Hekla volcano monitoring project

FINAL REPORT

Icelandic Met Office

Icelandic
Meteorological Office

ICAO

Veðurstofa
Íslands

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Disclaimer

The assessment of advanced warning times prior to a Hekla eruption is for discussion purposes only and should not be construed as a guarantee of public safety. A sudden, unforeseen eruption at Hekla volcano remains a possibility, as highlighted in the report.

Icelandic Meteorological Office, 30 June 2019.

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Executive summary

Hekla is a particularly dangerous volcano because historic eruptions comprise an initial violent, explosive phase and precursory signals may only occur within a very short time window prior to eruption onset. During its most recent eruptions (since 1970), the time period from the first detection of unusual seismicity to the eruption onset ranged between 23 to 79 minutes. In 3 out of 4 of these eruptions, no warning was issued prior to an eruption. Having a short (or no) warning time prior to Hekla eruptions increases the associated risk because of the frequency of airplanes flying very close to the summit on a daily basis. The Icelandic Meteorological Office (IMO) is the institution in charge of monitoring volcanoes and volcanic hazards in Iceland and, when possible, responsible for forecasting the occurrence of eruptions. IMO operates an extended geophysical network and a 24-hour monitoring room where the near real-time monitoring data are collected, processed and interpreted by specialists in house.

The capability to provide a timely warning prior to an eruption depends on 1) the presence of geophysical signals, 2) the capability to detect geophysical signals indicating a change in the volcanic system, 3) an expert, rapid and confident, interpretation of the monitoring data and 4) an effective way to communicate pertinent information about the situation to the official stakeholders, e.g. civil protection and aviation authorities, airline companies, national energy and road authorities. A delay in any of these four factors will result in a delay in issuing a warning, which is essential to reduce the risk of volcanic ash encounter or any other hazards to overflying aircraft (such as the initial shock wave and turbulence) posed by an unexpected eruption that could be otherwise catastrophic. Similarly, locals and hikers would need a timely warning to vacate the danger zone exposed to ground-based hazards including ballistic ejecta, pyroclastic flows, lava flows and gas emissions.

This project focused on assessing the current capabilities in place at IMO to provide an early warning for an eruption at Hekla volcano. It has been undertaken by investigating 1) the current monitoring system and its reliability (see sections 3 and 4); 2) the automatic system for the data processing and alert (see section 5) and 3) the procedures in place for responding to emergencies and communication protocols (see section 6). Table 1 summarizes the outcome of this analysis and provides an overview of the current monitoring level and capability in communicating an early warning. The analysis is done per type of monitoring instruments, which include seismic, deformation (continuous GPS (cGPS) and strainmeters) and geo-chemical networks. It reveals that the current setup of the monitoring network is fulfilling the minimum requirements designed for a high-risk volcano, and also that the level of reliability is quite satisfactory for the different systems. The reliability has been determined by computing the downtime of the whole network around Hekla over the last three years and is shown as a percentage of time. This in turn represents how often the real-time monitoring data were not available in the monitoring room. Currently, what is more critical is the need for additional real-time data streams that may provide automatic alerts, triggered by detected deviations from the background conditions. As it stands today, this automatic-alert (audio broadcast in the monitoring room) is setup and triggered only for the seismic data.

Table 1. Overview of the current early warning capability for Hekla volcano in place at IMO, evaluated for the time period 2016–2018.

	Data availability		**Data interpretation**		**Communication**
	Network setup	**Downtime (data not available in monitoring room)**	**Delay in data visualization (for automatic data processing)**	**Automatic early warning**	**Protocols**
Seismic	OK	0.02% (four closest stations)	Seconds	Operational, but requires additional modifications	Operator activates phone calls and SMS (SMS list does not include aviation end-users nor civil protection authorities)
cGPS	OK	0.10% (six closest stations)	24-hours	Not existing, but possible	
Strainmeter	OK	0%	10 minutes	Not existing, but possible	
Geochemical	OK	0%	30 min – 22 hours	Not existing, but in development	

This report includes in detail all the results of this analysis and quantifies what is the probability that the monitoring system at IMO will not be fully operational (making the detection of precursors impossible). The analysis has been done considering the period 2016–2018. The downtime represents the time period as a percentage, when the most important/closest stations around Hekla were simultaneously not sending data. The average downtime of the seismic stations during this period was 0.02% (for the four stations closest to the volcano). The average downtime of cGPS stations was 0.10% (for the six stations closest to the volcano). On no occasions during the reporting period, were the two strainmeter stations closest to Hekla (BUR and HEK) not operational (or streaming data) at the same time. Similarly, no coincident downtime of both the DOAS and MultiGAS geochemical stations occurred, although there were separate instances of downtime for both instruments.

A scenario-based analysis of operational response has been done in light of the current procedures in place and data availability. It reveals that if the process of magma migration to the surface is quicker than 24 minutes prior to the next eruption at Hekla, there will be no timely warning issued by IMO to support the safety of aviation operations, nor any other mitigation actions operated by the Civil Protection. Furthermore, in the event that the volcano does not provide any precursory signals (i.e. the eruption starts at T=0 min), it will also not be possible to issue a pre-eruptive warning.

In addition, this project identifies areas for improvements, both for what concerns the existing monitoring network and for potential new installations with the general aim of 1) reducing the delay time in issuing a warning and 2) building confidence with respect to data interpretation based on a multi-parametric system.

An analysis has also been performed to understand if there is the possibility to implement the monitoring network with additional instruments and sensors. The outcome of this survey identified the geochemical monitoring network to be the less developed and the one providing a more limited time-coverage in data availability due to configuration constraints.

The most urgent actions involve either improvements to existing or the implementation of new data processing workflows and implementation of the automatic alert based on multi-parametric datasets. The implementation of automatic alerts based on different types of monitoring data will assist the person on duty in the monitoring room, to make a rapid, confident assessment of on-going activity and issue timely alerts.

In terms of improving the communication protocols the main outcome of this analysis showed that a near real-time assessment of the health status of the monitoring system should be done automatically and the status should be communicated to IMO's stakeholders whenever it will be assessed to be below a minimum requirement. On these occasions, the capability to detect unrest at Hekla volcano will be strongly reduced, however, making the stakeholders aware of this situation will enable them to activate procedures to mitigate the risk of an unforeseen eruption.

The primary recommendations from this study are outlined below.

The **highest-priority recommendations concerning the existing monitoring system** emerging from this study are as follows (not listed in order of priority):

- Implement strain corrections and automatic alert based on strain-rate calculations
- Implement automated alerts based on the currently available geochemical data
- Implement the Track processing of the cGPS data aimed at the creation of an automatic alert
- Tune the existing early warning system considering the sensitivity of the current seismic network in order to reduce the occurrence of false positives
- Contact Síminn regarding serious concerns on the vulnerability of the mobile network
- Improve power supply to MultiGAS on Hekla summit
- Implement an automatic alert based on the status of the monitoring network at Hekla
- Implement a reliable backup system for all monitoring networks

The **highest-priority recommendations concerning additions** to the existing monitoring network are:

- Install a soil temperature probe in hut on the summit of Hekla and set-up continuous data streaming of measurements to IMO
- Undertake campaign measurements this summer (2019) to identify suitable locations for the installation of a permanent radon detector along with a feasibility study regarding operational requirements
- Pursue the redesign and installation of CO_2 in water instruments

The **longer-term strategy** would include:

- Feasibility study to assess the added value of implementing a tiltmeter network
- Purchase additional MultiGAS and DOAS instruments
- Upgrade all cGPS instruments within 10 km of the summit
- Implementation of SeisComP software
- Evaluation of performance of temporary seismometers

1 Rationale

This report is intended to assess and constructively review the current capability of providing an early warning for Hekla volcano prior the next eruption, to facilitate the aviation stakeholders to operate in safe conditions.

The report is structured in three main parts. The first provides background information about the concept of monitoring active volcanoes with a special focus on Hekla volcano; the second part investigates the monitoring system in place around Hekla, explaining how it works and how the procedures in place at IMO rely on these monitoring data and their processing/interpretation; finally, the third part addresses suggested improvements that could potentially increase the warning time and enhance the reliability of the alert system.

IMO is continuously striving to collect additional information on Icelandic volcanoes and improve its observing systems for monitoring volcanic activity. This includes the continued operation and improvements to IMO's in-situ measurements such as seismic, cGPS, gas, web-cams, infrasound etc. These data are used to monitor the status of Icelandic volcanoes, in order to identify the onset of unrest and early warning signals that may be precursory to an eruption, as well as to monitor co-eruptive activity.

A preliminary assessment of the monitoring level of all major volcanoes in Iceland has been undertaken based on criteria especially designed for Icelandic volcanoes. At the same time an analysis assessing the threat level of the 32 active volcanoes in Iceland has been performed, allowing the identification of those volcanoes (including Hekla) with the potential to have the highest impact on both aviation and the local population. This information is vital to evaluate IMO's capacity to provide timely warnings for impending eruptions. The response time to issue such a warning depends on both the time of the first detection of unrest (including the data interpretation) and the time to activate the internal procedures to provide warnings. This response time for explosive eruptions is considered acceptable for most Icelandic volcanoes, however not for Hekla volcano. For Hekla, the limited precursory period (observed prior to recent eruptions) is likely related to the structure of its volcanic system. For example, detectable seismicity and deformation/strain were only observed within 23–79 minutes preceding the eruption onset (as per the most recent eruptions since 1980 e.g. Soosalu & Einarsson, 2002; Soosalu et al., 2003; Soosalu et al., 2005; Einarsson, 2018).

Hekla volcano is one of the most active volcanoes in Iceland with 5 eruptions in the last 100 years. The last eruption at Hekla was in 2000 which generated an ash plume 12 km high, whereas in 1947 it generated a 30 km high plume. This volcano is of concern for aviation due to its proximity to an international air route reference point (64N 20W), and the presence of domestic flight air routes in the vicinity (Figure 1). Any improvements in monitoring Hekla volcano that might help to issue a timely early warning would be very valuable for aviation safety.

