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Medication use in populations exposed to the 2010 Eyjafjallajökull eruption: an interrupted time series analysis

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ABSTRACT

Objectives To assess the trends in medication use indicative of physical and psychological morbidity following the 2010 volcanic eruption in Eyjafjallajökull immediately after and during a 3-year period following the eruption.

Design Population-based register study.

Setting Eyjafjallajökull eruption in Iceland, 2007–2013.

Participants All residents in Iceland who received at least one medication dispensing were identified. Residents of exposed areas were classified into exposure groups (individual-level data) and residents in other parts of Iceland were included as a non-exposed group (aggregated data).

Intervention/exposure Eyjafjallajökull erupted on 14 April 2010 and continued for 39 days, producing heavy ash fall in South Iceland.

Main outcome measures Using interrupted time series analysis, we examined annual and quarterly changes in medicine use, measured as number of dispensed defined daily dose (DDD) per 1000 individuals. We calculated the level shift (immediate change) and change in slope from pre-eruption to post-eruption (long-term change) in medication dispensing.

Results Among exposed residents, there was a 6% decrease (95% CI -7% to -4%) in the annual number of dispensed DDDs 1-year post-eruption in the overall medication class, including analgesics (–5%, 95% CI -6% to -3%), hypnotics and sedatives (–9%, 95% CI -11% to -7%) and respiratory medications (–7%, 95% CI -9% to -5%; –8%, 95% CI -11% to -4%). Simultaneously, there was a 9% decrease (95% CI -14% to -4%) in the overall medication class among non-exposed residents. Moreover, among exposed residents, we observed change in slope of –4% (95% CI -7% to -1%) in the overall medication class, including for analgesics (–6%, 95% CI -8% to -3%) and other respiratory drugs (–10%, 95% CI -16% to -4%).

Conclusion Our findings indicate that the eruption did not lead to increases in medication dispensing among residents of exposed areas, rather decreases for some medicine classes. The results should be interpreted with caution since the content of each eruption differs.

Strengths and limitations of this study

⇒ This study defined an exposed population-based cohort using register data for an exact time-period of interest (before and after exposure to a volcanic eruption).
⇒ The outcome of interest (dispensing of respiratory, pain, anxiety, depressive or sleep medications) was based on data from the Prescription Medicines Register which contains data on all prescriptions filled in outpatient care in Iceland.
⇒ Interrupted time series (ITS) approach was used and is considered among the strongest quasi-experimental designs for estimating longitudinal impact following an intervention.
⇒ Generalisability to other volcanic eruptions might be limited, since each volcanic eruption differs in size, content and particle size of the ash.
⇒ The ITS approach cannot separate the effects of concurrent events.

BACKGROUND

Volcanic eruptions are life-threatening natural disasters[1] that occur approximately 50 times every year worldwide.[2] Due to Iceland's geological position on the mid-Atlantic ridge, the country has frequent volcanic activity,[3] with four volcanic eruptions during the past 20 years. The most recent began in March 2021 in the Southwest peninsula in Iceland, although relatively small and non-threatening to residential areas. Volcanic eruptions can cause disruption, severe damage and fatalities in exposed communities.[3] In addition, fallout of different airborne pollutants during eruptions can expose large inhabited areas to harmful particles.[2 4] Although most eruptions only last for weeks or months, the ash can remain in the local environment for years to decades later, which can adversely affect people's health, in particular respiratory health.[2 4–7] The degree to which volcanic

ash negatively impacts health depends on various factors, including the content and particle size of the ash, as well as the extent of exposure.[8 9]

Previous research suggests that the prevalence of both respiratory and psychiatric conditions is higher among residents of areas highly exposed to fallout from volcanic eruptions than those of low exposed areas.[7 10] Hospital admissions and emergency room visits for respiratory conditions have been more common in areas with high levels of air pollutants from volcanic eruptions.[5 10] Likewise, proximity to disaster has been found to affect individuals' psychological response, including prescription rates of medication for psychiatric conditions.[11 12] Long-term research also indicates that physical[1 13] and psychiatric[14 15] conditions may persist for years following disasters.

An important source of knowledge on health effects following disasters are pharmacoepidemiological studies on prescription rates, as these outcomes may develop slowly after a disaster. Therefore, observing changes in medication utilisation trends following natural disasters can provide an important evaluation of disaster impact on population health. Although pharmacoepidemiological research on exposure to volcanic eruptions is scarce, the evidence points towards an increased consumption of respiratory medication following other types of natural disasters such as wildfires.[10 16–19] In addition, increased prescription rates of psychotropic medications have been reported following natural disasters such as cyclone,[20] earthquake[17 21 22] and even industrial disasters including fires.[23] However, some studies have not found any changes in prescriptions rates following disasters, possibly because the impact on populations varies between studies, for example, individuals that have been affected to a greater degree would perhaps show more changes in the utilisation of health services.[22 24] Further studies on medication prescription rates following disasters would be helpful in this context.

The volcano in Eyjafjallajökull, situated in South Iceland, erupted on 14 April 2010. Even though the eruption did not cause direct fatalities, it resulted severe disruption in everyday life among residents of the exposed areas, as the civil protection evacuated some areas due to flood risks[25 26] and the close proximity of the volcano to communities and heavy ashfall[25 26] with potentially damaging effects on residents health[4 6] lead to concerns about negative health effects. Many residents were provided with psychosocial support because of the loud explosions from the eruption.[27] Our previous questionnaire studies on the health effects of the Eyjafjallajökull eruption found that individuals exposed to the eruption had increased risk of self-reported physical and psychological symptoms for up to 4 years following the eruption.[13] However, response rates in questionnaire studies may be biased by exposure status, perceived symptoms and decreasing follow-up rates with time. Therefore, a study of register data with full population coverage, pre-disaster and post-disaster may provide a more valid estimate of the health consequences among exposed populations.

The current study used high-quality population-based register data pre-eruption and post-eruption, to investigate whether exposure to the Eyjafjallajökull eruption resulted in change in medication use indicative of physical and psychological morbidity (analgesics, antidepressants, anxiolytics, hypnotics and sedatives and respiratory medication) during a 3-year period following the eruption, as compared with the 3 years prior. We hypothesised that medication dispensing would increase immediately following the eruption among the exposed groups (high, medium and low exposed) and decrease gradually over the 3-year period following the eruption as compared with the 3 years prior the eruption and compared with non-exposed.

