of tephra fallout on livestock, as it can contaminate water used for beverage (Wilson et al., 2009a; Dawson et al., 2010).

This list of exposed targets is not exhaustive but accounts for the main aspects generally considered in the literature. Amongst all these exposed targets, we selected the most significant for the national context based on practical considerations and data availability. Figure 2 shows maps of the considered features, based on several data sources: the national GIS dataset (Landmælingar Islands, 2012), the European statistics database (Eurostat, 2012) and the Iceland National Statistics (Statice, 2012). In detail, Fig. 2a shows the location of the critical features considered (hospitals and schools that could be potentially be used as shelters), and the national road network. Our systemic vulnerability analysis is based on the ease for population to reach critical facilities using the road network. Figure 2b shows the location of hydroelectric power plants and the electricity distribution network. The most densely populated areas and the main productive activities (aluminum smelters), also displayed in the map. Figure 2c shows the location of mobility nodes, relevant for the Icelandic socio-economic system. Airports can be directly disrupted by tephra fallout but also by tephra dispersal in atmosphere, which may cause airspace closure. Import/export activities at ports and airports can suffer indirect damage due to the disruption of road network, power plants and productive activities.

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3.2 Vulnerability assessment

As mentioned, our vulnerability assessment focuses on the systemic and economic dimensions of vulnerability. This choice results from numerous factors, related partly to scientific and methodological aspects including: (i) the low probability of exposed populations to suffer relevant structural failure of buildings and human casualties resulting from tephra accumulations suggested by the hazard analysis; (ii) the scale of the vulnerability and impact assessment (i.e. the whole country); (iii) the priorities for improving effective mitigation strategies in Iceland, defined through close cooperation between local stakeholders and the Icelandic Civil Protection and; (iv) the availability of accurate and up-to-date data. As a result, based on the different categories of exposed targets, we defined vulnerability themes and indicators (Table 2) focused on the following aspects:

- physical vulnerability, limiting the analysis to electric power plants and distribution network;
- systemic vulnerability, which refers to the interdependencies among exposed targets capable of reducing the overall functioning of the system itself and, namely, its capacity to react in the emergency phase following an event;
- economic vulnerability, which refers to the potential for temporary or permanent loss of economic activities and assets which are crucial for the Iceland economy and, consequently, for the maintenance of the level of welfare of population. It is worth noting that economic activities (such as agricultural activities) or economic assets (industries, energy production sites etc.) can be indirectly affected by, for example, the interruption of transportation services.

Physical vulnerability has been quantified considering the hydroelectric power plants and the electricity distribution network due to their high vulnerability to tephra fallout (Wardman et al., 2012). Geothermal and combined-power plants are not considered because, a priori, are much less vulnerable to tephra fallout given their thick reinforced concrete structure with few or no openings. We assign a vulnerability value of 1 to all exposed hydroelectric plants and aerial sections of the distribution network because detailed data to rank the vulnerability of each particular plant was not publicly available. The electricity distribution network has significant interdependencies with information infrastructures, other utilities and services and economic activities (Pederson et al., 2006; Laprie et al., 2007; Beccuti et al., 2012). As a result, a disruption of hydroelectric plants and/or distribution network may result in severe failures of depending sectors, as demonstrated by the blackouts in Italy (2003) and Germany (2006), which impacted large areas of Western Europe (Menoni and Margottini, 2011).

The systemic vulnerability assessment has been performed considering accessibility, which is a key issue during emergency situations. According to Bertolini et al. (2005), accessibility can be defined as "the amount and diversity of places that can be reached within a given travel time and/or cost". During a crisis, bi-directional accessibility is crucial for both evacuating population to safe areas and dispatching rescue teams (Galderisi and Ceudech, 2010). Although the disruption of mobility networks due to tephra accumulation is generally temporary, it can result significant cascade effects reducing accessibility to and from inhabited areas, emergency facilities, mobility nodes, power plants or industrial sites, with relevant consequences in terms of increasing losses and slowing recovery. Here we consider the accessibility to emergency facilities (hospitals and shelters) using the road network. The driving time is assessed using the *Spatial Analyst* toolbox in *ESRI ArcMap 10.2* (Esri, 2012). The hierarchy of the road network is accounted using the official speed limits. Figure 3 shows the analysis of accessibility from inhabited areas to shelters, hospitals and fire stations. Based on this accessibility analysis we obtain the map of the most vulnerable areas.

Finally, and given its complexity and quantity and diversity of data, the economic vulnerability assessment has been performed considering the agricultural sector only, assessing its relevance at a municipality level (Fig. 4). In order to estimate the importance of agricultural activities, we combine three different types of data: percentage of agricultural area, production of milk and production of wool. The percentage of agricultural area for each municipality was estimated by extracting pastures and crops from the CORINE Land Cover map (http://ec.europa.eu/agriculture/publi/landscape/about.htm), containing an inventory of soil use information at high resolution (100 m). The production of milk ($\mathrm{L\,year^{-1}}$) and wool for each municipality during 2012 was provided by the Icelandic Regional Development Institute (Byggdastofnun, 2012). Wool production is expressed in terms of "support entitlements", i.e. the National entitlements that municipalities receive from central government for their wool production and according to their percentage on the total production of the municipality (Á. Ragnarsson, personal communication, October 2012). Values of these three agricultural indicators have been classified in a 5-classes vulnerability ranking (very low, low, medium, high and very high vulnerability) using the natural breaks method (Jenks, 1967), commonly used in most GIS software and especially suitable for visualizing differences between classes (maps for each indicator are given in the Supplement Fig. S1).

3.3 Impact assessment

Before performing an impact analysis, it is necessary to determine the link between a quantitative hazard value (threshold) and each vulnerability indicator. Wilson et al. (2012) define critical values of ash deposition for infrastructures based on well-documented impacts of past eruptions. The accumulation of 5–10 mm of ash can produce tephra-induced insulation flash-over, while a > 10 cm fine ash fallout has a medium to high probability of causing electrical network failure (Wilson et al., 2012; Wardman et al., 2012). Regarding hydroelectric plants, ash can engulf in water channels and affect the turbines limiting the power plant functionality. Wilson et al. (2012) describe the effect of tephra-induced abrasion on turbines and point out that coarse ash is more likely to produce damage whereas a deposition of fine ash as thick as 50–100 mm may not cause strong abrasion. There are few evidences of tephra impacts on electricity power plants, but it is known that tephra fall is likely to produce its disruption or shut-down (Wardman et al., 2012). Regarding the road network, tephra depositions > 1 mm ($\sim 1\,kg\,m^{-2}$) can produce lack of visibility and disorient drivers, cause significant damage to vehicle's components and eventual engine failure (Wilson et al., 2012). However, this value does not take into account differences in road design, typology of vehicles and other aspects such as population preparedness and coping capacity, which are becoming an important element of risk analysis (Frischknecht et al., 2010). In the case of Iceland, critical deposition thresholds for road disruption could be considerably higher due to the characteristics of the fleet of vehicles and the resilience of population, used to cope with road traffic disruptions during winter snowfalls. We assume that a moderate disruption of the road network may happen with $\sim 10\,kg\,m^{-2}$ tephra accumulation, while $100\,kg\,m^{-2}$ would provoke the total blockage of road transportation (Biass et al., 2012). Finally, we consider that an accumulation of 1 cm ($\sim 10\,kg\,m^{-2}$) can produce damages to agriculture and impact livestock (Wilson et al., 2009a; Biass et al., 2012), as occurred during past eruptions in Iceland (Thorarinsson and Sigvaldason, 1972; Gudmundsson et al., 1992; Hoskuldsson et al., 2007).

Overlapping probabilistic hazard maps with vulnerable features allows for the identification of potential impacts. For each eruptive scenario, we estimated the number of power plants and the total length of the electricity network having respectively 5, 10, and 20 % probability of being impacted (i.e. covered by a critical tephra load > $10\,kg\,m^{-2}$). Impacted features are identified by performing a GIS-based overlap of a probabilistic hazard map and an exposed target map (Fig. 2b), then characterized by their vulnerability. Results are given in Table 3. Note that Katla has a high impact on power plants at any value of probability considered, due to its close proximity to 5 power plants. Moreover, tephra fallout from a Hekla-1947-type eruption can impact important electricity lines that connect power plants to the rest of the network, while a Hekla-2000 scenario has a low probability (< 5 %) of impacting power plants and electrical infrastructure. Both Hekla-1947 and Katla scenarios have a high probability (up to 20 %) of impacting important power lines that bring electricity to the southeastern region. An eruption of Eyjafjallajökull similar to that of 2010 could also impact these

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power lines (about 10 % probability). Finally, electricity power lines are also strongly impacted by the Askja scenario, that may disrupt an important line that connects the Eastern part of the country with geothermal and hydroelectric power plants located in the North, and provides electricity to an important aluminum smelter (Fig. 2b). Note that, although a Hekla-2000-type scenario does not seem to affect any power plant, Biass et al. (2014) show that low tephra accumulations ($\sim 1\,\mathrm{kg\,m^{-2}}$) can be produced in the area surrounding the volcano, so that the possibility of having impacts due to Hekla-2000-type scenario should not be discarded.