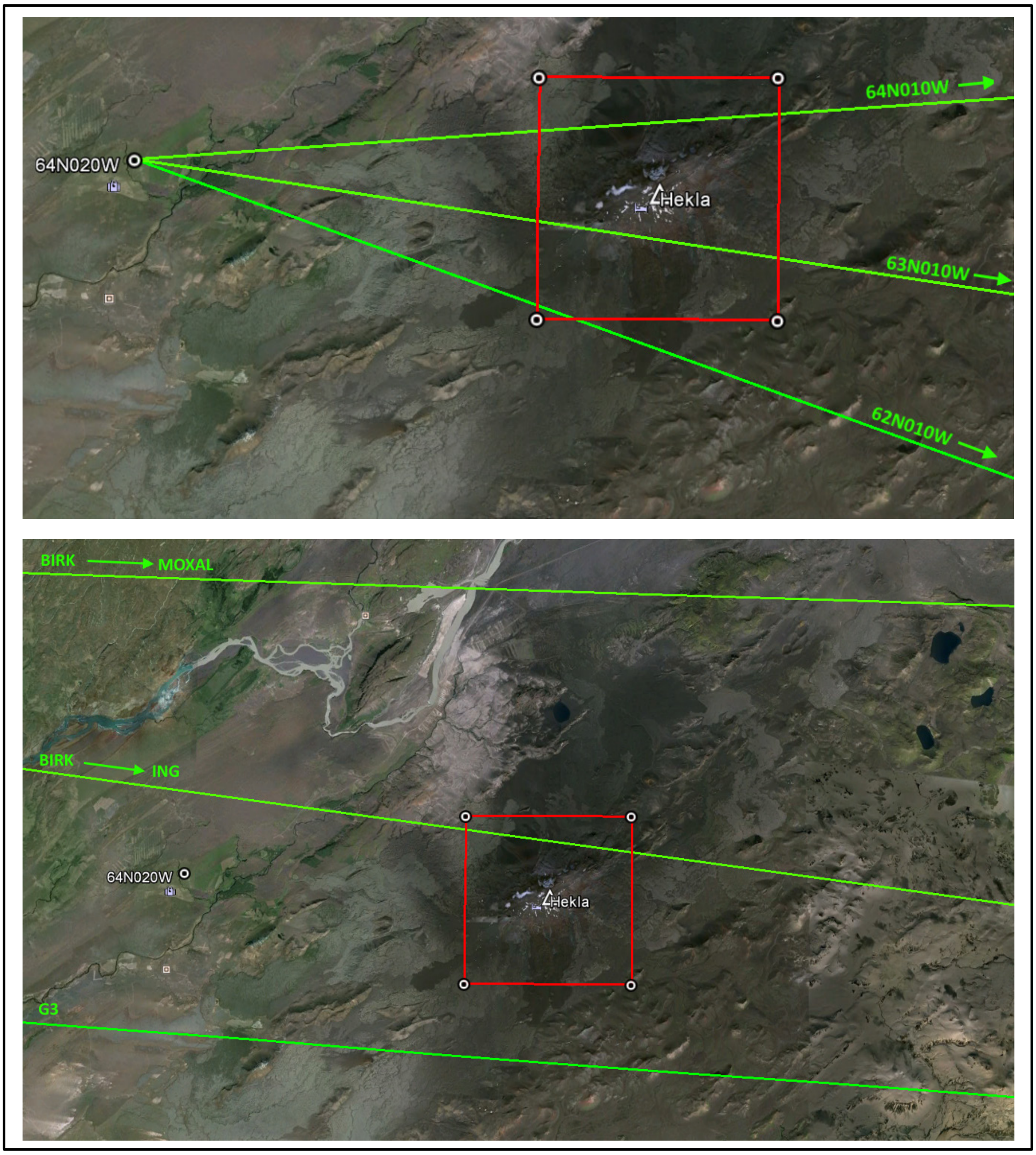


Figure 1. Air-routes in the vicinity of Hekla volcano. Top: Three international air-routes cross an area of 4×4 nautical miles around Hekla volcano. All the three routes point toward the coordinate 64N 20W. Bottom: The domestic flight between Reykjavík airport and Höfn in Hornafjörður (ING) approaches Hekla volcano from the northwest. Image kindly provided by Isavia.

2 Background

2.1 Monitoring volcanoes

Dangerous volcanoes require adequate monitoring to allow the identification of changes in their behavior that may indicate an increased likelihood of an eruption. By monitoring volcanoes we mean to observe and interpret signals that may indicate new magma is flowing into the roots of the volcano and it is preparing for an eruption. Monitoring volcanoes is essential 1) to anticipate the occurrence of an eruption, 2) to forecasts its hazards and, 3) to mitigate their impact. To be able to provide an alert prior to an eruption it is important to detect changes in the volcano behavior, that may be indicative of a new magmatic intrusion or influx of new melt to an existing magma body (phase A). As magma begins to ascend toward the surface it is beneficial to be able to determine the eruptive site and detect the eruption onset (phase B), and to estimate the size of the event and its hazards (phase C). Different types of monitoring equipment are required to assess various stages of unrest or eruption (see Table 2).

Many Volcano Observatories in the world employ multi-parameter monitoring strategies involving **at least seismology, geodesy and geochemistry** as reported in the "Handbook for Volcanic Risk Management" edited by the MIA VITA Project (http://miavita.brgm.fr/Documents/Handbook-VolcRiskMgt-lr.pdf) in the "Global Volcanic Hazards and Risk" book (Loughlin at el., 2015) and more recently in the summary of the three Volcano Observatory Best Practice Workshops (Pallister et al., 2019).

It is well-established internationally that the main components of a comprehensive volcano monitoring program for the identification of precursory signals include measuring:

- Ground motion or displacements (e.g. using seismometers, accelerometers, GPS, borehole strainmeters, satellite interferometry, etc.);
- Gravity changes to infer mass changes (gravimeters);
- Composition of volcanic gases, (air, soil and plume measurements) especially SO_2, and CO_2;
- Temperature of gas, water, fumaroles, soil.

The monitoring network currently operated by IMO for volcano surveillance purposes (both pre-eruptive and co-eruptive) is structured over three main pillars: geophysical and geochemical, atmospheric and acoustic, remote sensing and earth observations. They are out-lined in Table 2 and labelled (A, B and C) for their reference usage relative to the pre-defined phases listed above.

Given the variety of volcano types and volcanic hazards in Iceland, the level of monitoring differs from volcano to volcano.

Each volcano has been evaluated considering two main parameters: 1) the eruption frequency and 2) the potential for producing "large" eruptions. This information has been gathered from the Catalogue of Icelandic Volcanoes (Icelandic Meteorological Office et al., 2014). "Large" eruptions is here defined as eruptive events (explosive or effusive) that have occurred in past and had a significant impact on populations (fatalities) and/or critical infrastructures (with potential for disruption to society). In order to provide a consistent approach on how to define the level of monitoring needed, three main categories have been defined as those including volcanoes: erupting frequently AND with potential for a large eruption (Monitoring level 3); erupting frequently (with minor eruptions) OR with potential for a large eruption (Monitoring level 2); not belonging to categories 1 or 2 (Monitoring level 1). It seems reasonable to assume that any volcano will be moved to the highest monitoring level whenever it will show signs of unrest/imminent eruption.

Table 2. Overview of the main monitoring tools used at IMO for volcano surveillance. The primary use of each instrument or sensor is shown in brackets, as explained in the section above.

Geophysics and geochemistry	**Atmosphere and acoustic**	**Remote sensing and satellite**
Seismology (A, B, C)	Radar (C)	Satellite products for volcanic cloud mapping (C)
Volcanic gas geochemistry (A, B, C)	Radio sounding (C)	Visual cameras (B, C)
Hydrology (A, B, C)	Infrasound (B, C)	Infrared cameras (B, C)
Deformation (GPS, Bore hole strainmeter, tiltmeters) (A, B, C)	Lightning detectors (C)	Satellite interferometry (A, B, C)
	Ceilometers (C)	
	Lidar (C)	
	Optical particle counters (C)	

Each of the 32 active Icelandic volcanoes have been evaluated and they have been assigned to one of the three categories. Hekla volcano belongs to the Monitoring Level 3 (Table 3).

Table 3. Monitoring level assigned to each of the active Icelandic volcanoes.

Monitoring level 1 (all volcanoes not in level 2 and 3)	Monitoring level 2 (volcanoes either frequently erupting or with potential for large impact)	Monitoring level 3 (volcanoes frequently erupting and with potential for large impact (essentially occurrence of large eruption in the past); volcanoes in unrest)
Eldey, Esjufjöll, Fremrinámar, Grímsnes, Heiðarsporðar, Helgrindur, Hofsjökull, Hrómundartindur, Ljósufjöll, Langjökull, Prestahnúkur, Snæfell, Tungnafellsjökull, Þeistareykir	Askja, Eyjafjallajökull, Kverkfjöll, Snæfellsjökull, Tindfjallajökull, Torfajökull, Krafla, Reykjanes, Hengill, Krýsuvík, Brennisteinsfjöll, Vestmannaeyjar	**Hekla**, Katla, Grímsvötn/Þórðarhyrna, Bárðarbunga, Öræfajökull

2.2 Hekla volcano

Hekla is one of the most active volcanoes in Iceland with approximately 18 eruptions since 1104 (Larsen & Thordarson, 2014). In the last century it erupted 5 times producing predominantly VEI=3 eruptions (VEI is the Volcanic Explosivity Index as introduced by Newhall and Self in 1982 and it is a way to classify eruptions based on amount of emitted material and plume height). Over the past few decades, Hekla erupted at almost regular intervals (~10 year intervals) with the last four eruptions occurring in 1970, 1980–1981, 1991 and 2000. Each of these events has been characterized by a short-lived explosive phase, lasting over 2–3 hours, followed by an effusive phase. Despite this apparent regular trend of the most recent period of activity, Hekla has in fact exhibited significantly longer repose periods in the past. Figure 2 illustrates the relationship between repose time (interval between eruptions) and amount of volcanic material (tephra) emitted, plotted for historic eruptions since 1158 AD.

The observed correlation indicates that for a repose period of 19 years (approximately the current repose period) the estimated amount of material ejected would correspond to approximately 0.03 km^3.

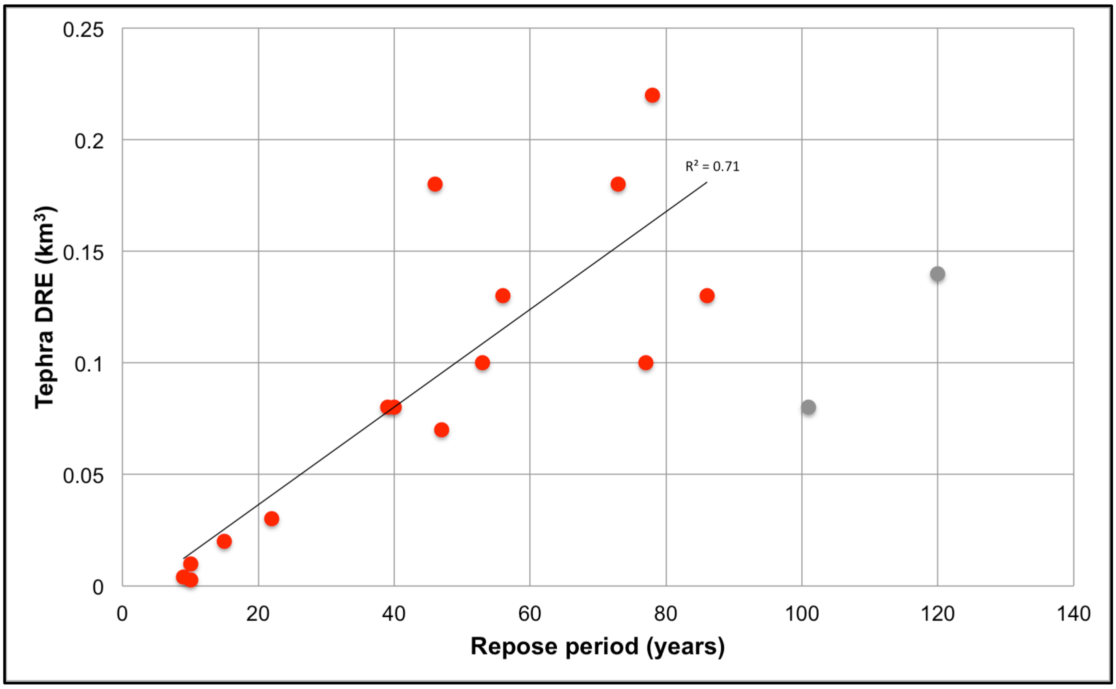


Figure 2. Plot showing the relationship between repose time and tephra dense rock equivalent (DRE) volume during Hekla eruptions since 1158 AD. The points marked by grey dots were not used in the R^2 calculation. These data points correspond to the 1947 and 1510 eruptions and have been treated as outliers. A possible explanation is an underestimate of the tephra volume due to extensive dispersal over the sea for the 1947 and/or possible erosion of the 1510 deposit. Tephra DRE volumes from Thordarson and Larsen (2007).