METHODS AND DATA

Study setting and data source

The volcanic eruption in Eyjafjallajökull began on 14 April 2010, which is defined as a starting point of exposure in this study. The eruption continued for about 6 weeks and produced heavy ash fall in a populated area.[25 26] During the eruption, an estimated about 8 teragrams (Tg) of fine ash were emitted, with the most severe effects in the regions of South and Southeast Iceland.[6 7 25 28] During the first few days, the eruption plume was very active with explosions and frequent lightnings. The explosive activity in the eruption tended to fluctuate unlike explosive eruptions that peak during the first few days.[26] For months following the eruption ash was resuspended by wind and human activity, a phenomenon that was reported from most parts of Iceland.[29] However, due to wind conditions and proximity to the eruption site, the rural communities south of the volcano experienced the most severe ash fall, where airborne particles in the townships of Vík í Mýrdal and in Hvolsvöllur were measured far above health limits for air quality in Iceland in early May 2010.[25 26]

Study population and exposure groups

The cohort included all residents in South Iceland with legal residence in the exposed communities (see figure 1) during the study period, 1 January 2007 to 2013 (3 December 2013 for annual analysis and 25 July 2013 for quarterly analysis). We divided the study area into exposure groups based on data on ash emission rate from satellite images of the eruption plume[28] (figure 1 and online supplemental figure S1). Similar distribution for the ash deposits have been found with measurements on the ground[29] and modelling as described in detail in Thorsteinsson *et al*.[25] Residents of Kirkjubæjarklaustur and Öræfi (population 534 in 2010) were included in the low exposed group, the medium exposure group included residents of Hvolsvöllur and Hella (population 3478 in 2010), and the high exposure group included residents of Vík í Mýrdal (population 510 in 2010). In 2010, most residents of the exposed areas lived in small municipalities (<200) (N=2527) or farmlands (N=1995).[30] Moreover, we obtained aggregated annual dispensing data for

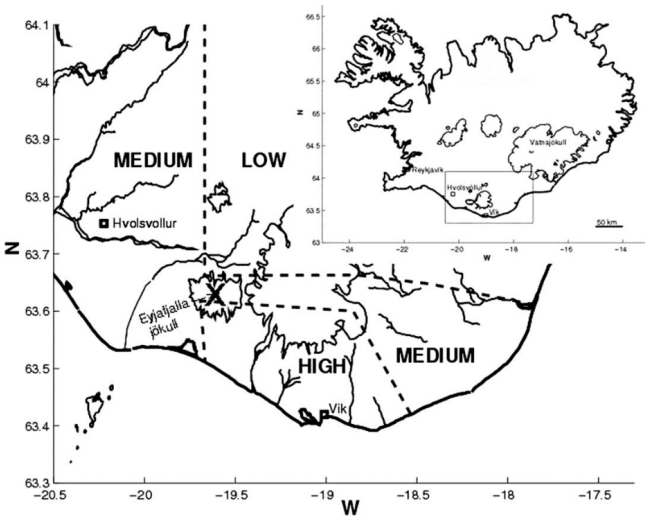

Figure 1 Map of Iceland and the study areas (defined in Carlsen *et al*.[7]). Inserted map of Iceland shows the location of the exposed area in South Iceland. The larger map of the exposed area shows Eyjafjallajökull (marked with X). Communities not labelled on the figure are Öræfi, Kirkjubæjarklaustur and Hella (figure taken from Carlsen *et al*[7] with permission).

all individuals with legal residence in non-exposed areas of Iceland who were less affected by the eruption (population size in non-exposed areas in 2010 was 308 973).

Medication of interest

To evaluate dispensed medication, we used the Prescription Medicines Register, which is maintained by the directorate of health and contains data on all prescriptions filled in outpatient care in Iceland from 2003 and onwards. The register includes detailed information on dispensed medications, including date, formulation and defined daily dose (DDD) dispensed,[31] as well as demographic information on the patient. The register does not capture over-the-counter medications nor indications for medication use. For the predefined exposure groups (low, medium, high), we obtained anonymised individual-level data on medication dispensing, but aggregate-level data on the medication dispensing among the non-exposed group. Additionally, we obtained population data from Statistics Iceland to calculate medication dispensation denominators.[30]

We categorised the medications of interest according to the WHO Anatomic Therapeutic Chemical (ATC) classification system.[30] The obtained data included information on dispensed medications from the following classes; analgesics (ATC N02A-N02C), antidepressants (ATC N06A), anxiolytics (ATC N05B), hypnotics and sedatives (ATC N05C), respiratory drugs for obstructive airway diseases (ATC R3), other respiratory drugs (ATC R01-R02, R05-R06) and overall medications (including all medication classes mentioned above). We measured medication use, as the number of medication dispensings and number of DDD per 1000 individuals. DDD is the assumed average daily maintenance dosage for a medication used for its primary indication in adults.[30]

Patient and public involvement

Our study's design, conduct, reporting and distribution plans were not influenced by patients or the general public.

Statistical analysis

First, we conducted a descriptive analysis of the data on the six medication classes (defined above). We calculated the annual and quarterly number of DDD dispensed per 1000 individuals, calculated per exposed (low, medium and high combined) and non-exposed groups in the annual analysis, and per exposure group (low, medium and high) in the quarterly analysis. For the non-exposed group, we received annual data and therefore could not assess quarterly dispensing for this group. Thus, the quarterly analysis is only assessed for the low, medium and high exposure groups to gain a better understanding of the change in time. We used an interrupted time series (ITS)[32] analysis to understand the change in trend in medication utilisation pre-eruption and post-eruption in 2010. Using quasi-Poisson regression models to calculate the coefficient estimates of the pre-eruption slope, the level shift at the time of the eruption and the change in slope from pre-eruption to post-eruption. The level shift represents the immediate level change following the eruption, calculated by the difference between observed and predicted values for the first data point following the eruption, and the change in slope represents the long-term impact of the eruption, calculated as the change in slope from pre-eruption to post-eruption.[33]

As a primary analysis, we investigated annual time series of the number of dispensed DDD per 1000 individuals among exposed and non-exposed group, using the year of the eruption as the intervention point. As a secondary analysis we further investigated this trend using quarterly time-series in each exposure group (low, medium, high), pre-eruption and post-eruption, using the 3 months following the eruption as an intervention point. To reduce the impact of underlying time trends and other concurrent factors, these analyses included data from 1 January 2007 to 25 July 2013 (quarter analysis) or 31 December 2013 (annual analysis). Primary and secondary analyses included the effects of independent variables for exposure groups, time (every year/quarter from 2007 to 2014), period (pre-eruption vs post-eruption), and the interaction term on time and period were calculated. We fitted the data for both models to three separate generalised linear models, assuming a quasi-Poisson distribution for the outcome variable. The models were used to calculate the coefficient estimates of the pre-eruption slope, the change in level at the time of the eruption and the change in slope from pre-eruption to post-eruption (see online supplemental table S1) for specific time periods used to calculate each coefficient estimate.