Biass et al. (2014) show that the probability of having tephra deposition of $1\,\mathrm{kg\,m^{-2}}$ is relevant ($> 50\,\%$) in southern and eastern Iceland in Katla LLERS and Askja OES 1875-type scenarios. The probability of accumulating $10\,\mathrm{kg\,m^{-2}}$ is also substantial in southeastern Iceland (Biass et al., 2014). Thus, agricultural activity in these areas can be impacted and livestock can suffer from fluorine intoxication due to water and soil contamination. For each eruptive scenario, we estimated the area devoted to agricultural activities that has 5, 10, and 20 % probability of being impacted (i.e. covered by a critical tephra load $> 10\,\mathrm{kg\,m^{-2}}$). Results are summarized in Table 4 and 5 and can be compared with the corresponding tephra accumulation hazard maps (Biass et al., 2014) and vulnerability maps (Fig. 4 and the Supplement Fig. S1). The highest impacts on crops are caused by Katla LLERS and the Eyjafjallajökull LLOES 2010-type eruptions, while pastures are expected to be particularly impacted by Askja OES 1875-type and Katla LLERS eruptions. The Hekla ERS 2000-type scenario does not impact agricultural activities.

Impacts are also estimated on the basis of the accessibility analysis using least-cost-distance models (Wood and Schmidtlein, 2012). Using the census contained in the official GIS database (i.e. polygons of habited areas; Landmælingar Islands, 2012), we calculated the size of population located in areas classified in terms of travel time (Fig. 5) to critical facilities: schools (Fig. 3a), hospitals (Fig. 3b) and police/fire stations (Fig. 3c). The *Spatial Analyst* toolbox of the *ESRI ArcMap 10.2* software was used calculate the shortest travel time from any pixel on the map to reach a critical facility

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using the road network. The hierarchy of the official road network (Landmælingar Islands, 2012) as well as the speed limit for each road class were respected and implemented in a cost raster for accessibility analysis.

4 European-scale vulnerability and impacts

As clearly demonstrated during the Eyjafjallajökull eruption in 2010, the European air traffic system is largely vulnerable to loss of functionality of its elements when exposed to volcanic ash. The magnitude of systemic impacts depends on the relevance of the disrupted elements, and impacts of ash clouds can occur very far from the source (Ceudech et al., 2011). Here, we analyze the systemic vulnerability of the European air traffic system and the socio-economic vulnerability of the areas hosting its main airports.

4.1 Exposed targets

We define vulnerability indicators based on the analysis of the European air traffic system, including main exposed airports and aviation routes. The analysis is performed at the European scale but we focus on those regions where our hazard assessment indicates that impacts from ash dispersal can be significant.

The European air traffic network has more than 2000 international airports handling approximately 170 000 overall daily flights on average (Wegner and Marsh, 2007). However, over 50 % of the European air traffic concentrates in the top 35 airports (Wegner and Marsh, 2007). The European air traffic network is scale-free (Wilkinson et al., 2011), meaning that these main hubs are the most relevant to the system, and therefore highly vulnerable to its failure. The main European hub is London Heathrow, with 61 million terminal passengers on international flights in 2010 (Heathrow Airports, 2013), followed by Paris Charles de Gaulle. The 5 London airports (Heathrow, Gatwick, Stansted, Luton and City) account together for more than 60 % of the total number

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of UK passengers according to the UK Department of Transport. In 2011, London's airports handled more than 120 million passengers and 1.7 million tons of freight (CAA, 2012). Moreover, the most intense freight traffic in Europe during 2009 was between UK and 4 European states: Germany, Netherlands, France, and Belgium (PricewaterhouseCoopers, 2011). The London area is therefore one of the most critical and strategic points within the European air traffic network and the airspace between London, Paris, Frankfurt and Amsterdam constitutes the densest part of the European civil aviation network. It therefore follows that the European air traffic network is particularly vulnerable to the failure of some of these strategic hubs.

At a national level, the Keflavík airport is also strategic for the Icelandic economy. In 2011, Keflavík handled 97.5 % of all international passengers (1.75 million; Keflavík international airport, 2012), 49.2 % of domestic passengers (0.75 million), and more than 99 % of all cargo operations. Air-based commercial relationships with Europe are very important for the Icelandic socio-economic system. In fact, the EEA market (i.e. the 27 EU countries plus Iceland, Norway and Liechtenstein) accounts respectively for 82.7 and 61.9 % of total Icelandic exports and imports. The main commercial partners are Netherlands, Germany, UK, and Norway. Iceland's imports come mainly from Norway, USA, Germany, Netherlands and the UK (Statice, 2012). According to the 2011 statistics, Keflavík's most important passenger destinations were Copenhagen, London and Oslo. During 2010–2011 the Icelandic airspace experienced a 9 % growth of traffic (counting over-flights) (Isavia, 2012) and, although peripheral in the European network, it is strategic for intercontinental flights from and to the USA and Canada. Disruption of air traffic connections can therefore impact substantially on both local and regional economies.

Based on these considerations, the exposed targets for our systemic vulnerability analysis are the main airports and routes to North and central Europe and the most relevant socio-economic features of the areas where the main airports are located. In order to have a vulnerability assessment meaningful to civil aviation stakeholders, we consider European airspace sectors, following the current

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classification (EUROCONTROL, 2005). Flight Information Regions (FIRs) are subdivided according to their specific role into CTA (Control Area), OCA (Oceanic Control Area), ACC (Area Control Center) and UAC (Upper Area Control), which are airspace sectors not hosting airports (EUROCONTROL, 2005). Aerial sectors represent a key component of the air traffic network because each sector has an associated capacity, which is the main parameter for air traffic management (Leal de Matos and Ormerod, 2000; Leal de Matos and Powell, 2002; Dell' Olmo and Lulli, 2003).

Finally, we note that the territorial context of an airport is also relevant for the estimation of socio-economic vulnerability and impact because the vulnerability of a region is proportional to its dependence on air traffic.

4.2 Vulnerability indicators

Table 5 summarizes the systemic and socio-economic vulnerability indicators defined for the European air traffic system. Figures 6–10 show vulnerability maps produced for the considered features (airports, routes, airspace sectors and European regions). Visualization is performed through the open source GIS Qgis (http://www.qgis.org/en/site/), using the European GIS database (GISCO, 2013) and European air traffic database (courtesy of EUROCONTROL). Unless specified otherwise, all indicators are reclassified in a qualitative 5-class ranking, ranging from very low to very high, using the natural breaks method (Jenks, 1967). Vulnerability indicators include:

1. Strategic airports. We assume that the higher the traffic of an airport, the higher its relevance and, consequently, the higher the vulnerability of the system to its potential disruption. We classified all European airports according to traffic of passengers and freight during 2012 (Eurostat, 2013) and this identified Frankfurt, London Heathrow, Amsterdam and Paris Charles de Gaulle as the strategic elements for the European air traffic system in terms of passengers and goods. Given that the probability of ash dispersal affecting southeastern Europe is low (Biass et al., 2014) and that we aim to assess the vulnerability within

a more constrained domain, we performed the same analysis for central and northwestern Europe. Having selected the most relevant airports in central and northern Europe in terms of air traffic values (Supplement Table S3), we ranked them according to passengers and freight values (Fig. 6). The most relevant airports are London Heathrow, Paris Charles de Gaulle, Frankfurt, Amsterdam, and Munich, which were already identified as main hubs at the European level. Copenhagen airport also has a high relevance for traffic to northern-Europe (including Iceland).