Hekla volcano also produced some of the largest eruptions in the country with VEI=5–6. These large eruptions appear to be more frequent in the past but an alternative explanation might be that old thin deposits (produced by smaller eruptions) were not well preserved (Figure 3).

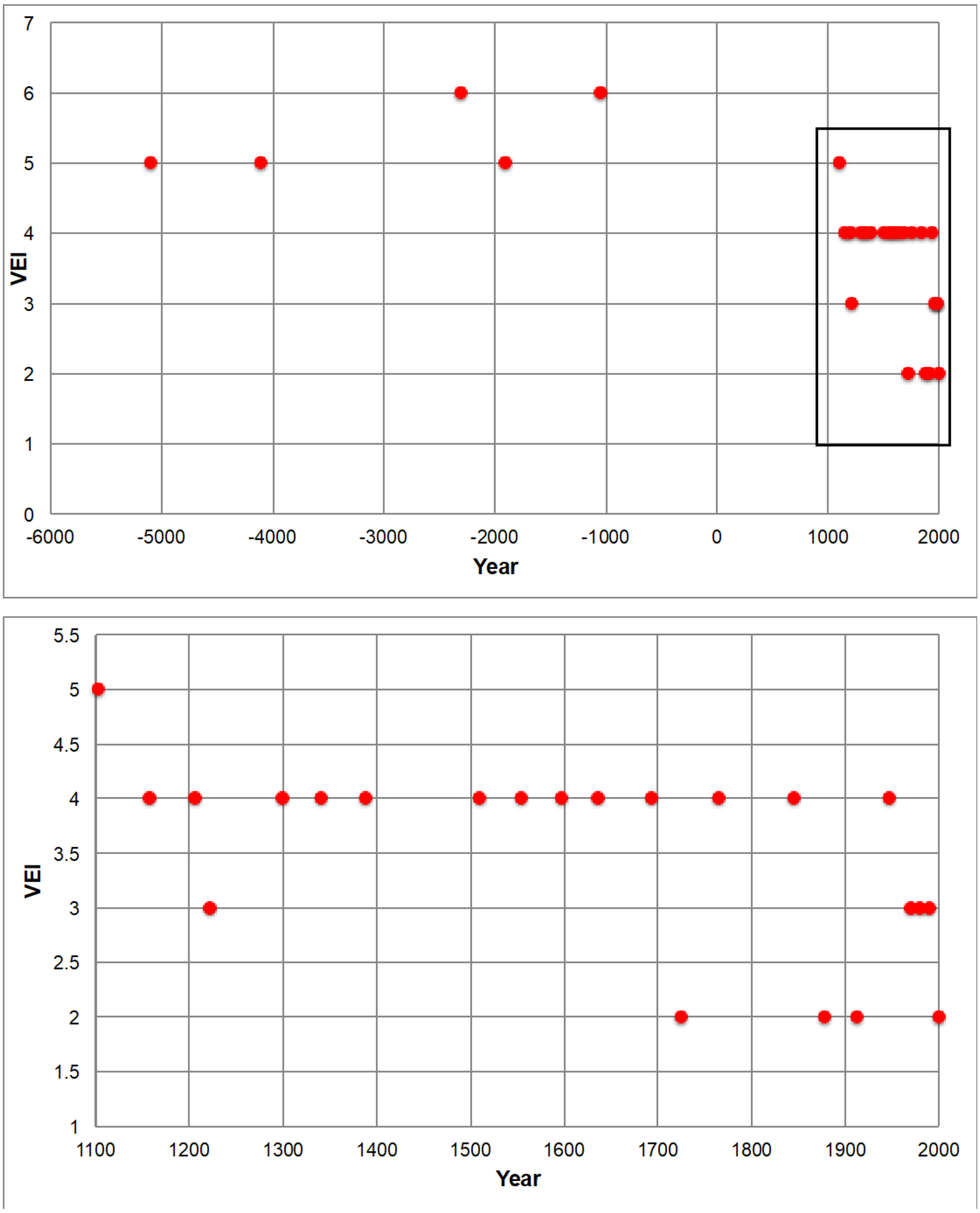


Figure 3. Volcanic Explosivity Index (VEI) of historic Hekla eruptions. Upper panel: VEI timeline of all known eruptions at Hekla volcano. Lower panel: VEI timeline of eruptions at Hekla volcano since 1104 AD (region within black box in upper panel). In the most recent years the most common VEI is equal to 3. VEI values from Larsen and Thordarson (2014).

Hekla volcano has been assessed as one of the most dangerous volcanoes in Iceland also by using the international ranking system as suggested by Loughlin et al. (2015) where the Volcanic Hazard Index (VHI) is evaluated in light of the Population Exposure Index (PEI) in a matrix-wise representation. VHI is a function of parameters including, frequency of eruptions, maximum VEI and potential to generate lethal hazards. PEI is calculated by considering the exposure in terms of loss of life. Hekla has been assessed to have a PEI equal to 5 and a VHI equal to III (Table 4). This system also ranks Hekla as one of the most hazardous volcanoes in Iceland. As a consequence, the level of monitoring needs to be well-designed, fully-tested and redundant.

Table 4. Threat level for Hekla, based on the VHI/PEI scheme suggested by Loughlin et al. (2015). PEI is scaled on Icelandic numbers, so it differs from the original one.

VHI	III					X		
	II							
	I							
		1	2	3	4	5	6	7
				PEI				

Furthermore, previous eruptions at Hekla have demonstrated that very few precursors may be generated prior to an eruption and, in the past, a pre-eruptive warning was only issued prior to the 2000 eruption (Table 5). During the last eruption in 2000, IMO issued a warning only 41 minutes before the eruption started. The warning was issued in light of both the strainmeter data and the seismicity (Figures 4–6).

Table 5. Summary of the most recent eruptions that occurred at Hekla since volcano monitoring was established (Einarsson, 2018). The colors reflect when: no warning was issued before the eruption onset (red) and a warning was issued within >30 minutes of the eruption onset (green). The 1981 eruption is considered as a separate eruptive phase, of the eruption that commenced in 1980.

	Eruption Date	First Precursory Earthquakes	First Strain Signal	First tremor detected	Warning Issued	Eruption beginning	Time interval from first detection to eruption start	Time interval from warning issuance to eruption start
Hekla 2000	26. Feb 2000	17:00	17:45	17:20	Yes - 17:38 (IMO)	18:19	79 min.	41 min
Hekla 1991	17. Jan 1991	16:30	16:36	17:02	No	17:00 - 17:02	30 - 32 min.	0 min
Hekla 1980-81	17. Aug 1980	13:04		13:27	No	13:27	23 min.	0 min
Hekla 1970	5. May 1970			19:58	No	20:23	25 min.	0 min

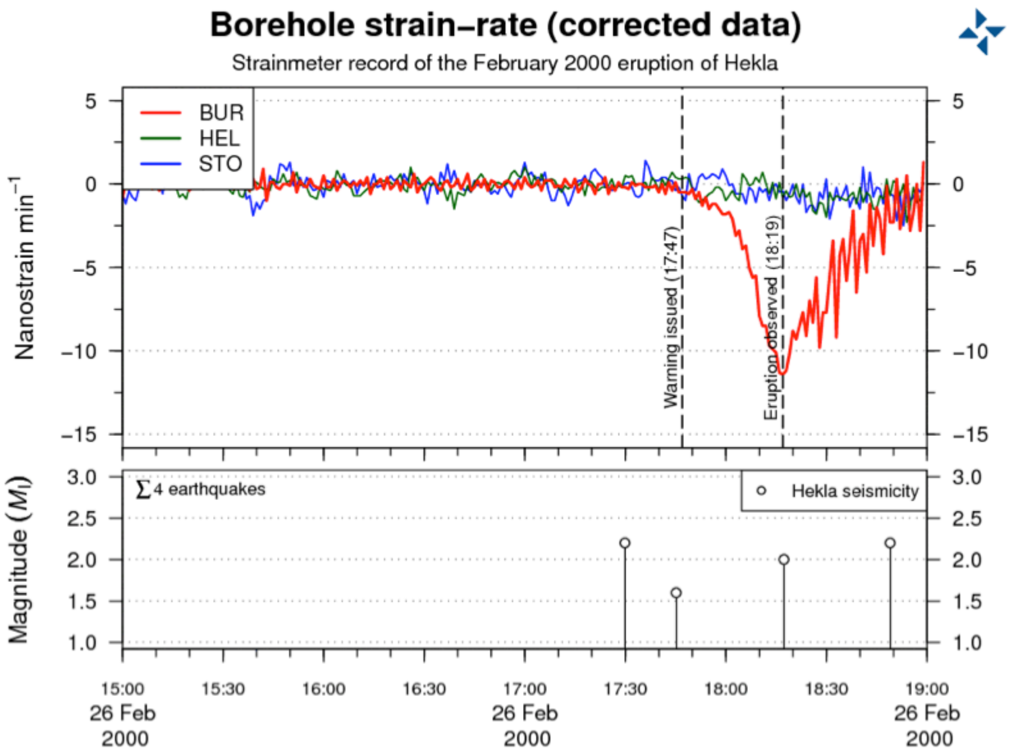


Figure 4. Strainmeter observations and earthquake activity prior to and during the 2000 eruption. The top panel shows the response of the strainmeters BUR (red line), HEL (green line) and STO (blue line). The bottom panel displays the earthquakes with M>1.5 detected prior to and during the eruption (data from IMO).

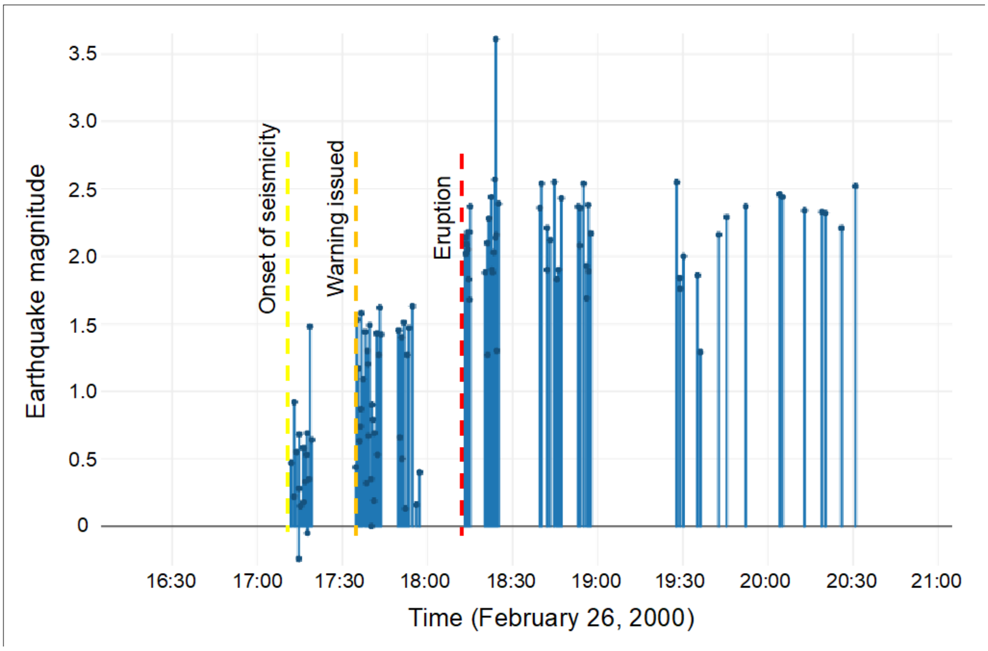


Figure 5. A-posteriori reconstruction of the earthquakes recorded by IMO's seismic network prior the onset of the eruption in 2000. The yellow line shows when the first earthquake is identified, the orange line when the warning was issued and the red line when the eruption started.