Table 1 Number of medication dispensings from 1 January 2007 to 25 July 2013, before and after the start of the Eyjafjallajökull eruption (14 April 2010)

	Pre-eruption			Post-eruption		
Medication class	Low (%)	Medium (%)	High (%)	Low (%)	Medium (%)	High (%)
Overall*	3065 (100)	33 448 (100)	3386 (100)	4776 (100)	31 864 (100)	5392 (100)
Analgesics	850 (27.7)	8072 (24.1)	861 (25.4)	1387 (29)	7574 (23.8)	1673 (31)
Antidepressants	470 (15.3)	5600 (16.7)	673 (19.9)	1008 (21.1)	4772 (15)	902 (16.7)
Anxiolytics	250 (8.2)	5046 (15.1)	291 (8.6)	435 (9.1)	4605 (14.5)	596 (11.1)
Hypnotics and sedatives	760 (24.8)	7833 (23.4)	961 (28.4)	969 (20.3)	8430 (26.5)	1426 (26.4)
Respiratory drugs for obstructive airway diseases	417 (13.6)	3182 (9.5)	290 (8.6)	476 (10)	2812 (8.8)	343 (6.4)
Other respiratory drugs	318 (10.4)	3715 (11.1)	310 (9.2)	501 (10.5)	3671 (11.5)	452 (8.4)

*Includes analgesics, antidepressants, anxiolytics, hypnotics and sedatives, respiratory drugs for obstructive airway diseases and other respiratory drugs.

All statistical analyses were performed using RStudio V.1.3.1093 running R V.4.0.2. Statistical tests were considered statistically significant at $p<0.05$.

Supplemental analysis

We carried out supplemental analyses to assess the robustness of our main findings with different analytical assumptions. These included additional IST models accounting for (1) the 2008–2009 global financial crisis by including a dummy variable for the year 2008 into the model and (2) regional differences in age and sex distributions by including sex and age as covariates into the model. Further, to make full use of the available data, we extended the study time period to include January 2005 until December 2019 for the annual and quarterly analyses of number dispensed DDD per 1000 individuals.

RESULTS

Over the study period, a total of 81 931 medications were dispensed among the exposed groups; 39 899 for the 3-year period prior to the eruption and 42 032 dispensed medications in total for the 3-year period following the eruption (table 1). Prior to the eruption, a total 15 645 individuals dispensed at least one medication of interest every quarter in the exposed groups (high, medium and low), compared with 16 435 individuals post-eruption. Throughout the study period, medication dispensing was higher among females than males, both pre-eruption (62.7% women) and post-eruption (62.3% women).

Pre-eruption slope

The annual number of dispensed DDD per 1000 individuals during a 3-year period prior the eruption, is presented in table 2 and figure 2. Prior to the eruption, there was an annual 5% increase (95% CI 4% to 6%) in number of dispensed DDD per 1000 in the overall medication class among the exposed group, with increases across all six medication classes. Similarly, we observed an annual 11% increase (95% CI 8% to 15%) in the overall medication class among residents of non-exposed areas during the 3-year period prior to the eruption.

The quarterly number of dispensed DDD per 1000 during a 3-year period prior the eruption is presented in table 3 and figure 3, showing increases especially among the high and low exposure groups.

Level shift following the eruption

The level shift for the annual number of dispensed DDD per 1000 individuals is presented in table 2 and figure 2. Among exposed residents at 1-year post-eruption, there was a 6% decrease (95% CI -7% to -4%) in number of dispensed DDD per 1000 in the overall medication class, including decreases among analgesics (–5%, 95% CI -6% to -3%), hypnotics and sedatives (–9%, 95% CI -11% to -7%), respiratory drugs for obstructive airway diseases (–7%, 95% CI -9% to -5%) and other respiratory drugs (–8%, 95% CI -11% to -4%). Decreases were pronounced among the high exposed group, with an 32% decrease (95% CI -42% to -21%) in the overall medication class, driven by analgesics (–42%, 95% CI -51% to -32%), antidepressants (–26%, 95% CI -36% to -15%), anxiolytics (–57%, 95% CI -64% to 48%), hypnotics and sedatives (–32%, 95% CI -38% to -25%) and other respiratory drugs (–39%, 95% CI -50% to -26%).

Among residents of non-exposed areas, we observed an 9% decrease (95% CI -14% to -4%) in dispensed number of DDD per 1000 in the overall medication class, 1 year following the eruption, with most pronounced decreases in hypnotics and sedatives (-17%, 95% CI -23% to -11%) (table 2 and figure 2).

The level shift for the quarterly number of dispensed DDD per 1000 individuals varied somewhat between high, medium and low exposure groups (table 3 and figure 3). Among the high exposed group at 3 months post-eruption, we observed a 42% decrease (95% CI -62% to -11%) among the class of respiratory drugs for obstructive airway diseases. Similarly, among the low exposed group at the first quarter post-eruption, a 29% decrease

Table 2 Quasi-Poisson regression models for annual number of dispensed DDD per 1000 individuals by medication class and level of exposure from 1 January 2007 to 31 December 2013