2. Strategic routes, classified in two ways. The first classification builds upon the average number of connections between each pair of European airports in 2012 (courtesy of Eurocontrol). We assume that the higher the number of connections the higher the importance of the route and the higher the systemic vulnerability of the system to its failure. This classification reveals that the top 5 connections are: Madrid–Barcelona (Spain), Istanbul–Izmir (Turkey), Paris–Toulouse (France), Oslo–Bergen (Norway) and Barcelona–Palma de Mallorca (Spain). Constraining the analysis to central and northwestern Europe, the most relevant connections are London–Paris, Paris–Frankfurt, London–Edinburgh, London–Dublin, Munich–Frankfurt, Copenhagen–Aalborg, Oslo–Trondheim, Oslo–Bergen and Oslo–Stavanger. This analysis underlines that the main city pairs are often composed of national connections between first and second largest cities, as described by Wegner and Marsh (2007). The second classification is based on air traffic (passengers and freight) for each city pair, that is, for the main routes between a considered airport and its partners (Eurostat, 2013). This kind of classification considers the relevance of European routes for a selected sub-system constituted by the considered airport and its main European partners. For example, we show two relevant cases: the London hub, strategic for European air traffic, and Keflavík airport, the most important in Iceland. The relative importance of routes is a measure of the vulnerability of the sub-system to the disruption of that particular route. In our analysis, the London hub includes the city's 4

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main airports: Heathrow, Gatwick, Stansted and Luton. Figure 7 shows strategic routes of London airports for passengers (left) and freight (right), for Heathrow airport (top) and for the other three airports, displayed together (bottom). The top London destinations (> 1.2 million passengers year^{-1}) are Dublin, Edinburgh, Paris and Frankfurt. London Heathrow–Dublin is the most important connection with more than 1.5 million passengers per year. In terms of cargo, Stansted is also an important hub with main destinations to Frankfurt, Brussels, Stockholm and Paris. Figure 8 shows the most important partners for Keflavík airport in terms of passengers (a) and goods (b). Copenhagen, London and Oslo are strategic destinations for passengers, whereas Amsterdam, London, Paris, and Koln–Bonn are main nodes for freight transportation. It is worth noting that the main passenger routes from Keflavík airport have the same order of magnitude as the less relevant route for the London hub (~ 300 000 passengers per year). Keflavík routes, if classified using the same range used for the London airports, would fall into the low vulnerability class and their relevance would be diminished in the subsequent impact analysis. Using a scale-dependent classification criterion allows identification of routes that can be secondary at a broader European scale but are strategic for the national scale.

3. Number of daily European flights in each airspace sector, which gives a measure of the airspace congestion. For simplicity, our analysis uses data of one of the peak days during 2012 (29 June) and assumes that this particular day is representative of high-traffic situations in Europe. For each airspace sector, we counted how many times per day the sector is crossed by flights at any FL and assign a vulnerability value accordingly. Figure 9 shows that the most congested airspace sectors are located in France (Brest, Paris, Marseille FIRs), southern UK (London FIR), Germany (Langen, Bremen, Hannover FIRs), Netherlands (Amsterdam FIR) and Italy and Spain (Milan, Rome, Madrid FIRs). Some FIRs show lower traffic rate compared to the surrounding areas, for example Ireland (Shannon FIRs) and other regions of France (Bordeaux and Reims FIRs).

4. Relevance of air traffic for European regions, based on a combination of four regional indicators: population (Eurostat, 2013, data from 2012), total number of passengers and tons of freight transported by air (Eurostat, 2013, data from 2011) and multi-modal accessibility, which takes into account the presence/absence of alternative transport modes and their cost (ESPON, 2004; TRACC, 2010, p. 17). We use multi-modal accessibility produced by the ESPON project (ESPON©, 2013) as an indicator of vulnerability: areas having low multi-modal accessibility are therefore more vulnerable to the failure of one transportation mode due to the limited variety of alternative transportation modes available. According to Fürst et al. (2000) multi-modal indicators have much more explanatory power with respect to regional economic performance than any accessibility indicator based only on a single mode. We propose a first-level assessment of socio-economic vulnerability by combining these four indicators under the assumption that vulnerability increases when the dependency on air traffic is higher and the multi-modal accessibility lower. All indicators are referred to the 2003 NUTS-2 regions (Nomenclature of Territorial Units for Statistics), a hierarchical system for dividing the economic territory of the EU for the application of regional policies. We combine the 4 indicators by summing the values for each NUTS2 region, and reclassifying the resulting map into 5 vulnerability classes. Population, air traffic and multi-modal accessibility are classified in 5 equal interval classes, while the multi-modal accessibility database produced by the ESPON project is already ranked in to 5 qualitative classes, ranging from 1 (highly below average) to 5 (highly above average). Air traffic data show that the areas which most rely on air traffic correspond to the regions hosting the main European cities of London, Paris, Frankfurt and Amsterdam. But socio-economic vulnerability is not only related to the volume of air traffic: for example Ireland has a low multi-modal accessibility (Supplement Fig. S2), but a considerable population (Supplement Fig. S2). The resulting vulnerability map (Fig. 10) facilitates recognition of the areas most dependent on air traffic, where a relatively high population and/or

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air traffic values are associated with low multi-modal accessibility. The most vulnerable NUTS-2 areas are therefore the ones hosting the cities of London, Paris, Frankfurt and Amsterdam. Also, Ireland, Norway and northern France show a medium-high vulnerability. Due to the intrinsic nature of being an island, air traffic cannot easily be substituted with an alternative transportation means. For this reason, Ireland has medium vulnerability to air traffic disruptions.

Given the differences in the indicators of vulnerability we evaluate the expected impacts for each single vulnerability feature, i.e. for the national-scale assessment, we do not merge the different thematic vulnerability maps (Figs. 6–10) into a single map. However, once the strategic elements and their relevance are identified, it is possible to assess the expected impacts of each eruptive scenario through a GIS-based overlap of hazard and vulnerability maps.

4.3 Impact assessment

We propose three different methods for assessing the impacts of tephra dispersal on European air traffic. Each method focuses on producing specific results, and could be used to support risk management strategies at different levels.

The first method consists of a qualitative GIS-based visual overlap of hazard and vulnerability maps. The graphical overlap allows for an immediate identification of the routes that have the highest probability of being disrupted for each scenario. For example, the overlap of the Askja hazard map for all FLs (Biass et al., 2014) and the main passenger routes between London Heathrow and Europe (Fig. 7a) reveals which routes would have the highest probability of being disrupted in this scenario. The overlap of hazard and vulnerability can also be performed using hazard maps for specific FLs (Biass et al., 2014) and averaged arrival time and persistence maps, which allow for the potential duration of a disruption to be inferred.

The second method estimates the impact (movements disrupted, passengers and freight stranded) at given airports by multiplying the average atmospheric persistence time of a given hazardous ash concentration for a given eruptive scenario (Biass et al., 2014) by the hourly-averaged traffic. Here, we assume that, if the critical ash concentration is reached at any FL over an airport, all flight operations are disrupted. For example, Tables 6 and 7 show the expected impacts at London Heathrow and Keflavík airports for the different eruptive scenarios considered, respectively. Air traffic values for London Heathrow are estimated dividing yearly averages (CAA, 2012; Heathrow airport, 2013) by 365. Keflavík air traffic values are inferred from Keflavík airport 2011 facts and figures (Keflavík International Airport, 2011). According to Biass et al. (2014) the probability of having more than 24 h of disruption at London airports from Askja-1875 and Katla-1918 scenarios is about 5 and 1 % respectively. The probability of having more than 24 h of disruption due to Hekla activity are lower than 1 %. Thus, there is a substantial probability of having strong disruptions in the London area due to high-magnitude explosive volcanic eruptions at Askja and Katla, and a low probability of having impacts at London due to lower magnitude events at Hekla volcano.