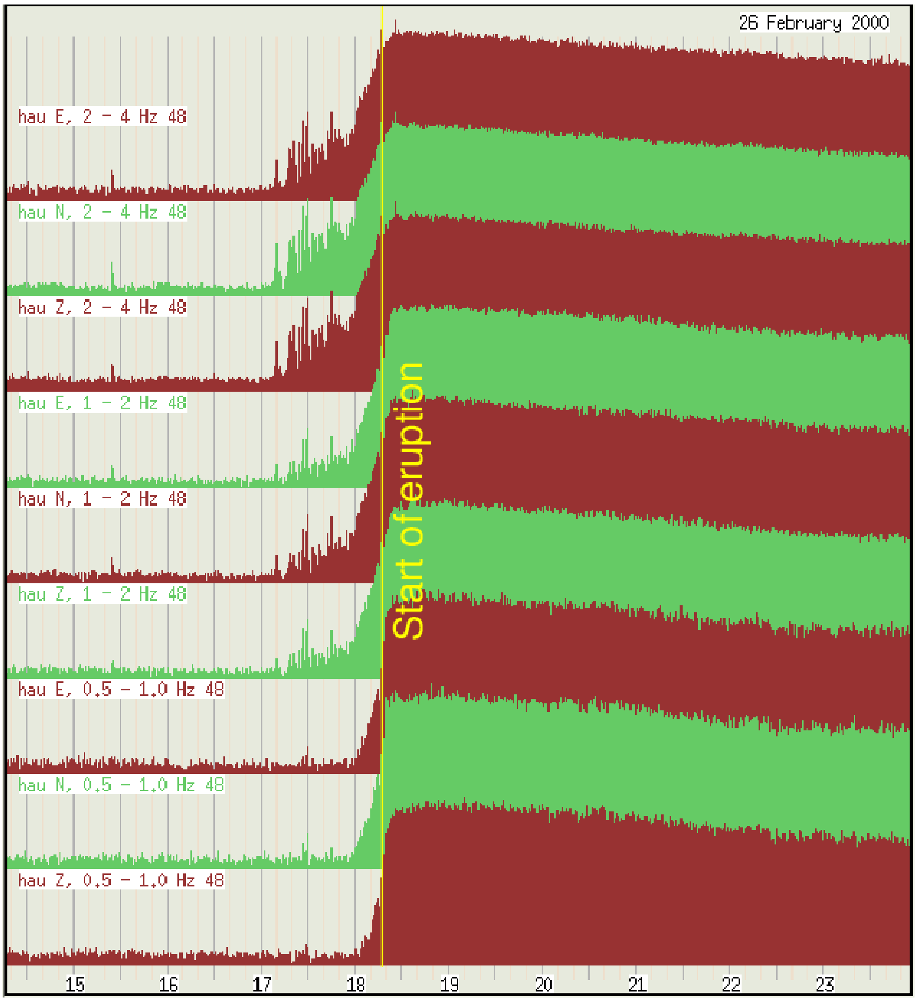


Figure 6. Tremor plot (scaled RSAM) displaying averaged seismic amplitude data (in different frequency bands) from the seismic station HAU. The yellow line represents the onset of the eruption. The horizontal axis displays time in hours.

2.3 Concept of early warning

The capacity to firstly, detect an unrest phase which might evolve into an imminent eruption and secondly, provide a timely forecast of eruption onset and volcanic hazards depends on two main factors:

- the volcanic context, and
- the level of surveillance

By *volcanic context* we mean those features characterizing the nature of the volcano, the type of the eruption (explosive vs. effusive) and the magma migration processes.

By *level of surveillance* we mean the ensembles of data collection, processing, transfer and procedures that should work and be activated from the initial detection of the magma movement toward the surface until the communication to the final users. This includes three main elements:

1) How well a volcano is monitored (**type and reliability of the monitoring data**),
2) How quickly and reliably the data interpretation is carried out by the specialists on duty (**quality of raw and processed data, automatic alert**) and eventually,
3) How efficiently this information is disseminated (**communication protocols**).

Since we have no control over the volcano itself, the type of eruption or when this will occur, we can only improve the early warning by strengthening the level of surveillance. This study investigates the three main elements concerning the level of surveillance currently provided by IMO for Hekla volcano.

An early warning would allow stakeholders such as London VAAC (Volcanic Ash Advisory Centre) and Isavia (the national airport and air navigation service provider of Iceland) to issue aviation warnings for the diversion of aircraft away from the vicinity of Hekla. An early eruption warning would also be beneficial to Almannavarnir RLS (the Department of Civil Protection and Emergency Management of the National Commissioner of the Icelandic Police) as SMS warning messages could be sent immediately to all active mobile telephones in the affected region. The warning would also allow rescue teams to be mobilised. The same warning would be used by the power-production company Landsvirkjun and the power-distribution company Landsnet to invoke emergency measures at the nearby Búrfell hydro-power station. Other stakeholders include the road authorities (Vegagerðin) and local authorities.

3 Current operational monitoring system around Hekla

A variety of sensors for real-time volcano monitoring purposes are installed in the vicinity of Hekla volcano. Using a variety of sensors to measure different parameters should improve the capability to detect and interpret signals prior a volcanic eruption.

The current operational monitoring network includes (Figure 7):

- Seismometers
- Continuous GPS stations
- Bore-hole strainmeters
- Multiple gas sensors (DOAS and MultiGas)
- Visual web-cams and
- Infrasound detectors

All data from the above instruments are streamed to IMO where they are processed (automatically and/or manually) and can be visualized in the monitoring room (but with variable time delays for different datasets).

3.1 Seismometers

The seismic network around Hekla (operated by IMO) comprises 12 broadband/intermediate period seismometers within 50 kilometers of the volcano, of which 4 are within 15 km (FED, MJO, HES and HAU). Stations FED and MJO were installed in June 2010. They are currently operating with Guralp ESP broadband sensors with a corner frequency of 60 Hz. HES was installed in October 2016. This site is operating a 6TD sensor with a 10 Hz corner frequency. The equipment at HES is owned by the Dublin Institute for Advanced Studies (DIAS). The station HAU was installed by IMO in 1989 and is now operating a Lennartz sensor with a corner frequency of 5 Hz. These instruments detect ground motion in the vicinity of the volcano (earthquakes and tremor related to both tectonic and volcanic activity). The data are collected in real-time at a rate of 100 samples per second (SPS). IMO is receiving (when operational) a stream from one of the stations in the array on top of Hekla. DIAS presently sample only two of these stations at 100 SPS and intend to change them all to 200 SPS. When this occurs the data stream will need to be down-sampled, to be used in the current IMO automatic analysis.

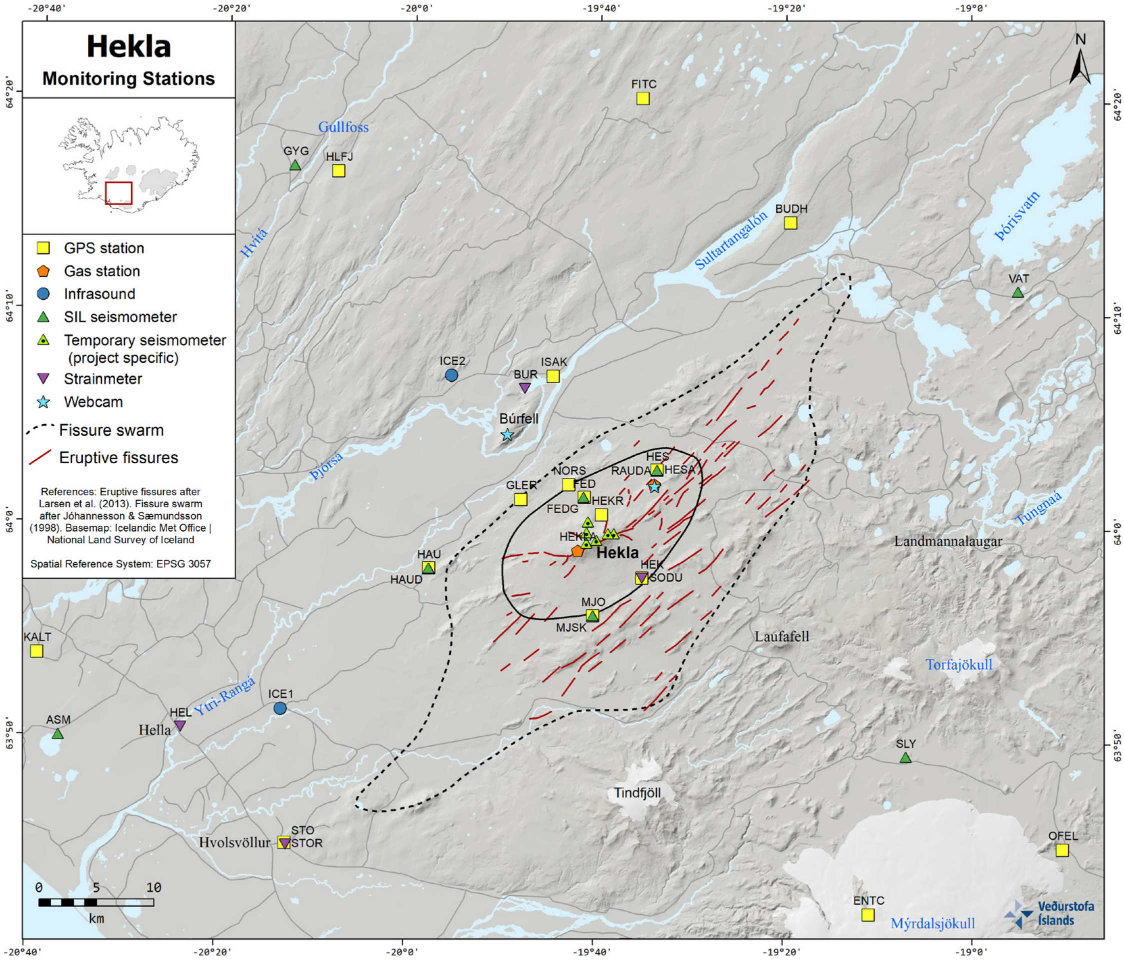


Figure 7. Overview of the current monitoring network of Hekla volcano.

3.2 Continuous GPS (cGPS) stations

The Hekla cGPS network comprises 7 stations within a 15 km radius and an additional 2 stations within 30 km. No stations within 10 km are owned by IMO, but access to the data is guaranteed. These instruments measure both horizontal and vertical ground displacements. The current data streaming and processing strategy provides daily solutions (i.e. one measurement per day) with plots updated around 10:00 GMT the following morning.

All GPS stations collect and stream raw data from the GNSS receivers to IMO. On site we collect 15-second data, which is downloaded daily for processing average coordinates for 24-hour periods. Every morning, the coordinates are estimated for the last 24 hours and the long- and short-term changes are analysed for detecting potential changes in deformation (http://brunnur.vedur.is/gps/hekla.html). These time series give the best estimate of any long-medium- term changes around volcanoes. Current ongoing work is being done to establish real-time processing aimed at early warning triggering. All the components for this processing strategy are ready, however it is currently not implemented. This should be achieved within the next 12–24 months. All stations stream raw 1Hz data to IMO and are ready for being tapped for real-time processing. As a backup and for archiving purposes all 1 Hz data are also stored on site and downloaded every hour in order to ensure full data recovery, as real-time streams are prone to data gaps. In addition, for the newer types of instruments, we collect >=20 Hz data, in order to use for post event research (for large earthquakes and/or eruptions). These very high rate data are also very high in terms of volume and data storage requirements and as such are only collected for large events. Unfortunately, the Hekla GNSS network is becoming old and outdated (in terms of the GPS receivers) thus only a fraction of the Hekla network has the capability of collecting these very high rate data.