Medication class	Level of exposure	Pre-eruption slope (95% CI)	Level shift (95% CI)	Change in slope (95% CI)
Overall*	Exposed combined	1.05 (1.04 to 1.06)	0.94 (0.93 to 0.96)	0.96 (0.93 to 0.99)
	Low	1.50 (1.25 to 1.81)	0.68 (0.51 to 0.91)	0.60 (0.36 to 1.02)
	Medium	1.01 (1.00 to 1.03)	0.97 (0.94 to 1.00)	1.05 (1.00 to 1.12)
	High	1.46 (1.32 to 1.61)	0.68 (0.58 to 0.79)	0.62 (0.47 to 0.82)
	Non-exposed	1.11 (1.08 to 1.15)	0.91 (0.86 to 0.96)	1.01 (0.91 to 1.12)
Analgesics	Exposed combined	1.08 (1.07 to 1.08)	0.95 (0.94 to 0.97)	0.94 (0.92 to 0.97)
	Low	1.54 (1.22 to 1.96)	0.68 (0.47 to 0.97)	0.64 (0.34 to 1.24)
	Medium	1.00 (0.99 to 1.01)	1.07 (1.05 to 1.09)	0.99 (0.96 to 1.03)
	High	1.61 (1.44 to 1.79)	0.58 (0.49 to 0.68)	0.64 (0.48 to 0.85)
	Non-exposed	1.07 (1.04 to 1.10)	0.97 (0.92 to 1.02)	0.98 (0.90 to 1.08)
Antidepressants	Exposed combined	1.03 (1.01 to 1.06)	0.98 (0.94 to 1.03)	0.98 (0.90 to 1.06)
	Low	1.40 (1.23 to 1.60)	0.88 (0.72 to 1.07)	0.68 (0.47 to 1.00)
	Medium	1.02 (0.99 to 1.05)	0.98 (0.94 to 1.03)	1.09 (1.00 to 1.19)
	High	1.36 (1.24 to 1.48)	0.74 (0.64 to 0.85)	0.71 (0.56 to 0.92)
	Non-exposed	1.09 (1.05 to 1.13)	0.96 (0.90 to 1.02)	1.05 (0.94 to 1.19)
Anxiolytics	Exposed combined	1.05 (0.99 to 1.11)	0.95 (0.86 to 1.05)	0.89 (0.75 to 1.07)
	Low	1.42 (1.22 to 1.65)	0.76 (0.61 to 0.96)	0.74 (0.48 to 1.13)
	Medium	1.00 (0.93 to 1.08)	0.98 (0.85 to 1.13)	0.89 (0.70 to 1.15)
	High	1.90 (1.68 to 2.14)	0.43 (0.36 to 0.52)	0.40 (0.30 to 0.54)
	Non-exposed	1.00 (0.96 to 1.04)	0.99 (0.92 to 1.06)	1.05 (0.92 to 1.21)
Hypnotics and sedatives	Exposed combined	1.06 (1.04 to 1.07)	0.91 (0.89 to 0.93)	1.00 (0.96 to 1.05)
	Low	1.49 (1.25 to 1.76)	0.57 (0.43 to 0.76)	0.60 (0.37 to 0.97)
	Medium	1.05 (1.01 to 1.10)	0.90 (0.84 to 0.97)	1.14 (0.99 to 1.30)
	High	1.40 (1.32 to 1.48)	0.68 (0.62 to 0.75)	0.66 (0.56 to 0.78)
	Non-exposed	1.19 (1.14 to 1.24)	0.83 (0.77 to 0.89)	0.96 (0.84 to 1.09)
Respiratory drugs for obstructive airway diseases	Exposed combined	1.04 (1.03 to 1.05)	0.93 (0.91 to 0.95)	0.96 (0.92 to 1.00)
	Low	1.56 (1.16 to 2.11)	0.58 (0.36 to 0.96)	0.51 (0.22 to 1.19)
	Medium	0.99 (0.97 to 1.00)	0.96 (0.93 to 0.99)	1.06 (1.00 to 1.13)
	High	1.46 (1.06 to 2.01)	0.74 (0.43 to 1.28)	0.50 (0.20 to 1.28)
	Non-exposed	1.04 (1.01 to 1.06)	0.97 (0.92 to 1.02)	1.00 (0.92 to 1.10)
Other respiratory drugs	Exposed combined	1.08 (1.06 to 1.10)	0.92 (0.89 to 0.96)	0.90 (0.84 to 0.96)
	Low	1.62 (1.29 to 2.03)	0.58 (0.41 to 0.83)	0.56 (0.31 to 1.03)
	Medium	1.02 (0.98 to 1.06)	0.97 (0.90 to 1.04)	1.02 (0.89 to 1.17)
	High	1.61 (1.42 to 1.83)	0.61 (0.50 to 0.74)	0.56 (0.40 to 0.78)
	Non-exposed	1.05 (1.03 to 1.07)	0.98 (0.94 to 1.01)	1.02 (0.96 to 1.09)

*Includes analgesics, antidepressants, anxiolytics, hypnotics and sedatives, respiratory drugs for obstructive airway diseases and other respiratory drugs.
DDD, defined daily dose.

was observed for antidepressants (95% CI -47% to -4%) and 20% increase (95% CI 9% to 31%) in the medium exposure group in the dispensing of hypnotics and sedatives. No other significant changes were found in the quarterly number of dispensed DDD per 1000 during the first quarter following the start of the eruption.

Change in slope

The change in slope for the annual number of dispensed DDD per 1000 individuals in the exposed and non-exposed groups are presented in table 2 and figure 2. Among the exposed group we observed a change in slope of –4% (95% CI -7% to -1%) in the slope post-eruption for the overall medication class, including analgesics