Finally, the third method consists of overlapping hazard and vulnerability data and combining the values on a cell-by-cell basis, i.e. multiplying hazard and vulnerability values within each cell. To do that, hazard and vulnerability maps are converted to raster format (geotiff) using GRASS GIS (Neteler et al., 2012). We use probabilistic hazard maps for each scenario that account for the probability of disruption at any FL (Biass et al., 2014) and vulnerability maps of the airspace sectors (Fig. 9). Such maps are then overlapped on a cell-by-cell basis and the resulting impact map is reconverted to vector format, aggregating the maximum impact value over FIRs areas. The final results are impact maps containing impact values for each FIR, reclassified in 5 qualitatively impact classes (very low to very high impact) using the method of natural breaks. These results are shown in Fig. 11. It has to be stressed that the resulting impact represents relative comparison between FIRs rather than a quantitative impact. The Hekla ERS 2000-type scenario (Fig. 11a) produces very high impacts in the Reykjavík FIR, high impacts in the London FIR and low impacts in the Shanwick and

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Norway FIRs, but is not expected to affect central Europe. The Hekla ERS 1947-type scenario (Fig. 11b) produces very high impacts in the Reykjavík FIR, and Paris, Brest and Marseille FIR, high impacts in the London FIR and low impacts in the Shanwick Norway and Sweden FIRs. Such a scenario is also likely to result in low impacts in the northern Germany and Poland FIRs. Both the Katla LLERS (c) and the Askja OES 1875-type (d) scenarios are likely to produce high impacts in the Keflavík FIR as well as the southern UK and France FIRs, mostly due to their high traffic rates (and therefore, high vulnerability). These scenarios can also produce high impacts in the Norway, Sweden, Austria and Germany FIRs. Low impacts are expected in the rest of Europe.

5 Discussion

5.1 National-level vulnerability and impact assessment

The methodology presented here to assess vulnerability to tephra fallout at a national scale was developed for the particular case of Iceland in cooperation with local stakeholders and the Icelandic Civil Protection Department, and uses only publicly available data. However, the method could potentially be applied in different geographic and socio-economic contexts where similar public censuses are available. The list of exposed features identified in Sect. 3.1 is valid elsewhere and Table 8 lists the type of data that, ideally, should be included in any comprehensive vulnerability assessment. For example, from a socio-economic point of view, the role of productive activities and the number of employees for activity or sector should be taken into account. Industrial and tertiary activities, for example, often constitute the backbone of the socio-economic system, driving local development and distribution of resources. In terms of transportation, one inconvenience is that national statistics are rarely given by transport mode, making it difficult to identify the precise contribution of air traffic to the socio-economic system. Also, water supply has been recognized as an exposure target in

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a few isolated cases (Sect. 3.1) but not taken into account for the estimation of impacts, because it needs to be treated at a more local scale. Census of water supply systems (for example, water quality control and monitoring) may support response strategies, in particular for areas with strong agricultural sectors (Fig. 4) that can suffer substantial impacts from tephra fallout (Sect. 3.3). Finally, only a few datasets were available at a municipality level or in the form of disaggregated data (that is, data available at the same administrative level used for collection). For example, most economic and labor market indicators were produced at the national level. This lack of disaggregated data is a common problem in most risk assessments, and the availability of disaggregated datasets, or data sources defined at lower administrative levels, would improve the vulnerability assessment presented here.

Results from national vulnerability and impact assessments allow definition of priority areas for risk mitigation strategies. In particular, comparison of population values with other vulnerability indicators can support the prioritization of interventions for long-term vulnerability mitigation plans. For example, northeastern Iceland has a substantial probability of being affected by deposition of tephra from Askja, and this hazardous phenomenon should be considered in long-term territorial plans. Recent population statistics (Byggðastofnun, 2012) show a positive trend in this area due to the construction of a dam and the consequent generation of employment. The increase of population and the arrival of non-local workers, less familiar with an active volcanic environment, should be taken into account, e.g. through educational programs. The results of the impact assessment can also support Icelandic policies in the main strategic sectors such as transportation, economic activities, or location of critical facilities. Table 3 shows that the largest impacts are expected from the selected eruption scenarios (Table 1) at Askja, Katla and Hekla volcanoes due to the presence of power plants and a main power line in their surroundings. Results suggest that moderate tephra fallout from Hekla volcano can produce major impacts on the surrounding power plants. A low-magnitude activity such as the Hekla ERS 2000-type does not seem to produce such major impacts but, given its very high frequency of

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activity (10 years repose time, Höskuldsson et al., 2007), should also be taken into account. In fact, repeated tephra fallout could have long-term impacts on power plant equipment and external components. Expected impacts on agricultural activities are in general limited to the few crops located in the southeast of the island. Table 4 shows that the major impacts on crops are expected for the Katla LLERS and Eyjafjallajökull LLOES 2010-type scenarios. In particular, ash fallout from the Askja OES 1875-type and Katla LLERS scenarios is expected to cover several square km of pasture in the south and east of Iceland (Table 4). Due to the importance of agricultural activities (wool in particular) for the Icelandic economy, these results should be taken into account in order to improve preparedness and reduce impacts on the national socio-economic system.

In this study we have considered the same ash load thresholds for all eruptive scenarios ignoring that impacts can depend on ash grain-size and composition (Wilson et al., 2009a). Even though we adopted different grain-size distributions for each eruptive scenario (Biass et al., 2014), no study exists on ash load threshold dependency on granulometry and composition.

Wilson et al. (2009a) pointed out the seasonal character of vulnerability, an important factor for certain activities such as agriculture and farming that have a seasonal character (Jóhannesson, 2010). For example, the same hazardous phenomenon could produce higher impacts to crops during the sowing, growth and flowering phases, while less impacts are expected to unplowed fields. The adoption of seasonal thresholds would support the definition of specific seasonal strategies. Finally, ash load thresholds are often given in a range of values and, consequently, impact assessments should reflect this variability in the results.

Figures 3 and 4 allow identification of the spatial distribution of the most vulnerable areas and targets according to the considered vulnerability themes. It is important to stress that the vulnerability scores, expressed either as numerical scores or qualitative judgments, normally represent comparative (i.e. relative) values. This makes the merging of different vulnerability maps into a single final map a complex process.

On one hand, the perspective of single indicators can be lost when combined with others. On the other hand, single merged maps are more synthetic and workable if they involve no loss of information. In this work, and given the very different nature of the indicators considered, we prefer not to overlap maps of different vulnerability categories. Nonetheless, the comparison of information related to each vulnerability indicator can provide a significant support both to land use and emergency planning.

Results of the accessibility analysis (Figs. 3 and 5) help the identification of zones with limited access to critical infrastructure by classifying the population in terms of travel time to strategic features (hospitals, police/fire stations and potential shelters). This analysis accounts for the travel speed of the road network, where pixels outside the road network are only allowed an average walking speed. Note that unlike agent-based strategies, the resulting model is time-independent and does not attempt to account for dynamic travel time costs due to route capacity or road congestion (Wood and Schmidtlein, 2012). However, least-cost-distance models still provide key information for preparedness and planning by identifying heterogeneities in the accessibility over the entire territory rather than modeling the behavior of individuals. A combined look at Figs. 1 and 3 highlights how most of the critical infrastructures are clustered around the main towns, with the main zone of low accessibility being the Vatnajökull area. Figure 5 is a combination of the analysis performed in Fig. 3 and the population census, and helps visualize the number of people as a function of the travel time to critical infrastructures. Figure 3c also shows that although inhabited, Vestfjörður, the northwesternmost peninsula, has a low accessibility to police/fire stations. This is clearly reflected in Fig. 5, where a travel time greater than 3 h is associated to thousands of people. As a result, such a method is valuable to plan the implementation of additional critical infrastructures for future crises.

Finally, it is worth noting that performing vulnerability and impact assessments at a national scale has relevant pros and cons (Fekete et al., 2008). On one hand, it allows large-scale processes, trends and dependencies (particularly relevant to understanding the systemic and socio-economic aspects of vulnerability) to be

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captured and to identify priority areas at a national scale. Also, large-scale risk assessment, although recognizing the importance of the multiple facets of vulnerability (Lirer et al., 2010) generally results from overlapping exposure and hazard maps. On the other hand, analysis at a national scale does not allow some relevant components of vulnerability to be considered, for example risk perception (requiring local scale analysis) or characterization of the physical vulnerability of specific elements, for example buildings and infrastructures. For this reason, the methodology proposed here could be integrated with other types of analyses and contribute to the development of an enhanced multi-scale methodology.