3.3 Bore-hole strainmeters

Hekla's borehole strainmeter network comprises four Sacks-Evertson dilatometers. The instruments were provided and installed by the Carnegie Institution of Washington, in collaboration with IMO. The network was established to record crustal deformation caused by strong earthquakes in south-west Iceland, but it has proven to be more useful for volcano monitoring as it has observed strain changes prior to and during eruptions of Hekla. Analysis of borehole strain data from the 2000 eruption reveals a deviated signal at station BUR, more than 20 minutes prior to the eruption (Sturkell et al., 2013). Such measurements enabled IMO to issue a public warning shortly before the eruption onset (see Table 5). The warning time quoted in Table 5 reflects the time since the first precursory activity for IMO to issue a warning, however it should be noted that the University of Iceland issued an earlier warning 18 minutes after the first earthquake was detected.

3.4 Gas sensors (MultiGAS and DOAS)

There are two different kinds of gas instruments used to monitor Hekla today. Differential Optical Absorption Spectroscopy (DOAS) is a ground-based remote sensing technique that measures the amount of SO_2 in the atmosphere, and in conjunction with meteorological models, can provide the emission rate of SO_2. At the Icelandic volcanoes, very little SO_2 is emitted into the atmosphere in between times of volcanic unrest, as most of the SO_2 is removed from the volcanic gas by interaction with rocks and water before the gases can reach the surface. The DOAS system at Hekla was developed to exploit this, as the presence of elevated SO_2, can be an early warning sign that there has been a change in the volcanic system and an eruption may be imminent. DOAS operates continuously, however only during daylight hours. Figure 8 shows how the number of hours per day that DOAS instrument is able to measure SO_2 in the atmosphere changes over the course of the year, with a minimum of about four hours in winter to a maximum of about twenty hours in summer. The FUTUREVOLC project (European volcanological supersite in Iceland: a monitoring system and network for the future, a project funded by the FP7 Environment Programme of the European Commission 2012–2016, https://futurevolc.hi.is/) enabled the installation of the first continuous gas monitoring stations in Iceland at Hekla (Ilyinskaya et al., 2015; Di Napoli et al., 2016). In March 2013, two continuous scanning DOAS were installed to monitor Hekla, one at Rauðaskál and one at Feðgar. Currently only the Rauðaskál site is operational as the Feðgar site was discontinued due to insufficient wind power. A grant from the Nordic Council of Ministers Luft og Klima group was used to maintain the DOAS instruments at Hekla from the end of FUTUREVOLC until January 2019. The current permanent DOAS system at Rauðaskál, Hekla comprises two spectrometers and a webcam. One spectrometer has a fixed field of view, which is optimized for detecting the initial presence of SO_2 (pre-eruptive monitoring) and one spectrometer is continually scanning the sky, which is optimized for calculating the emission rate of SO_2 (co-eruptive monitoring). We also have two ready-to-be-deployed DOAS systems that could be rapidly installed on Hekla, or any other Icelandic volcano, if there are signs of unrest.

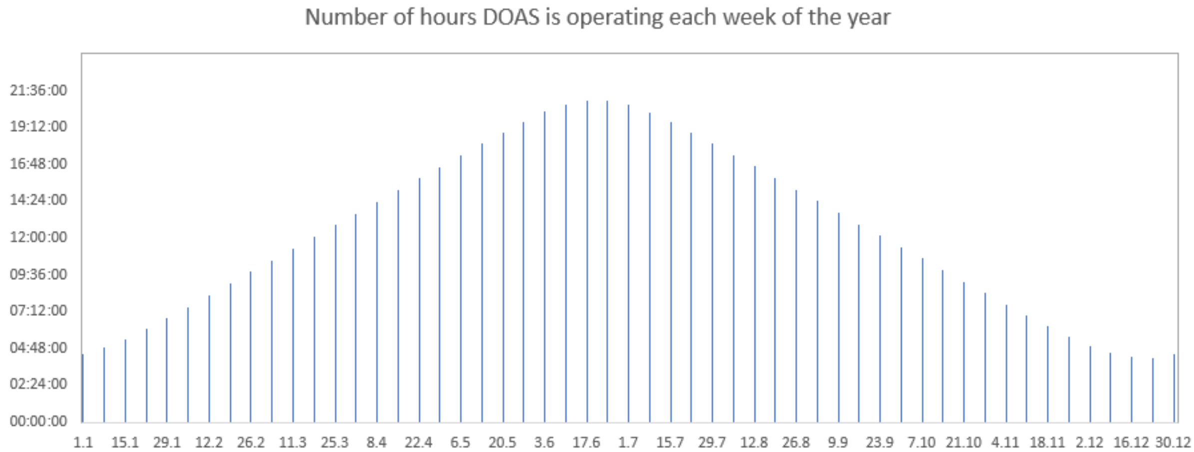


Figure 8. The number of hours for each day the DOAS can measure SO_2 in the atmosphere for each week of the year based on sunrise and sunset times.

The second kind of geochemical monitoring instrument on Hekla is the MultiGAS. This is an in-situ instrument that uses a pump to pull air samples through a series of gas detectors to provide the concentration of CO_2, SO_2, H_2S, and H_2 in the air sample. It also measures relative humidity and temperature from which H_2O is calculated. The first MultiGAS was installed on the summit of Hekla in April 2013 within the FUTUREVOLC project. Since the end of this project the IMO institutional budget has been maintaining the MultiGAS. It is extremely challenging to maintain any continuous instrumentation on top of Hekla, and we have been continually improving the system. The system relies on solar panels, which ice over within minutes in the winter due to the steam coming up through the ground (the same steam that we are measuring for gases). As a result of power limitations, we have been running the system four times a day in summer and two times a day in winter. Each sample comprises about one hour of data, so this means the MultiGAS is collecting data for two or four hours per day (two in winter, four in summer). A new development of the MultiGAS was installed in April 2019, which will consume less power and have a significantly larger battery bank. As a result of these improvements, the instrument may provide more frequent measurements, but this will only be determined as the year progresses.

Figure 9. A view of the summit of Hekla volcano as seen by webcams at Burfell (left) and Rauðaskál (right) on the 15 March 2019, at 12:30 pm and 12:28 pm respectively.

All the geochemical data are available for viewing on a public website, http://brunnur.vedur.is/gas/hekla.html, and are displayed in the monitoring room at IMO. Checking the geochemical data is part of the daily duty of the day-shift of the natural hazard specialists.

3.5 Visible light web-cams

There are currently two operational web-cams run by IMO both located on the NNW side of the volcano (Figure 9). One is in Burfell and provides an image every 10 minutes. The second one is located in Rauðaskál (co-located with the DOAS) and provides an image approximately every 15 minutes. Both cameras have a view toward the summit of the volcano. The current images are not calibrated therefore it is currently not possible to extract any quantitative information from the images (e.g. plume height estimates). In case of an eruption the images will be used for determining location, onset or confirmation of an ongoing eruption and possibly to obtain a qualitative description of the size and type of the eruption.

3.6 Infrasound detectors

Four infrasound arrays are currently installed in Iceland for volcano monitoring purposes. The installation and the data processing have been possible thanks to the FUTUREVOLC project and the collaboration with the University of Florence (UF) (Italy). The real-time data are streamed to both IMO and UF and are visible on the web-page maintained by the latter at: http://lgs.geo.unifi.it/index.php/monitoring/volcanoes/hekla. For a rapid detection of the onset of an eruption in Iceland, the target volcano should be within a distance of 80 km from the arrays. This would allow the detection of direct acoustic arrivals. In addition, two independent detections from two arrays are needed to achieve an optimal infrasonic monitoring network. Hekla is "seen" by two arrays located respectively at 30 km (ISL array) and 19 km (ICE2 array) from the volcano. With this setup the onset of an eruption could *potentially* be detected with a maximum delay of 2.5 minutes (this estimate includes the propagation of acoustic waves in the atmosphere and the time required for data processing).

3.7 Monitoring level 3 minimum requirements

Hekla has been assessed to belong to the highest-ranking category (Monitoring Level 3) as explained in Section 2.1. The monitoring requirements, needed to adequately monitor the volcanoes belonging to this category, have been recently defined by a dedicated team at IMO. Table 6 outlines the criteria for the minimum monitoring network needed and the color code in the bottom row reflects the current monitoring status for Hekla (where green indicates that the required monitoring level has been satisfied). The results of this analysis indicate, that given the current number, type and installation distances/orientation of the different instrumentation around Hekla, the current level of monitoring satisfies the minimum requirement.

Table 6. Minimum monitoring requirement for volcanoes belonging to the Monitoring Level 3. The number of instruments and the optimal installation distance depends on the type of the sensors and the purpose of the monitoring.

Type of instrument	**Seismic**	**cGPS**	**Strain**	**Gas**	**Visual cameras**	**Infrasound**
Minimum monitoring requirement	*1 station within 10 km* *3 stations within 20 km* *8 stations within 50 km*	*3 GPS within 10 km* *6 GPS within 30 km*	*3 strain-meters*	*2 continuous subaerial gas sensors*	*2*	*2*
Status for Hekla volcano (*stations*)	*(FED, MJO, HES, HAU, HRA, SLY, SMJ, BAS, SAU, MID, ENT, GOD, GYG, VAT, ASO, AUS)*	*(FEDG, SODU, NORS, MJSK, HESA, GLER)*	*(BUR, HEK, STO, HEL)*	*DOAS at Ruadaskál, MultiGas on summit*	*Burfell, Rauðaskál*	*ICE1 (Gunnarsholt), ICE2 (Þjórsárdalur)*

4 Reliability of the monitoring system

An analysis has been performed between the period 01.01.2016–31.12.2018 to estimate how often the monitoring system (both data transmission and data processing) has been fully up and running and to quantify the amount of time the system would have been considered not reliable enough for the detection of precursors at Hekla. A summary of the results is displayed in Table 7 (same as Table 1 in the Executive Summary).

Table 7. Overview of the current early warning capability for Hekla volcano in place at IMO, evaluated for the time period 2016–2018.

	Data availability		Data interpretation		Communication
	Network setup	**Downtime (data not available in monitoring room)**	**Delay in data visualization (for automatic data processing)**	**Automatic early warning**	**Protocols**
Seismic	OK	0.02% (four closest stations)	Seconds	Operational, but requires additional modifications	Operator activates phone calls and SMS (SMS does not include aviation end-users)
cGPS	OK	0.10% (six closest stations)	24-hours	Not existing, but possible	
Strainmeter	OK	0%	10 minutes	Not existing, but possible	
Geochemical	OK	0%	30 min – 22 hours	Not existing, but in development	

4.1 The seismic network

This analysis has been done by looking into the data availability from the four closest permanent seismic stations around Hekla. The results are summarized in Figure 10, where the histogram shows the percentage (over the three years) of down-time for the four stations.

On percentage:

- FED (3.7 km from Hekla summit) has been out for more than 30 minutes during 9.3% of the time (as calculated from 01.01.2016 until 31.12.2018
- MJO (6.9 km) has been out for more than 30 minutes during 6.4% of the time.
- HES (7.5 km) has been out for more than 30 minutes during 2.4% of the time.
- HAU (15.3 km) has been out for more than 30 minutes during 1.5% of the time.