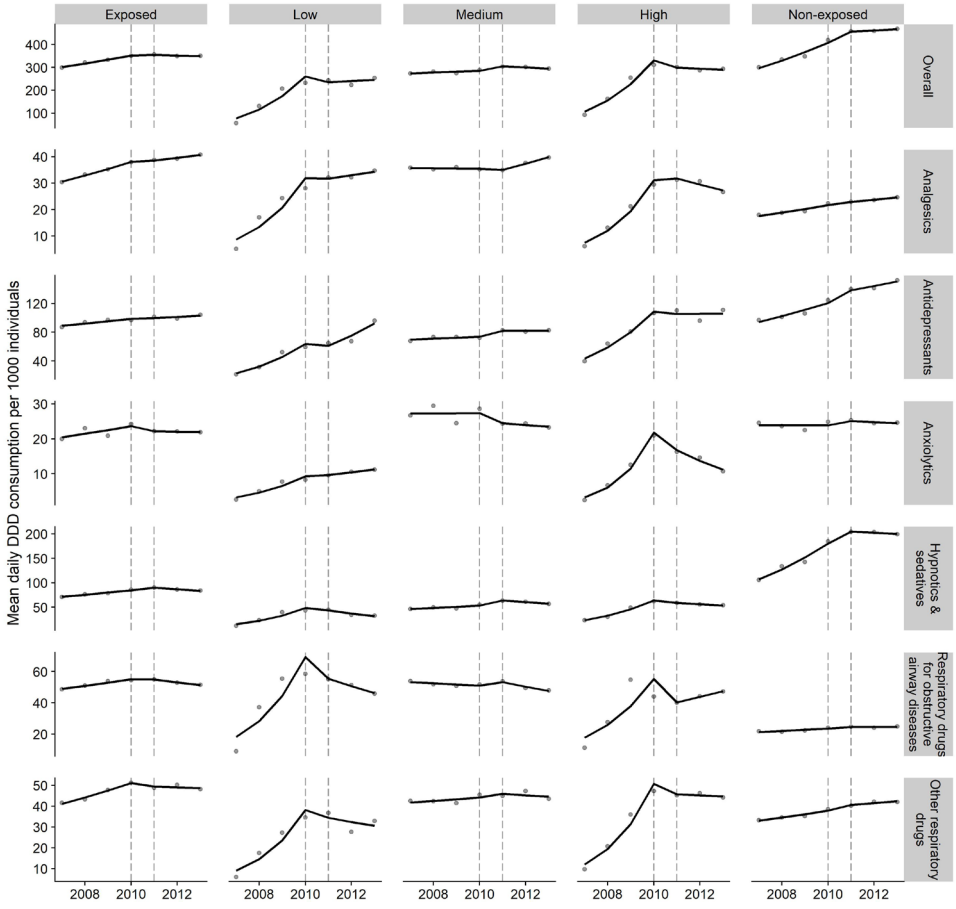

Figure 2 Annual average daily dispensed number of DDD per 1000 individuals by medication classes and level of exposure from 1 January 2007 to 31 December 2013. Observed data and fitted ITS predictions. Dashed lines represent the time between the start of the eruption and the first datapoint after.
DDD, defined daily dose; ITS, interrupted time series.

(−6%, 95% CI -8% to -3%) and other respiratory drugs (−10%, 95% CI -16% to -4%). While the change in slope for the overall medication class was minimal for the medium exposure group (5%, 95% CI 0% to 12%), it was −38% (95% CI -53% to -18%) among the high exposure group and varied by medication class. We did not observe any substantial change in slope among residents of non-exposed areas.

In the quarterly analyses (table 3 and figure 3), we observed a change in slope of −11% for the overall medication class every quarter during the 3-year period post-eruption among the high (95% CI -14% to -9%) and low (95% CI -15% to -8%) exposure groups, including decreases for all medication classes. No change in slope was observed for the medium exposure group.

Supplemental results

Additional analysis accounting for the (1) global financial crises, (2) age and sex, and (3) using data from January 2005 until December 2019 revealed little additional information (online supplemental tables S2–S6 and figures S2–S5).

DISCUSSION

The results of this population-based register study on the long-term health effects following the 2010 eruption in Eyjafjallajökull indicate an immediate decrease in dispensing of the overall medication class, analgesics, hypnotics and sedatives, respiratory drugs for obstructive airway diseases and other respiratory drugs for the exposed group. We also observed a change in slope for dispensing of the overall medication class, analgesics and other respiratory drugs. Among the non-exposed group, an immediate decrease in the overall medication class and hypnotics and sedatives was also observed. Our findings indicate that the 2010 volcanic eruption did not lead to increases in medication dispensing among people living in exposed areas, rather decreases for some medicine classes.

A strength of this study is the ability to define an exposed population-based cohort using register data for an exact time period of interest. The ITS approach is considered among the strongest quasi-experimental designs for estimating the longitudinal impact following an intervention such as exposure to volcanic eruption.[33 34] However, ITS analysis cannot separate the effects of concurrent events, though we conducted an analysis accounting for the

Table 3 Quasi-Poisson regression models for the quarterly number of dispensed DDD per 1000 individuals by medication class and level of exposure from 1 January 2007 to 25 July 2013

Medication class	Level of exposure	Pre-eruption slope (95% CI)	Level shift (95% CI)	Change in slope (95% CI)
Overall*	Low	1.14 (1.10 to 1.17)	0.75 (0.56 to 1.00)	0.89 (0.85 to 0.92)
	Medium	1.00 (1.00 to 1.01)	1.05 (0.99 to 1.11)	1.00 (0.99 to 1.00)
	High	1.12 (1.09 to 1.14)	0.89 (0.73 to 1.08)	0.89 (0.86 to 0.91)
Analgesics	Low	1.15 (1.11 to 1.20)	0.74 (0.53 to 1.04)	0.89 (0.84 to 0.93)
	Medium	1.00 (0.99 to 1.01)	0.93 (0.85 to 1.01)	1.01 (1.00 to 1.02)
	High	1.15 (1.12 to 1.19)	0.94 (0.73 to 1.21)	0.86 (0.83 to 0.89)
Antidepressants	Low	1.11 (1.07 to 1.15)	0.71 (0.53 to 0.96)	0.94 (0.91 to 0.98)
	Medium	1.01 (1.00 to 1.01)	1.03 (0.94 to 1.13)	1.00 (0.99 to 1.01)
	High	1.08 (1.06 to 1.11)	1.02 (0.80 to 1.29)	0.92 (0.89 to 0.95)
Anxiolytics	Low	1.12 (1.08 to 1.16)	0.78 (0.56 to 1.09)	0.92 (0.88 to 0.96)
	Medium	1.00 (0.99 to 1.01)	1.01 (0.87 to 1.17)	0.99 (0.97 to 1.01)
	High	1.19 (1.14 to 1.25)	1.11 (0.80 to 1.56)	0.78 (0.74 to 0.82)
Hypnotics and sedatives	Low	1.13 (1.09 to 1.16)	0.87 (0.66 to 1.16)	0.86 (0.82 to 0.90)
	Medium	1.01 (1.00 to 1.02)	1.20 (1.09 to 1.31)	0.99 (0.98 to 1.00)
	High	1.10 (1.07 to 1.14)	0.90 (0.68 to 1.17)	0.90 (0.86 to 0.93)
Respiratory drugs for obstructive airway diseases	Low	1.16 (1.10 to 1.22)	0.69 (0.44 to 1.06)	0.85 (0.80 to 0.91)
	Medium	1.00 (0.98 to 1.01)	1.03 (0.86 to 1.23)	0.99 (0.97 to 1.01)
	High	1.14 (1.09 to 1.20)	0.58 (0.38 to 0.89)	0.88 (0.83 to 0.94)
Other respiratory drugs	Low	1.16 (1.09 to 1.23)	0.86 (0.51 to 1.43)	0.85 (0.79 to 0.92)
	Medium	1.00 (0.99 to 1.02)	1.05 (0.90 to 1.24)	0.99 (0.97 to 1.01)
	High	1.14 (1.11 to 1.18)	0.90 (0.69 to 1.18)	0.87 (0.83 to 0.90)