5.2 Vulnerability and impact assessment of European air traffic

We have proposed a vulnerability assessment that identifies the elements (airports, routes and airspace sectors) likely to cause major impacts to the European air traffic system in the case of tephra dispersal from eruption of an Icelandic volcano. London is recognized to be the core of the European aviation system, followed by Paris, Amsterdam and Frankfurt according to the number of connections handled (Fig. 6). Our analysis has also identified the routes that have the highest socio-economic relevance, constrained to central and northwestern Europe based on the outcome of the hazard assessment (Biass et al., 2014). The analysis emphasizes the role of minor connections that, despite being secondary at European level, are strategic for national economies. For example, the analysis of air traffic at London and Keflavík airports showed that London–Dublin and Reykjavík–Copenhagen are very important routes (Figs. 7 and 8) and their disruption could affect national economies and those of their commercial partners. We also estimated vulnerability of FIRs (Fig. 9) based on traffic data from a peak day. This first-order estimation could be enhanced using air traffic data during a larger time interval to account for weekly/seasonal traffic variability. Moreover, other indicators for FIRs, for example accounting for the different types of flights (charter, commercial, business, cargo) could also be considered. Despite these methodological limitations, the identification of strategic airspace sectors is an

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important result itself given that current air traffic management procedures are based on airspace capacity (Cook, 2007).

The methodology proposed in this work is flexible enough to include new administrative boundaries and new procedures in the vulnerability assessment. This is important if, as expected, regulation changes occur. At a European level, new trends in air traffic management are driven by the Single European Sky Commission Project (SESAR, http://ec.europa.eu/transport/modes/air/sesar/), aimed at ensuring capacity and safety needs to European aviation. The SESAR program includes the constitution of Functional Airspace Blocks (FABs), expected to be operative in the next few years, which would reduce airspace fragmentation and supportintegrated airspace management (Arroyo, 2008). In case of ash-contaminated airspace, the new SESAR regulation framework could be included in the analysis to support the development of new centralized strategies. It has also been suggested that the short-term capacity of sectors may be negotiated in order to allow rerouting of flights to opened FIRs, thus improving the performance of the network. However, procedures to be adopted in the case of ash-contaminated airspace (e.g. the possibility of overflying ash clouds) are still under discussion. The idea that the airlines will be able to decide whether to fly or not in ash-contaminated airspace has been proposed by EUROCONTROL and implemented during the 2011 VOLCEX exercise, as described in the final report (ICAO, 2011). This new paradigm could be implemented in the EUR/NAT region by several stakeholders that, after the approval of a Safety Risk Assessment (SRA; Bolić and Sivčev, 2011; EASA, 2012), would be able to decide whether to fly or not through ash-contaminated airspace sectors. The introduction of SRA underlines the importance of having a long-term perspective in risk-management procedures and plans. Long-term risk management plans could also avoid secondary impacts, e.g. the lack of fleet at non-contaminated areas during the closure of main airports. For example, Icelandair managed to move aircraft from Keflavík to a secondary hub in the UK (Ulfarsson and Unger, 2011) to maintain operations in non-contaminated areas (and in particular, Intercontinental routes). Long-term hazard assessment (Biass et al.,

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2014) and vulnerability and impact analysis can therefore support SRAs and mitigation measures and enhance the response in the case of volcanic ash contaminated airspace.

In this work, we have proposed several ways of estimating impacts on the air traffic system and our results give a wide perspective of the spatial and temporal magnitude of impacts. According to Fig. 11, all eruptive scenarios produce impacts in the London area, but the Askja OES 1875-type and Katla LLERS scenarios can result in major impacts for the whole European air traffic system. Low-magnitude, short-duration activity such as Hekla ERS 2000-type does not result in high impacts to central European air traffic, but can disrupt relevant connections for the national economies involved (i.e. Reykjavík–Copenhagen, London–Dublin). The probability of having hazardous mass concentrations for more than 12 h (Biass et al., 2014) show that high-magnitude scenarios such as the Askja OES 1875-type event can produce major disruptions (> 1 % probability) to London air traffic. Also, lower-magnitude but long-lasting activity such as a Katla LLERS scenario has a > 1 and > 5 % probability of producing 12 h lasting disruption respectively to London and Scotland, where the important airports of Glasgow and Edinburgh could be affected. Tables 6 and 7 show expected disruptions to Keflavík and London airports, based on averaged data. Note that this first-level impact assessment does not take into account the hour of the day and/or the day of the year in which a disruption occurs, which neglects differences between peak and off-peak (night and early morning) times. Average persistence times give information on the expected duration of disruptions, but given that the standard deviation for persistence time is in the order of 5–10 h (Biass et al., 2014), a high uncertainty is associated with these values. Nevertheless, this analysis allows estimation of the order of magnitude of expected impacts and may support the definition of an "acceptable risk" based on averaged long-term values, which could eventually support a practical framework for risk management. Finally, average arrival time maps (Biass et al., 2014) identify which airports and areas may need response plans and gives an idea of how much time is available for operations such as moving

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aircraft into hangars or part of the fleet to other airports. In fact, Guffanti et al. (2010) have shown how most damaging incidents during the last 60 years occurred within the first 1000 km from source volcanoes and within the first 24 h after eruption onset. The results of this impact assessment may therefore support the definition of strategies for many stakeholders involved in air traffic management during volcanic eruptions.

We also estimated impacts on FIRs (Fig. 11), accounting for the presence of ash at all FLs. The same impact analysis has been performed at specific FLs (Supplement Fig. S3) leading to significantly different results. In fact, impacts at a given FL strongly depend on the range of column heights of each eruption scenario, which in turn influences the probability of having ash at different FLs. For example, the Hekla ERS 2000-type scenario does not produce impacts at FL300 but only at lower levels. Consequently, a long-term impact assessment based on FL300 underestimates the expected impacts of low-magnitude eruptions such as the Hekla ERS 2000- and 1947-types. Analogously, impact assessment at airports (Tables 6 and 7) could be done considering all FLs or restricted at FL050, where most takeoff and landing operations take place. Given that air traffic management is based on the capacity of airspace sectors and these include several FLs (Cook, 2007), the second option seems more useful for decision-making. For these reasons, we encourage the use of expected impact maps at FIRs, that are comprehensive of all FLs and provide a synthetic, conservative and meaningful support for the development of a Safety Risk Assessment (SRA) and other risk management plans.

Finally, this work has estimated the socio-economic vulnerability of Europe to air traffic disruptions. The 2010 eruption of Eyjafjallajökull demonstrated that impacts at strategic airports such as London produce major systemic impacts to the rest of the European air traffic network and indirect socio-economic impacts at a global scale (Oxford Economics, 2010). One example is the interruption of Kenya exports to the UK (BBC News, 2010), which caused an economic impact to Kenyan agricultural sectors (Alexander, 2013). Here we did not describe such interactions, but proposed a methodology to compare different sources of information that quantifies

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the dependency of European areas on air traffic. The combination of demographic, trade and accessibility information (Supplement Fig. S3) identifies NUTS-2 regions with higher dependency on air traffic (Fig. 10), that is, more vulnerable to air traffic network disruptions. Moreover, the comparison of vulnerability maps for NUTS-2 regions and impact assessment results (Fig. 11 and Tables 6 and 7) identifies the most impacted areas from explosive eruptions in Iceland. For example, Ireland has a high vulnerability because it is an island (which inherently has a low multi-modal accessibility) and has strong social and commercial relationships with UK, resulting in high socio-economic impacts in case of air traffic disruption. Also Nordic countries such as Denmark and Norway are likely to be affected, in particular those regions with lower multi-modal accessibility. Flexibility of the transportation system and multi-modal accessibility are in fact critical factors that strongly influence the societal response to air traffic disruptions (Alexander, 2013). Finally, civil aviation disruption is not only a problem for private stakeholders, but affects all of society, requiring procedures to mitigate the socio-economic risk (Vainikka, 2010). Results of the vulnerability and impact assessment performed at European level can support a socio-economic impact analysis and the development of risk management plans. Data from European projects such as Eurostat, ESPON and TRACC are extremely relevant to support this analysis.

6 Conclusions

This work is the first example of a multi-scale impact assessment for tephra dispersal and deposition. This assessment was applied to various activity scenarios of selected Icelandic volcanoes but could also be applied to other volcanic settings with the potential to affect both neighboring communities and airspaces. Our vulnerability assessment could support decision-making at a national scale. In particular, impact maps could improve preparedness and help develop risk mitigation actions. Our outcomes could also support long-term risk management plans at the European scale, such as SRA for companies that operate in the European airspace. Based on our analysis of the economic system at national level and of critical airports, FIRs and air traffic routes at the European scale, we can draw the following conclusions:

At the national scale:

- The electricity network is the most exposed element to an Askja OES 1875-type eruption, resulting in a 10 % probability of 655 km of the network being impacted. Eruptions of Katla LLERS, Hekla ERS 1947-type and Eyjafjallajökull LLOES would result in impacts to 267, 263, and 122 km of the electricity network (at a 10 % probability);
- In terms of number of power plants affected, a Hekla ERS 1947-type eruption would be the most problematic with a 10 % probability of affecting 5 of them. Eruptions of Askja OES 1875-type and Katla LLERS have both a 10 % probability of affecting 4 power plants. Other eruptions are associated with negligible probabilities;
- Based on all eruption scenarios, there is a 10 % probability of affecting 1–10 km^2 of croplands. However, eruptions of Askja OES 1875-type and Katla LLERS have a 10 % probability of affecting 287 and 125 km^2 of pasturelands, respectively.