In order to evaluate the redundancy of the system a first order analysis would be to assess how often the failure of equipment or data streaming was occurring simultaneously at these 4 stations, as this would affect IMO’s ability to detect earthquakes at Hekla <M1.0, as well as their location. On some occasions all four stations have been out for more than 30 minutes, all at the same time. Four days have been identified when this occurred (Table 8). In fact, during these periods the entire IMO seismic network was down. This means that no precursory earthquakes would have been detected during these times. The overall downtime (in hours) corresponds to a percentage of 0.02% (considering the time period 01.01.2016–31.12.2018).

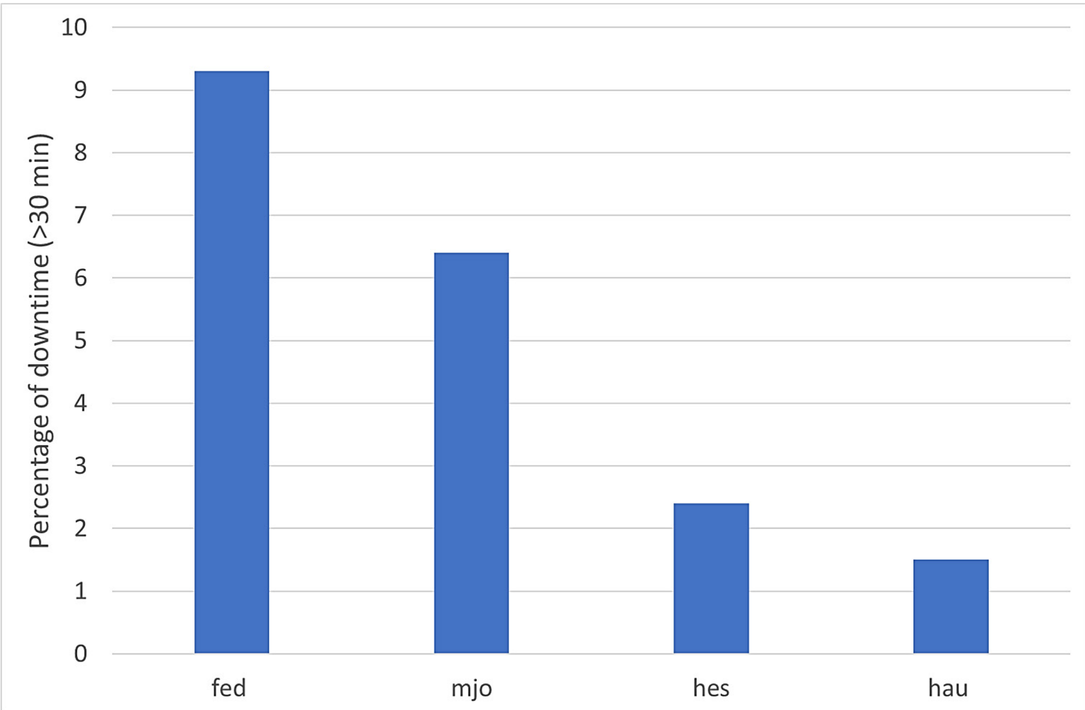


Figure 10. Histogram displaying the percentage of down-time longer than 30 minutes at the four closest seismic stations around Hekla.

Table 8. List of the days during which all four closest seismic stations around Hekla have been out all at the same time for more than 30 minutes.

Date	All four seismic stations out at the same time	Down-time	Cause of failure
25/12/2016	FED, MJO, HAU, HES	1 hour	Internal disk crash
2/3/2017	FED, MJO, HAU, HES	2.4 hours	Internal disk crash
3/5/2017	FED, MJO, HAU, HES	0.6 hours	Internal disk crash
13/8/2018	FED, MJO, HAU, HES	1.1 hours	Internal issues (DNS updates in July 2018)

The three outages occurring on the 25/12/2016, 2/3/2017 and 3/5/2017 were all related to a disk crash on NAM1 (this receives the seismic data streamed from the field stations). At the same time the backup system NAM2 did not start automatically. On the 13/8/2018 the cause was still an internal issue linked to an update done on the DNS in July 2018. In the event of disk failure on NAM1, NAM2 is in place as a backup, but has to be started manually (to receive and transfer the seismic data). This did not occur seamlessly during the abovementioned outages. The system should be modified such that NAM2 automatically starts receiving and transferring the seismic data in the event of disk failure on NAM1.

4.2 cGPS network

The cGPS network status is monitored through the Grafana system. The analysis of data acquired during the time period 01.01.2016–31.12.2018 (displayed in Table 9), shows that the downtime for the receivers spans between 2% and 24% (for the eight closest stations located within 15 km from the Hekla summit). An analysis was also done for two key stations in the far field (Table 10). The downtime for these stations is between 1 and 69%.

Table 9. Overview of downtime for the cGPS stations within 15 km from Hekla volcano.

Station (distance in km) - NEAR FIELD	Downtime over three years (router)	Downtime over three years (router + receiver)
FEDG (3.7)	7%	8%
SODU (5.0)	21%	24%
NORS (5.3)	13%	16%
MJSK (6.9)	13%	15%
HESA (7.5)	6%	7%
GLER (7.7)	6%	8%
ISAK (14.5)	1.19%	4%
HAUD (15.3)	1.75%	1.88%

Table 10. Overview of downtime for two cGPS stations in the far field for monitoring Hekla volcano.

Station (distance in km) - FAR FIELD	Downtime over three years (router)	Downtime over three years (router + receiver)
BUDH (31.8)	52%	69%
STOR (38.4)	1.14%	1.14%

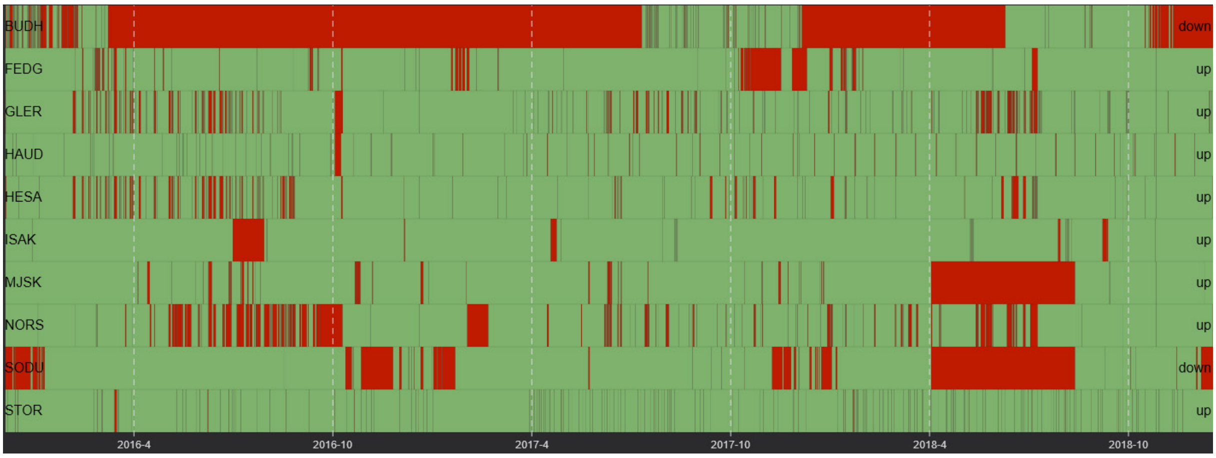


Figure 11. Graph produced by Grafana for all the cGPS stations considered in this report. The graph shows the downtime (red areas) and the uptime (green areas).

At no time during the observation period were all the near- or far-field stations not functional at the same time. However, there was a period in July 2018 (Figure 11) when the six closest stations were not operational at the same time, for a period of 27 hours in total. This was the result of a number of different unrelated reasons at different sites, including communication disruptions and problems with infrastructure. In addition, the far-field station BUDH was not operational for 69% of the time during the analysed period. This was primarily the result of an old malfunctioning Trimble NetRS receiver (from 2005) which has since been replaced.

4.3 Strainmeter network

The data from the four strainmeters within the Hekla network were also analysed over a similar time period. Stations BUR and HEK are those considered to be the most critical. Given their proximity to the volcano edifice, they are considered to be more sensitive to changes in the volcanic system in the event of magma migration prior to an eruption. The results are summarised in Table 11.

Table 11. Overview of the downtime for the four strainmeters closest to Hekla volcano over the period 01.01.2016–01.11.2018.

	BUR	HEK	HEL	STO
Hours of downtime	2528	616	4980	3891
Percentage down-time	10.2%	2.5%	20.0%	15.7%

The downtime has been estimated by checking the completeness of the daily file size, as shown Figure 12. These data are transferred in Seismic Analysis Code (SAC) format. On no occasions, were the two stations closest to Hekla not operational at the same time.

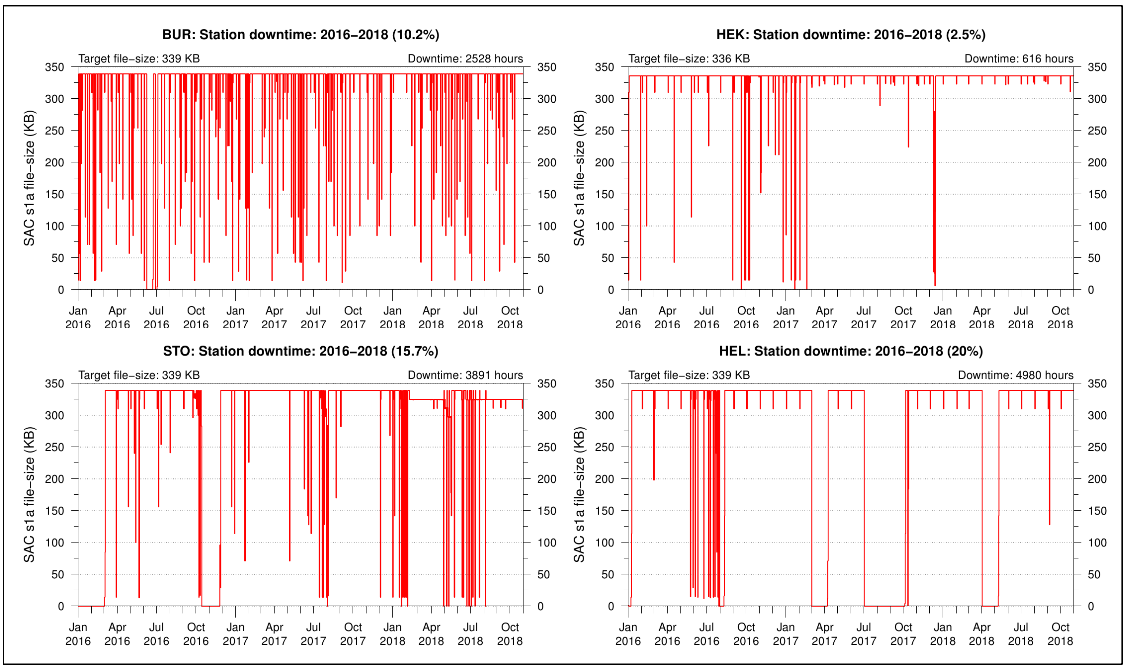


Figure 12. Downtime for the strainmeter stations for the period 01.01.2016–01.11.2018 expressed as completeness of the daily SAC file size. A complete file is represented by a horizontal flat red line with a file size of 339 KB, whereas missing data are represented by the vertical red lines.