*Includes analgesics, antidepressants, anxiolytics, hypnotics and sedatives, respiratory drugs for obstructive airway diseases and other respiratory drugs.
DDD, defined daily dose.

global financial crisis in 2008 that showed little difference to the main analysis (online supplemental figures S2,S3 and tables S2,S3). Other limitations that should be considered when interpreting the results include for example, that the data did not include over-the-counter medication dispensing. In addition, some individuals may have dispensed medications in other places than in their registered legal residence, meaning that individuals could have been staying elsewhere and therefore they may not have been as impacted by the eruption as expected based on their defined exposure status. Therefore, the data may not reflect a complete picture of the medication utilisation among residents. Also, despite this being a population-based study, the low and high exposure groups were relatively small (total population in 2010 was 510 in the high exposed group and 534 in the low exposure group) which might have limited the statistical power of our analyses, however, we addressed this by combining the three exposure groups. The small sizes in the high and low exposure groups could also explain the different trends among the high, medium and low exposure groups seen in online supplemental figures 2,3,S2–S6.

Long-term health studies on volcanic eruptions and health effects are important, as associated diseases may not become evident until several years after the exposure.[4] Our findings that the eruption did not lead to any increases in medication dispensing among people living in exposed areas, rather decreases for some outcomes, came as a surprise. Our previous questionnaire studies on the health effects of the 2010 Eyjafjallajökull volcanic eruption, indicated an increased likelihood of experiencing physical and psychological symptoms, and utilisation of psychotropic, pain and respiratory medication among the exposed population and for some individuals the reported symptoms persisted for up to 4 years.[1 6 7 13 33] Also, previous studies from other countries in Asia, Europe and Australia have shown increased medication utilisation, including psychotropic, pain and respiratory medication, for up to 4 years post-disaster.[16 17 20 21 23] Therefore, the findings of the current study are not in line with these results. Our findings raise the question of potential health improvements in the population following the eruption, given patterns observed, for example, in annual analysis for analgesics and anxiolytics among the highly exposed.

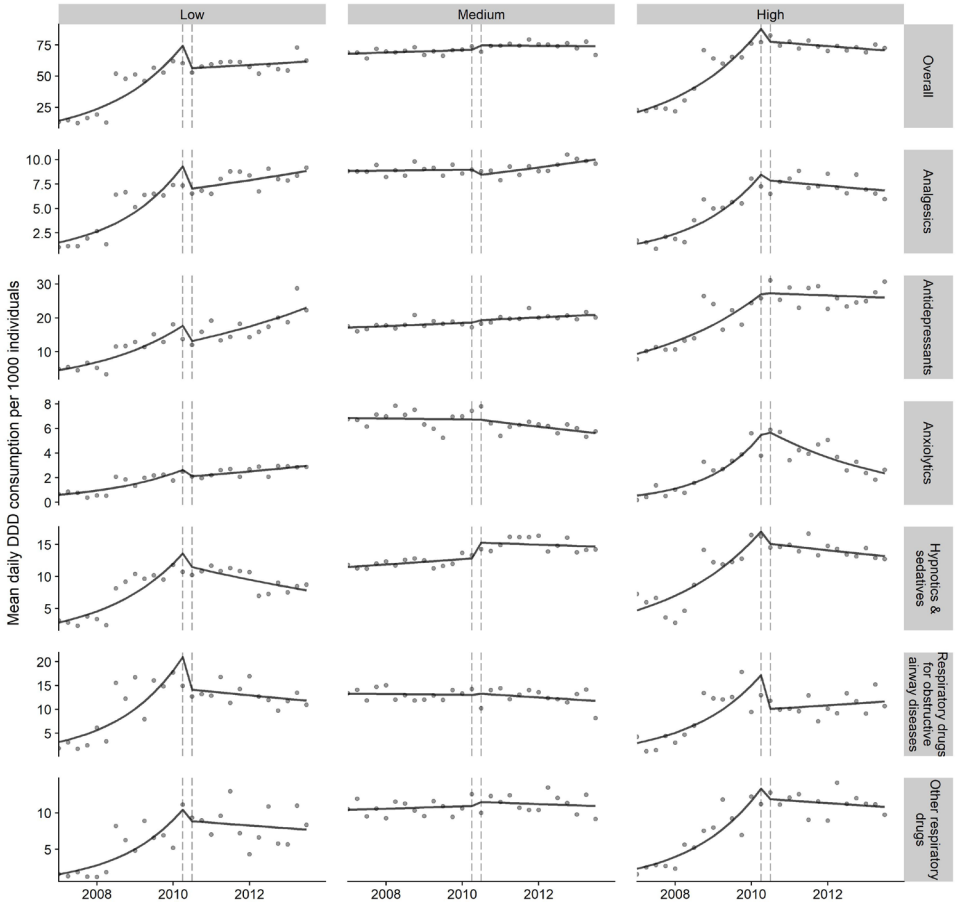

Figure 3 Three-month average daily dispensed number of DDD per 1000 individuals by medication class from 1 January 2007 to 25 July 2013. Observed data and ITS predictions. Dashed lines represent the time between the start of the eruption and the first datapoint after.
DDD, defined daily dose; ITS, interrupted time series.