At the European scale:

- A Hekla ERS 2000-type eruption is likely to cause very high impacts to the Reykjavík FIR (∼ 950 passengers stranded for at least 5 h) and high impacts for the London FIR (∼ 23 000 passengers stranded for at least 3 h);
- A Hekla ERS 1947-type eruption is likely to cause very high impacts to the Reykjavík FIR (∼ 1500 passengers stranded for at least 8 h) and high impacts for the London FIR (∼ 27 000 passengers stranded for at least 4 h). The FIR of Paris, Brest and Marseille would also be strongly impacted;
- An Askja OES 1875-type eruption is likely to cause very high impacts to the Reykjavík FIR (∼ 3600 passengers stranded for at least 18 h) and high impacts

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for the London FIR (~ 60 000 passengers stranded for at least 8 h). FIRs above France, Germany and Scandinavia would also be impacted;

- A Katla LLERS eruption is likely to cause a very high impact to the Reykjavík FIR (~ 4300 passengers stranded for at least 21 h) and high impact for the London FIR (~ 78 000 passengers stranded for at least 10 h). It is also likely that FIRs above France, Germany and Scandinavia would be strongly impacted.

Supplementary material related to this article is available online at http://www.nat-hazards-earth-syst-sci-discuss.net/2/2531/2014/nhessd-2-2531-2014-supplement.pdf.

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Table 1. Synthesis of the eruptive scenarios considered in the tephra hazard assessment (Biass et al., 2014). ERS: Eruption Range Scenario, OES: One Eruption Scenario, LLERS: Long Lasting Eruption Range Scenario LLOES: Long Lasting One Eruption Scenario. Tephra accumulation and dispersal was assessed for Hekla, Askja and Katla, while for Eyjafjallajökull only tephra accumulation was modeled (Biass et al., 2014).

Volcano	Modeling strategy	Reference eruption	Column height (km)	VEI	Eruption duration
Eyjafjallajökull	LLOES	2010	2.5–7.8	2	40 days
Hekla	ERS	2000	16.0–30.0	2	0.5–1 h
Hekla	ERS	1947	6.0–16.0	3	0.5–1 h
Katla	LLERS	Historical moderate/large[a]	10.0–25.0	–	1–4 days
Askja	OES	1875 (C + D phases)	22.8–26.0	5	1 h + 1.5 h (C + D phases)

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Table 2. Indicators (and estimators) defined for the systemic vulnerability from tephra fallout.

Category	Theme	Indicator (at municipality level)
Physical	Electric power plants and distribution network	Constant vulnerability = 1
Systemic	Accessibility	Travel time to critical facilities, energy production sites and mobility nodes
Socio-economic	Agricultural areas	Combination of 3 factors: agricultural area, milk and wool production

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Table 3. Estimated impacts to electricity generation and distribution systems for different eruptive scenarios. For each eruptive scenario, we calculated the length of the electricity distribution system and the number of power plants having 5, 10 and 20 % probability of being affected by a critical ash fallout of 10 kg m^{-2}. Note that the Hekla ERS 1947-type has the highest impact on power plants due to the location of the volcano, close to 5 power plants.

Eruptive scenario	Length impacted (km)			Number of power plants		
Probability (%) for 10 kg m^{-2}	5	10	20	5	10	20
Hekla EES	0	0	0	0	0	0
Hekla ERS	500	263	106	6	5	4
Askja OES	1400	655	109	5	4	1
Katla LLERS	671	267	135	6	4	0
Eyjafjallajokull LLOES	207	122	73	2	0	0

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Table 4. Estimated impacts to agricultural activities for different eruptive scenarios. Area of crops and pasture having 5, 10 and 20 % probability of being affected by a critical ash fallout of 10 kg m^{-2}. Katla LLERS and Eyjafjallajökull LLOES 2010-type scenarios cause the greatest impacts to crops, while pastures are particularly affected by eruptions of types Askja OES 1875 and Katla LLERS.

Eruptive scenario	Crops impacted (km^2)			Pastures impacted (km^2)		
Probability (%) for 10 kg m^{-2}	5	10	20	5	10	20
Hekla EES	0	0	0	0	0	0
Hekla ERS	10	0	0	281	13	0
Askja OES	10	1	0	586	287	26
Katla LLERS	14	7	1	361	125	101
Eyjafjallajokull LLOES	12	9	7	12	9	7

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Table 5. Indicators (and estimators) defined for systemic vulnerability of the European air traffic system to tephra dispersal.

Vulnerability category	Vulnerability Theme	Vulnerability Indicator	Vulnerability Estimator
Systemic Relevance of features		Airports (all Europe and North-West Europe)	Passengers ($n\,\mathrm{day}^{-1}$) Good ($\mathrm{t\,year}^{-1}$)
		Routes (all Europe)	Number of average daily connections
		Main Routes (North-West Europe)	Passengers ($n\,\mathrm{day}^{-1}$) Goods ($\mathrm{t\,year}^{-1}$)
		Airspace sectors (FIRS, All Europe)	Traffic rate per FIR
Socio-economic	Air traffic and development	Population Air traffic	Population/Nuts2 goods/Nuts2 passengers/nuts2
		Accessibility	Multi-modal accessibility/Nuts2

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Table 6. First-order estimation of expected impacts at London Heathrow airport for different eruption scenarios based on the averaged persistence. Air traffic values are based on yearly averages (CAA, 2012).

Eruptive Scenario	Mean persistence all FLs (h)	Movements disrupted (n)	Passengers stranded (n)	Freight stranded (t)
Hekla-2000 ERS	~ 3	~ 160	$\sim 23\,000$	~ 600
Hekla-1947 ERS	~ 4	~ 180	$\sim 27\,000$	~ 700
Katla LLERS	~ 10	~ 530	$\sim 78\,000$	~ 2000
Askja OES	~ 8	~ 410	$\sim 60\,000$	~ 1500

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Table 7. First-order estimation of expected impacts at Keflavík airport for different eruption scenarios based on the averaged persistence. Air traffic values are based on Keflavík airport 2011 facts and figures (Isavia, 2012).

Eruptive scenario	Mean persistence all FLs (h)	Movements disrupted (*n*)	Passengers stranded (*n*)	Freight stranded (t)
Hekla-2000 ERS	~ 5	~ 20	~ 950	~ 20
Hekla-1947 ERS	~ 8	~ 30	~ 1500	~ 40
Katla LLERS	~ 21	~ 90	~ 4300	~ 110
Askja OES	~ 18	~ 70	~ 3600	~ 90

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Table 8. Availability, sources and type of data used for the vulnerability assessment to tephra fallout at national scale.