4.4 Geo-chemical network

The analysis of downtime for the DOAS system at Rauðaskál is displayed in Figure 13. This shows the dates when there were no DOAS retrievals, either by the fixed field of view spectrometer, or the scanning spectrometer, which is turned on when the fixed field of view spectrometer fails. The results indicate that for 1% of the recording period (between 01.01.2016 – 31.12.2018) no data was received. However, this instrument varies from the geophysical instruments, because it is only possible to collect data during sunlight hours, so this is not a percentage of time, but rather a percentage of the possible recording period when daylight permits observations.

The analysis of downtime for the MultiGAS at the summit is displayed in Figure 14. This shows dates when there were no measurements. This reveals that the MultiGAS system was down for 36% of the recording period between 01.01.2016 – 31.12.2018. Similarly to the DOAS there are restrictions on the operational recording time of the MultiGAS. The instrument is only acquiring data for approximately two hours per day in winter and four hours per day in summer.

Downtime for the MultiGAS instrument is usually due to insufficient power over the winter months, due to icing of the solar panels. However, the MultiGAS was down from June 2018 – April 2019 due to a combination of instrument failure due to its age and persistently poor weather, therefore the impossibility of reaching the summit to diagnose the problem. The motherboard broke in June 2018 and could not be retrieved or diagnosed until August 2018. A new instrument was ordered and paid for by IMO funding, however the instrument was not installed until April 2019 when there was a sufficiently good weather window to undertake the installation.

During the time period analysed, data was acquired by at least one of the two geochemical monitoring instruments, although as previously mentioned, these instruments are not recording (or streaming) continuous measurements throughout the day.

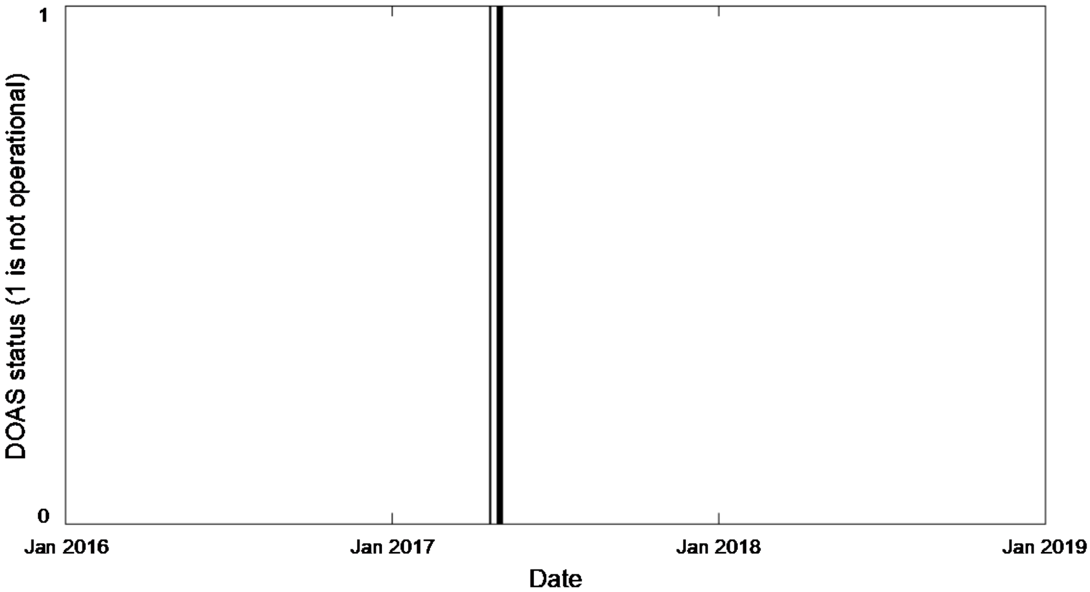


Figure 13. Dates when there were no DOAS retrievals between 01.01.2016-31.12.2018.

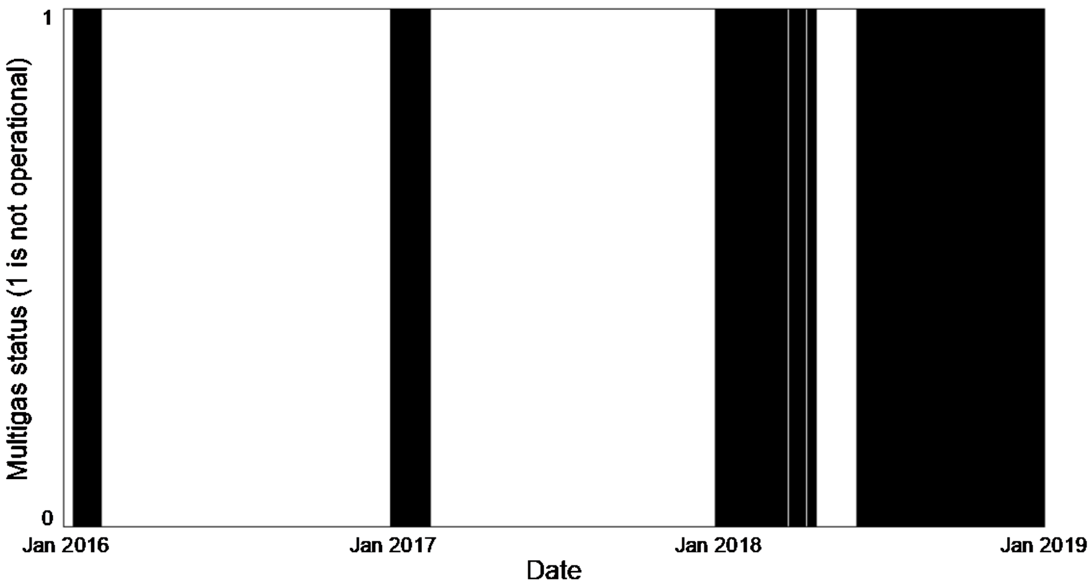


Figure 14. Dates when there were no MultiGAS measurements between 01.01.2016–31.12.2018. The continuous vertical black areas represent the period over which no data were available at IMO.

4.5 Data transmission vulnerabilities

The main aim of IMO's data transmission policies is to facilitate secure and reliable, real time data transfer. With modern mobile connections this is becoming a feasible objective for most of IMO's monitoring networks. Although the mobile system enables reliable, secure real-time data streams, such a large reliance on this single system, also introduces vulnerabilities.

Currently the majority of IMO's data connections utilize the mobile system. Other systems in use are landline connections where possible, and in a few cases direct radio links.

The high reliance on the mobile system poses a serious vulnerability. If this system fails in part or completely, IMO will lose access to the affected stations, and may in some monitoring areas loose access to all stations in a specific region. In addition, the mobile system's reliability is completely out of IMO's control, as private companies manage its operation with limited responsibilities regarding civil protection. It would thus be prudent to reduce the dependence on this system, however there are no easy alternatives. This is the only widespread infrastructure in place and building an alternative system or utilizing satellite connections (which introduce another set of vulnerabilities), would be very expensive.

The dependence of the monitoring network at Hekla, is to a large extent relying on the mobile system (Table 12). Overall, 70% of the Hekla network is dependent on this. The strainmeter network has the lowest dependency with 50% of the instruments using the mobile network for data transfer, followed by the seismic (at 60% dependency) and the cGPS network (70% dependency). The gas network is fully dependent on the mobile network for transferring data making this data stream the most vulnerable to disruptions in the mobile network. In addition, a critical point of weakness is the Síminn telecommunications hub in Breiðholt through which three seismic stations, two strainmeters (BUR and HEL), 7 of the cGPS stations and both the MultiGAS and DOAS instruments transmit data.

Table 12. Dependency of Hekla monitoring network on the mobile 3G/4G system.

	Total # of stations (on 3G/4G)	Percentages of stations on 3G/4G
Seismic	4 (3)	75%
GPS	10 (7)	70%
Strain	4 (2)	50%
Geochemical	2 (2)	100%
Total	20 (14)	70%

5 Automatic alert system in place for Hekla

Presently, the only automatic alert system in place is based on seismicity.

5.1 Automatic seismic data processing

The current warning system is based on the number and magnitude of earthquakes automatically detected and calculated within a specific area encompassing the volcano over the last 24 hours. Thresholds have been defined by considering the background condition at each single volcano and the unrest phases experienced in the past. The alert system relies on five levels and, for Hekla volcano, it is currently defined by the parameters displayed in Table 13, based on the local magnitude of individual earthquakes (MAGNITUDE), the number of earthquakes within a time interval (NUMEROFREQ), a dimensionless measure of moment release during the same time interval (STRAINRATE), a time-weighted measure of the number of events (NUMBERWEI) and a time-weighted measure of accumulated moment release (STRAINWEI). This criteria needs to be re-evaluated following changes to the seismic network.

Table 13. Criteria established to trigger an automatic warning for the Hekla volcano.

	Level 1	Level 2	Level 3	Level 4	Level 5
MAGNITUDE	0.1	0.1	1.0	1.5	2.5
NUMEROFEQ	0.1	0.1	1	2	3
STRAINRATE	1.0e+04	5.0e+04	1.0e+05	5.0e+05	1.0e+07
NUMBERWEI	28	40	58	100	200
STRAINWEI	5.0e+05	1.0e+06	5.0e+06	1.0e+07	200

So for example, an alert level 4 is triggered if the magnitude of the earthquakes (M) >= 1.5 or the number of earthquakes (NE) is >=2 during the last 24 hours. A level 5 warning is triggered if M >=2.5 or NE >= 3 during the last 24 hours. Different levels trigger different warnings. The automatic system is capable of sending emails and SMS with the warning messages, however the audio-warning, intended to alert the person on duty in the monitoring room at IMO, is considered the most important alert. Today, with the 24/7 monitoring, the warnings are broadcasted in the monitoring room as audio warnings. The audio warning system is tested daily at 11 am. It is a part of the daily routine check-list of the natural hazard specialist on duty, to make sure that the 11 am audio warning test is working.

Figure 15, displays how many times since 2005 the different warning levels have been triggered for Hekla, based on the different parameters considered. A general increase in the number of the triggered alerts is evident (mainly type 2 and 3 – green and yellow dots) since 2012 when two key seismic stations (MJO and FED) were installed. These two additional stations allowed the minimum detectable earthquake size to be lowered, resulting in an increase of warnings due to the number of small, detected earthquakes. In addition, in late 2016 the station HES was installed and this has likely further enhanced the networks capability to measure more earthquakes.

These plots indicate that the seismic (SIL-based) warning system has been working regularly for several years and can be considered reliable in its functionality.