Such improvement could be related to unity in the population while dealing with the aftermath of the eruption, hence stronger social cohesion. Further examination of this would require more detailed data (eg, collected by survey or qualitatively) than available in this study. The psychosocial support that was provided for residents[27] might also have played part in this regard. Although there is growing literature on the harmful health consequences of disasters, there is evidence suggesting that the majority of disaster exposed individuals prove to be resilient and continue to function normally in the aftermath of disasters.[12 35 36] Bradshaw *et al*[36] for example, used questionnaire data from 1392 participants to investigate the prevalence of respiratory symptoms following exposure to airborne volcanic ash particles following the Mount Ruapehu eruption in New Zealand in 1995. They concluded no link between proximity of the volcano and having asthma symptoms or using asthma medication. Another study conducted by Bryant *et al*[35] assessed psychological outcomes 3–4years following a bushfire in Australia. They found that the majority of exposed individuals demonstrated resilience without indicators of psychological distress, although, there was a minority in the high exposed group that reported persistent psychological difficulties. Some research has also reported fewer suicides and reductions in unhealthy behaviour in the difficult times following crisis.[24 37] Although, not all studies have found such optimistic results, for example, Karanikolos *et al*[37] performed a systematic narrative review on the health effects of the global financial crisis in 2008 in high-income countries. They reported increased prevalence of poor mental health with the greatest impact on the countries that suffered the largest economic impact and vulnerable groups with pre-existing problems. This might explain, at least in part, the high dispensed number of DDD prior the eruption in 2010.

Although many studies indicate increased medication utilisation following disasters, the impact on populations differ between events and studies. This study provided an evaluation of the total population including groups with varying exposure to the eruption. While some shorter-term health effects were exposed following the eruption,[6 15] it is possible that the long-term health impact of the volcanic eruption was minimal or at least not to a level that resulted in increased medication dispensing. These studies were based on different data sources, the questionnaire studies included self-reported and subjective measurements on different health outcomes, while

the current study is based on healthcare utilisation data, more specifically on the dispensing of medication for a specific outcome. Thus, the increased symptoms detected in our prior research following the Eyjafjallajökull eruption[1 6 7 13 38] did not necessarily equate to a level of severity that required medication. Another possible explanation is that exposed individuals do not seek treatment for the mental distress they may have experienced following the eruption. According to a study by Van der Velden *et al*[39] on mental health services utilisation after a firework disaster in the Netherlands disaster survivors with mental health problems were less willing to seek mental health treatments than they would be under normal circumstances. In addition, it may also have been difficult for residents too access pharmacies or other services to dispense medication at the time of the eruption. Some individuals could also have left the area shortly after exposure and might therefore not be included in our analysis on the exposed areas. This trend could also be a natural development on medication dispensing in Iceland after the increased dispensing over a long period of time. Lastly, composition of the ash from the Eyjafjallajökull eruption is also of importance here. Most ash samples were found to have little potential for damaging health[40] and the utilisation of protective equipment and staying indoors during the heaviest ash fall may have prevented more harmful or long-term respiratory symptoms.[6 40]

Our findings indicate that the 2010 volcanic eruption in Iceland did not lead to any substantial increases in medication dispensing among people living in exposed areas. While these findings are encouraging and positive for populations that are frequently exposed to volcanic eruptions, the results should be interpreted with caution since each volcanic eruption differs in size, content and particle size of the ash, as well as the extent of exposure individuals experience. The 2010 eruption caused no fatalities or severe destruction of houses, and the subsequent surge in tourists to the area brought economic benefits, which could also alleviate the acute mental health reported in previous papers. Further studies investigating changes in prescription rates of different types of medication in exposed areas following volcanic eruptions are necessary. In addition, it is important to investigate this association for other long-term outcomes and identify possible predictive factors for seeking treatment in larger populations. Since volcanic eruptions are uncontrollable, destructive and might threaten health of exposed populations in many ways, both directly and indirectly, this knowledge base needs to be strengthened and enlarged even further.

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Contributors AH and HZ (guarantors) supervised the study and had full access to all the data in the study. AH and HZ took responsibility for the integrity of the data and the accuracy of the data analysis. AH, BGGJ, HZ and RBG conceived and design the study as well as analysing and interpreting the data. RBG drafted the manuscript. All authors (RBG, BGGJ, UV, HKC, HH, HS, EBT, GP, HB, TGi, TGu TT, HZ and AH) provided critical revision of the manuscript for important intellectual content. AH, BGGJ, HZ provided administrative, technical, or material support. The corresponding author (RBG) attest that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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REFERENCES