Data	Available	Source	Coverage	Type
Population	Yes	Statice	Municipalities	Number
Population trends	Yes	Byggðastofnun	Municipalities	Percentage
Population age	Yes	Statice	Municipalities	Number
Power plants	Yes	Landmælingar Islands http://www.or.is/en/about	Disaggregated	Location
Aluminum smelters	Yes	Landmælingar Islands	Disaggregated	Location
Hospitals	Yes	Landmælingar Islands	Disaggregated	Location
Shelters	Yes	Landmælingar Islands	Disaggregated	Location
Police stations	Yes	Landmælingar Islands	Disaggregated	Location
Fire stations	Yes	Landmælingar Islands-	Disaggregated	Location
Road Network	Yes	Landmælingar Islands	Disaggregated	Digital map
Electricity network	Yes	Landmælingar Islands	Disaggregated	Digital map
Ports (import-export)	Yes	Statice	Disaggregated	Import/export values
Airports (air traffic)	Yes	Isavia	Disaggregated	Passengers/freight values
Land use	Yes	Corine Land Cover	Homogeneous areas	Corine classification
Milk production	Yes	Byggðastofnun	Municipalities	Liters/support entitlements
Wool production	Yes	Byggðastofnun	Municipalities	Support entitlements
Civil protection units	No	–	–	–
Productive activities	No	–	–	–
Employees for productive activities/sectors				
Average income	No	–	–	–
Water supply	No	–	–	–

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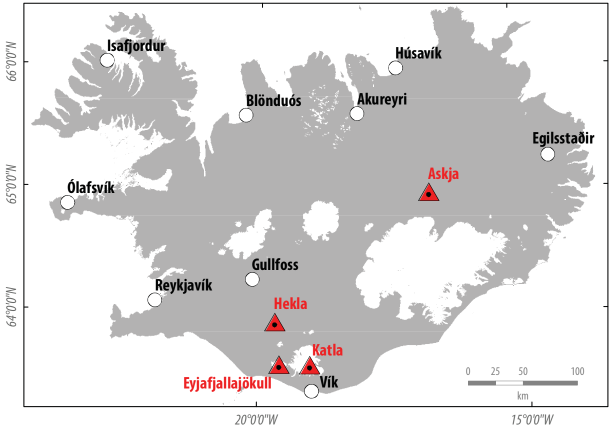

Fig. 1. Map of Iceland showing the location of the 4 volcanoes considered in the hazard assessment and the main towns. The administrative units (municipalities) used for the national vulnerability analysis are given in the Supplement.

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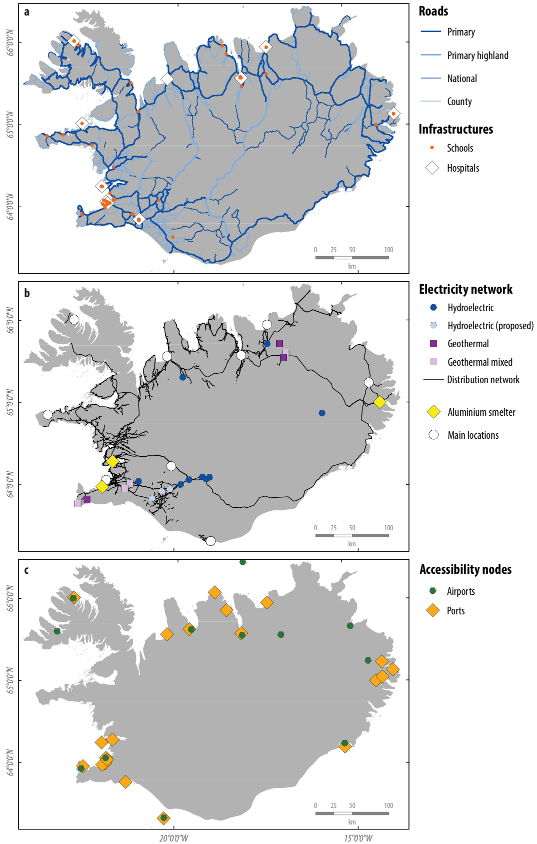

Fig. 2. Exposure maps for: **(a)** the road network and critical infrastructures (hospitals, local health care centers and schools, that can be used as ash shelters), **(b)** electricity distribution network, hydroelectric and geothermal power plants, production sites and main locations (urban areas), **(c)** main transport nodes: ports and airports.

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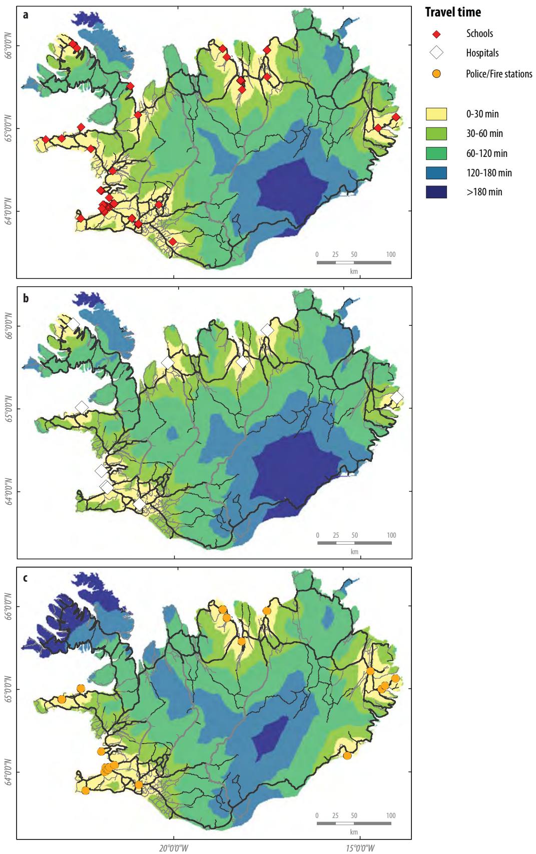

Fig. 3. Accessibility to critical facilities including, from top to bottom, hospitals, schools and fire stations. All maps display the time in minutes required to reach a given facility by road.

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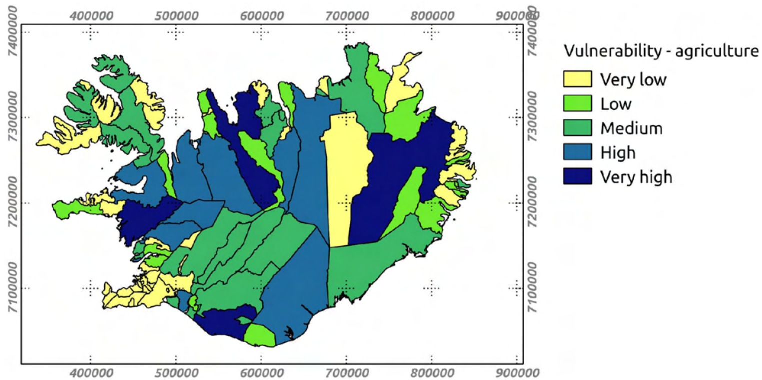

Fig. 4. Thematic vulnerability map for agriculture. The 5-class qualitative ranking is based on a combination of three indicators: production of milk, production of wool and percentage of agricultural area, all available at a municipality level. Maps for each indicator are given in the Supplement.

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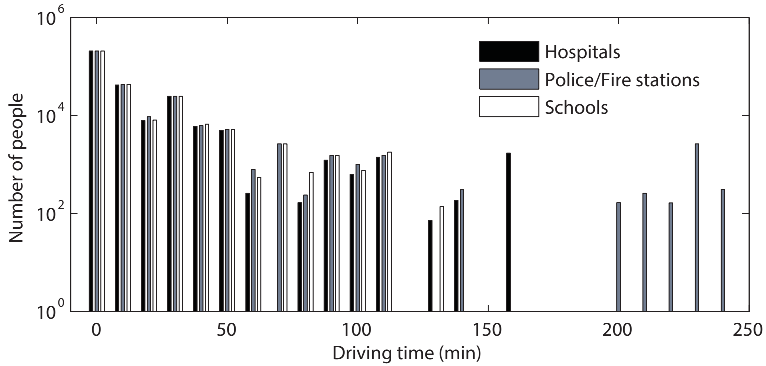

Fig. 5. Number of people as a function of driving time to reach the closest critical infrastructures (i.e. hospital, police/fire station and schools).

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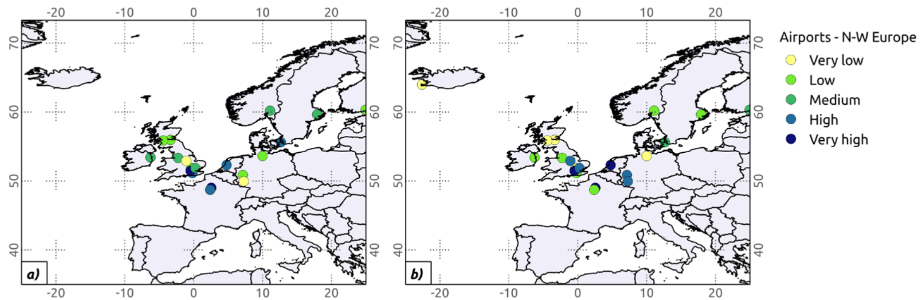

Fig. 6. Main airport hubs in central and northwestern Europe depending on the traffic of passengers **(a)** and goods **(b)** during 2010 (Eurostat, 2012). The values represent the relevance of these airports for passengers and freight air traffic. The most relevant airports are London Heathrow, Paris Charles de Gaulle, Frankfurt, Amsterdam, and Munich.

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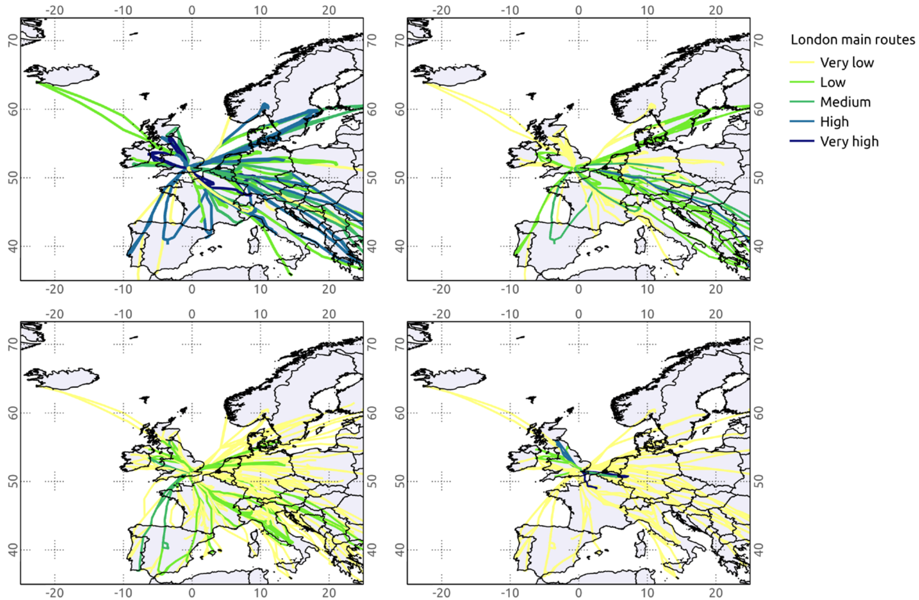

Fig. 7. Main European routes from/to London Heathrow (top) and the rest of the airports in Greater London (Gatwick, Luton and Stansted, displayed together, bottom). Routes are ranked according to their importance in terms of passengers (left) and freight (right) traffic. The vulnerability classification is based on the whole range of air traffic data between main London airports and the considered European airports in 2010 (Eurostat, 2012). The same classification criterion is used for all figures and the comparison underlines that Heathrow airport handles the most strategic routes (corresponding to more than 1.2 million passengers per year).

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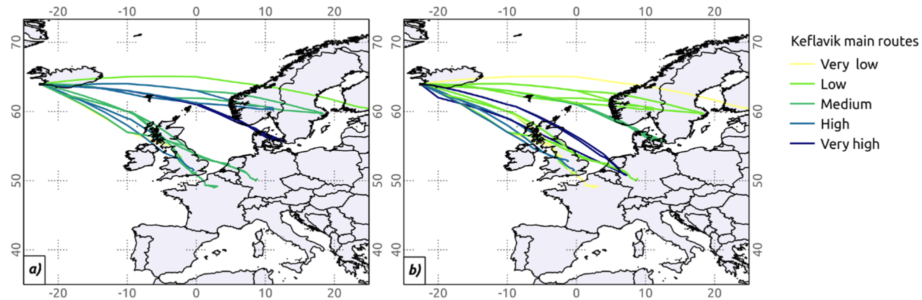

Fig. 8. Main European routes of passengers **(a)** and freights **(b)** from/to Keflavík airport. Analysis is performed for the routes connecting the main airports shown in Fig. 6. The vulnerability classification is based on 2010 data (Eurostat, 2012).

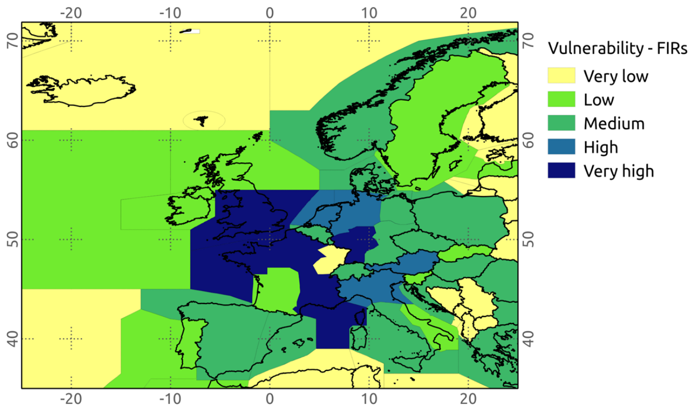

Fig. 9. Vulnerability classification of the European airspace sectors, based on the air traffic rate in the sector during a peak day of 2012 (source: EUROCONTROL). FIRs with very high vulnerability values (blue) are London, Paris and Munich.

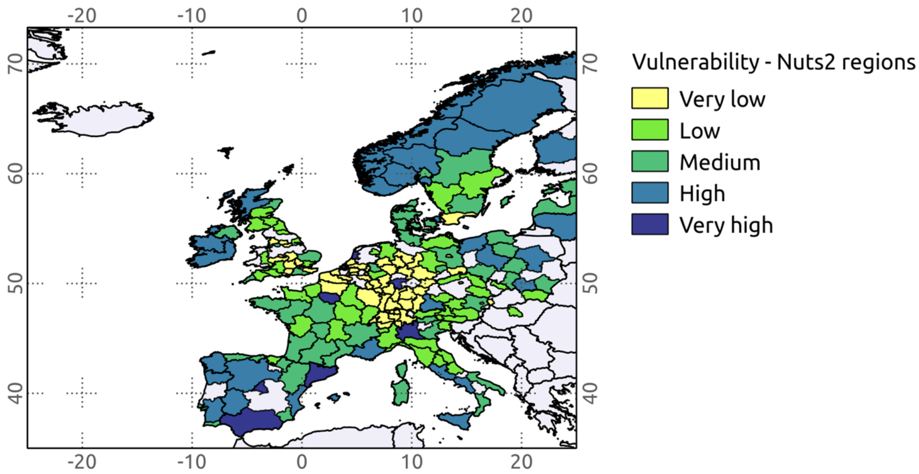

Fig. 10. Vulnerability of the NUTS-2 regions, calculated as a combination of population, air traffic values and multi-modal accessibility value (see the Supplement Fig. S2 for individual maps). High vulnerability areas are those having high population and low accessibility rates, for example Ireland and Norway.

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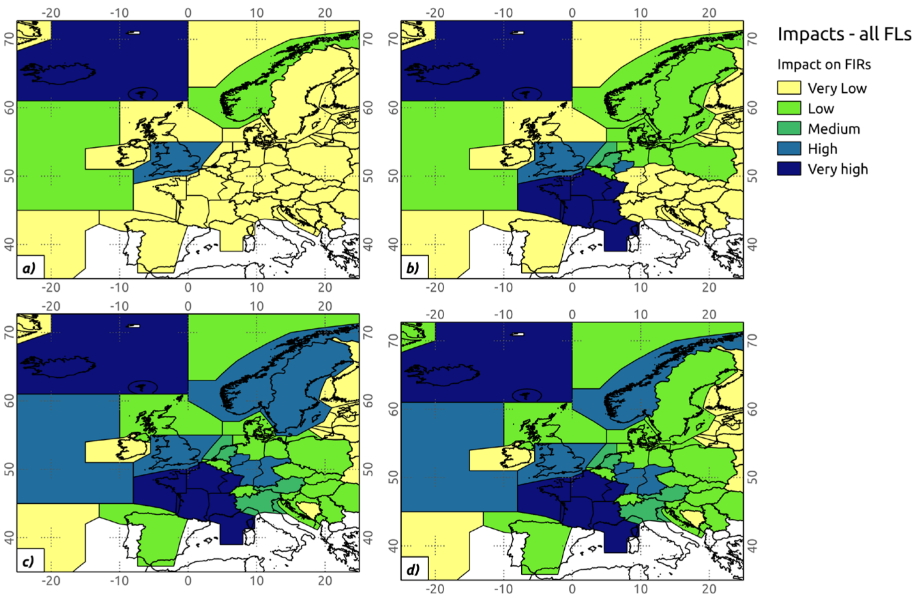

Fig. 11. Expected impacts of tephra dispersal on European airspace sectors (FIRs) for different scenarios: **(a)** Hekla 2000-type, **(b)** Hekla 1947-type, **(c)** Askja 1875-type and **(d)** Katla scenarios.

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