1 Hlodversdottir H, Thorsteinsdottir H, Thordardottir EB, *et al*. Long-term health of children following the Eyjafjallajökull volcanic eruption: a prospective cohort study. *Eur J Psychotraumatol* 2018;9:1442601.
2 Longo BM, Longo AA. Volcanic ash in the air we breathe. *Multidiscip Respir Med* 2013;8:52.
3 Heaviside C, Witham C, Vardoulakis S. Potential health impacts from sulphur dioxide and sulphate exposure in the UK resulting from an Icelandic effusive volcanic eruption. *Sci Total Environ* 2021;774:145549.
4 Horwell CJ, Baxter PJ. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bull Volcanol* 2006;69:1–24.
5 Baxter PJ, Ing R, Falk H, *et al*. Mount ST Helens eruptions, may 18 to June 12, 1980. An overview of the acute health impact. *JAMA* 1981;246:2585–9 http://www.ncbi.nlm.nih.gov/pubmed/7029020
6 Carlsen HK, Gislason T, Benediktsdottir B, *et al*. A survey of early health effects of the Eyjafjallajokull 2010 eruption in Iceland: a population-based study. *BMJ Open* 2012;2:e000343.
7 Carlsen HK, Hauksdottir A, Valdimarsdottir UA, *et al*. Health effects following the Eyjafjallajokull volcanic eruption: a cohort study. *BMJ Open* 2012;2:e001851.
8 Gudmundsson G. Respiratory health effects of volcanic ash with special reference to Iceland. A review. *Clin Respir J* 2011;5:2–9.
9 Butwin MK, Pfeffer MA, von Löwis S, *et al*. Properties of dust source material and volcanic ash in Iceland. *Sedimentology* 2020;39:3067–87.
10 Carlsen HK, Valdimarsdóttir U, Briem H, *et al*. Severe volcanic SO_2 exposure and respiratory morbidity in the Icelandic population - a register study. *Environ Health* 2021;20:23.
11 DiMaggio C, Galea S, Madrid PA. Population psychiatric medication prescription rates following a terrorist attack. *Prehosp Disaster Med* 2007;22:479–84.
12 Neria Y, Nandi A, Galea S. Post-traumatic stress disorder following disasters: a systematic review. *Psychol Med* 2008;38:467–80.
13 Hlodversdottir H, Petursdottir G, Carlsen HK, *et al*. Long-term health effects of the Eyjafjallajökull volcanic eruption: a prospective cohort study in 2010 and 2013. *BMJ Open* 2016;6:e011444.
14 Jia Z, Shi L, Duan G, *et al*. Traumatic experiences and mental health consequences among child survivors of the 2008 Sichuan earthquake: a community-based follow-up study. *BMC Public Health* 2013;13:104.
15 Thienkrua W, Cardozo BL, Chakkraband MLS, *et al*. Symptoms of posttraumatic stress disorder and depression among children in tsunami-affected areas in southern Thailand. *JAMA* 2006;296:549–59.
16 Caamano-Isorna F, Figueiras A, Sastre I, *et al*. Respiratory and mental health effects of wildfires: an ecological study in Galician municipalities (north-west Spain). *Environ Health* 2011;10:48.
17 Sepehri G, Meimandi M-S. Pattern of drug prescription and utilization among Bam residents during the first six months after the 2003 Bam earthquake. *Prehosp Disaster Med* 2006;21:396–402.
18 Elliott CT, Henderson SB, Wan V. Time series analysis of fine particulate matter and asthma reliever dispensations in populations affected by forest fires. *Environ Health* 2013;12:11.
19 Carlsen HK, Ilyinskaya E, Baxter PJ, *et al*. Increased respiratory morbidity associated with exposure to a mature volcanic plume from a large Icelandic fissure eruption. *Nat Commun* 2021;12:2161.
20 Usher K, Brown LH, Buettner P, *et al*. Rate of prescription of antidepressant and anxiolytic drugs after cyclone Yasi in North Queensland. *Prehosp Disaster Med* 2012;27:519–23.
21 Rossi A, Maggio R, Riccardi I, *et al*. A quantitative analysis of antidepressant and antipsychotic prescriptions following an earthquake in Italy. *J Trauma Stress* 2011;24:129–32.
22 Trifirò G, Italiano D, Alibrandi A, *et al*. Effects of L'Aquila earthquake on the prescribing pattern of antidepressant and antipsychotic drugs. *Int J Clin Pharm* 2013;35:1053–62.
23 Diène E, Geoffroy-Perez B, Cohidon C, *et al*. Psychotropic drug use in a cohort of workers 4 years after an industrial disaster in France. *J Trauma Stress* 2014;27:430–7.
24 Beaglehole B, Bell C, Frampton C, *et al*. The impact of the Canterbury earthquakes on prescribing for mental health. *Aust N Z J Psychiatry* 2015;49:742–50.
25 Thorsteinsson T, Jóhannsson T, Stohl A, *et al*. High levels of particulate matter in Iceland due to direct ash emissions by the Eyjafjallajökull eruption and resuspension of deposited ash. *J Geophys Res* 2012;117.
26 Petersen GN. A short meteorological overview of the Eyjafjallajökull eruption 14 April-23 May 2010. *Weather*2010;65:203–7.
27 Thordardottir EB, Gudmundsdottir B, Petursdottir G, *et al*. Psychosocial support after natural disasters in Iceland-implementation and utilization. *Int J Dis Risk Red* 2018;27:642–8.
28 Stohl A, Prata AJ, Eckhardt S, *et al*. Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: the 2010 Eyjafjallajökull eruption. *Atmos Chem Phys* 2011;11:4333–51.
29 Gudmundsson MT, Thordarson T, Höskuldsson A, *et al*. Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland. *Sci Rep* 2012;2:572 http://www.ncbi.nlm.nih.gov/pubmed/22893851
30 Statistic Iceland. Hagstofa Íslands 2021. Available: http://px.hagstofa.is/pxis/pxweb/is/Ibuar/?rxid=fa861cad-0661-46a9-b31f-189ebdf91fd6 [Accessed 12 Mar 2021].
31 World Health Organization. Collaborating centre for drug statistics methodology, guidelines for ATC classification and DDD assignment, 2021. Available: https://www.whocc.no/atc_ddd_index_and_guidelines/guidelines/ [Accessed 2 Jan 2021].
32 Wagner AK, Soumerai SB, Zhang F, *et al*. Segmented regression analysis of interrupted time series studies in medication use research. *J Clin Pharm Ther* 2002;27:299–309.
33 Jandoc R, Burden AM, Mamdani M, *et al*. Interrupted time series analysis in drug utilization research is increasing: systematic review and recommendations. *J Clin Epidemiol* 2015;68:950–6.
34 Kontopantelis E, Doran T, Springate DA, *et al*. Regression based quasi-experimental approach when randomisation is not an option: interrupted time series analysis. *BMJ* 2015;350:h2750.
35 Bryant RA, Waters E, Gibbs L, *et al*. Psychological outcomes following the Victorian Black Saturday bushfires. *Aust N Z J Psychiatry* 2014;48:634–43.
36 Bradshaw L, Fishwick D, Kemp T, *et al*. Under the volcano: fire, ash and asthma? *N Z Med J* 1997;110:90–1 http://www.ncbi.nlm.nih.gov/pubmed/9137309
37 Karanikolos M, Heino P, McKee M, *et al*. Effects of the global financial crisis on health in high-income Oecd countries: a narrative review. *Int J Health Serv* 2016;46:208–40.
38 Gissurardóttir Ólöf Sunna, Hlodversdóttir H, Thordardóttir EB, *et al*. Mental health effects following the eruption in Eyjafjallajökull volcano in Iceland: a population-based study. *Scand J Public Health* 2019;47:251–9.
39 Van der Velden PG, Grievink L, Kleber RJ, *et al*. Post-disaster mental health problems and the utilization of mental health services: a four-year longitudinal comparative study. *Adm Policy Ment Health* 2006;33:279–88.
40 Horwell C, Baxter P, Hillman S. Respiratory health hazard assessment of ash from the 2010 eruption of Eyjafjallajökull volcano, Iceland. A summary of initial findings from a multi-centre laboratory study. *Int Volcanic Health Hazard Network Report* 2010 https://www.ivhhn.org/images/pdf/iceland_ash_health_report.pdf