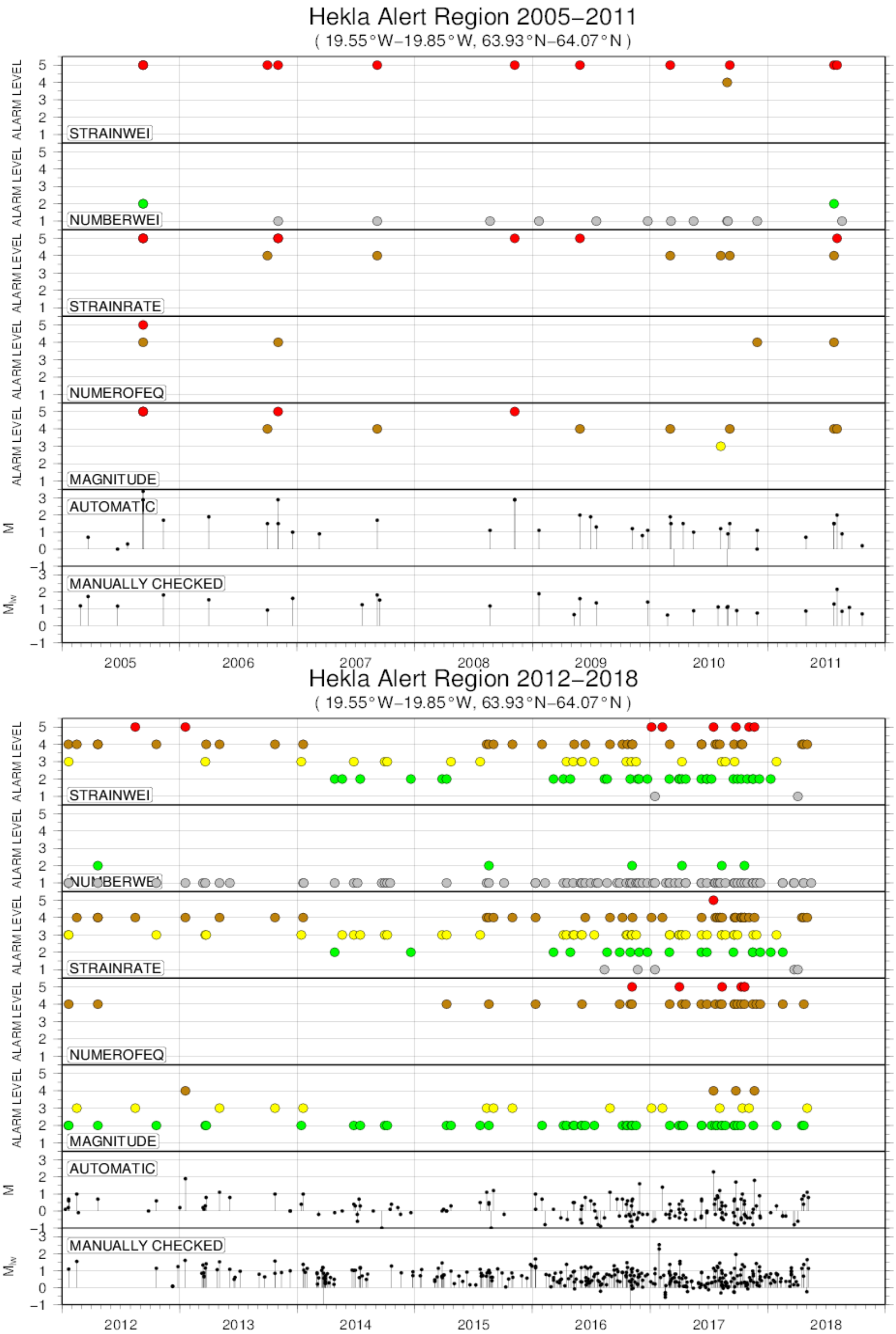


Figure 15. Temporal overview (2005–2018) of the numbers and types of alerts triggered based on the seismic activity at Hekla. The grey dots correspond to level 1, green to level 2, yellow to level 3, brown to level 4 and red to level 5.

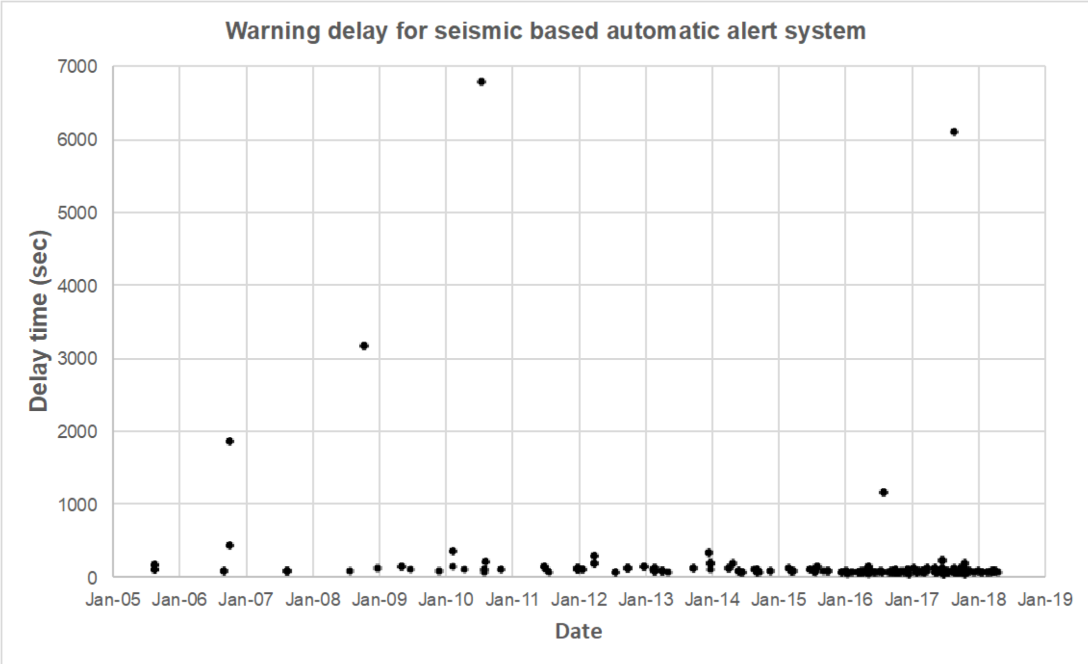


Figure 16. Warning delay time for seismic based automatic alert system.

The plot displayed in Figure 16 summarizes the amount of time taken between the triggering earthquake and the warning being issued (emails, SMS and/or audio). On average the delay time is approximately 3 minutes, however, there have been instances where the warning time was significantly longer e.g. once on the 8/8/2010 the time delay was 1.8 hours and more recently on the 20/9/2017, when the delay time was 1.69 hours. In this most recent example, the data were received in house, however there was a problem with the data phase-logs that prevented automatic earthquake detection and consequently activation of the alert, thus the audio warning was not triggered in the monitoring room.

5.2 cGPS network

No automatic alert system is in place at present based on GPS data. However, this could be possible once the real-time data processing is implemented.

5.3 Strainmeter network

No automatic alert system is currently in place based on the analysis of strain data. However, strain data are streamed in near real-time to the monitoring room at IMO, so deviations in strain-rate at key sites can be observed (e.g. at stations HEK and BUR). The setup of an automatic alert system based on strain measurements is possible and is outlined in section 7.

5.4 Geo-chemical network

Work is ongoing to set up an automatic email alert if gas concentration thresholds, measured by the MultiGAS instrument, are exceeded. Following this, a similar alert will be setup for the DOAS system.

6 Communication protocols between IMO and aviation stakeholders

The monitoring room at IMO is manned 24 hours a day by specialists on duty (four during day-time working hours and two during the night). The specialists comprise both meteorologists and natural hazards specialists. In case of an imminent eruption the specialists on duty at IMO, follow contingency plans. It is the responsibility of the meteorologist to inform the aviation stakeholders (i.e. Isavia and London VAAC) by a phone call as a first action. During this first phone call essential information including: the name of the volcano, its ICAO identification number, the current aviation color code, the current ongoing activity and the estimated plume height (based on past eruptions if the eruption has still not started) are provided. Shortly after, a Sigmet (Significant Meteorological event) is issued by IMO.

These actions are practiced regularly, almost every month, during the VOLCICE exercises. By checking the log of the exercises it was possible to estimate the time needed to call Isavia, since the unrest is declared and the contingency plans are activated, this delay is typically between 2 to 6 minutes.

It is possible to evaluate the delay in forwarding the alert to Isavia by looking into different scenarios to estimate how much time it would take for the specialist on duty to react to unusual behavior at Hekla volcano. Here we have considered the best-case scenario, i.e. the unrest starting during normal working hours (Tables 14 and 15). The timeline displayed in Table 14 has been calculated considering the shortest delays in detecting specific geophysical precursors during historical eruptions. The timeline displayed in Table 15 has been calculated considering the longest delays in detecting specific geophysical precursors during historical eruptions. For the strainmeter detection we have added an additional 10 minutes due to the current operational delay in data processing/visualization.

In both scenarios the assumption is two-fold: 1) that the monitoring system as designed today will be 100% operational and 2) that volcano will display pre-eruptive unrest signals that will trigger geophysical signals detectable by the present-day monitoring network. It is possible that the volcano may not display any detectable precursory signals prior to the next eruption. In this event it will not be possible for IMO to issue a pre-eruptive warning.

Table 14. Hypothetical timeline for internal communications, considering the shortest delays observed in detecting precursors during previous eruptions. The assumption is that the entire monitoring system is up and running and that the volcano displays precursory signals before the onset of the eruption.

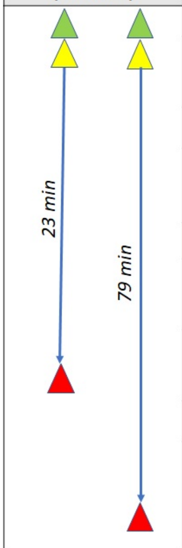
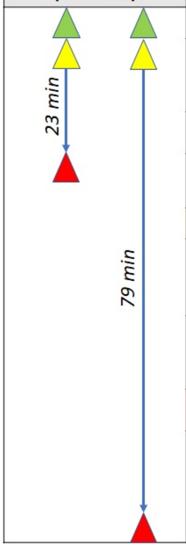
Volcano timeline (unknown)	Time	Observation	Actions
 		Background level	Normal monitoring
	T0	First unusual seismic detection (either earthquakes or tremor)	Person on duty double checks the seismic data, checks other monitoring data, and consults with other specialists in-house
	T0+3 min		Automatic alert in the monitoring room
	T0+16 min (as in 1991)	Strainmeter indicates deviations confirming unusual events at Hekla	Automatic alert in the monitoring room
	T0+18 min		Initial phone call to ISAVIA and Civil Protection for pre-alerting
	T0+20 min (as in 2000)	Tremor detected at several stations	Activation of contingency plans (VÁE-031)
	T0+22 min	All data confirm a general trend suggesting an imminent eruption	Meteorologist on duty activates her/his contingency plan (VÁE-005)
	T0+24 min		Phone call to ISAVIA and Civil Protection

Table 15. Hypothetical timeline for internal communications, considering the longest delays observed in detecting precursors during previous eruptions. The assumption is that the entire monitoring system is up and running and that the volcano displays precursory signals before the onset of the eruption.

Volcano timeline (unknown)	Time	Observation	Actions
 		Background level	Normal monitoring
	T0	First unusual seismic detection (either earthquakes or tremor)	Person on duty double checks the seismic data, checks other monitoring data, and consults with other specialists in-house
	T0+3 min		Automatic alert in the monitoring room
	T0+32 min (as in 1991)	Tremor detected at several stations	Automatic alert in the monitoring room
	T0+34 min		Initial phone call to ISAVIA and Civil Protection for pre-alerting
	T0+45 min (as in 2000)	Strainmeter indicates deviations confirming unusual events at Hekla	Activation of contingency plans (VÁE-031)
	T0+47 min	All data confirm a general trend suggesting an imminent eruption	Meteorologist on duty activates her/his contingency plan (VÁE-005)
	T0+53 min		Phone call to ISAVIA and Civil Protection

The analysis reveals that in the best-case scenario the current procedures and monitoring system in place might enable a first pre-warning to be issued (via a phone call) between 18–34 minutes after the first detection of unusual seismicity at Hekla (orange cells). This scenario suggests that a final alert would be triggered between 24–53 minutes after the first detected signal of unrest (red cells). This would represent the minimum amount of time required prior to the alert being triggered and this number should be put into the context of the volcano timeline, i.e. the time passed from the beginning of the unrest to the onset of the eruption. As in the past, this period has *varied between 23 to 79 minutes, the capability to issue a timely warning strongly depends on how distinctive the geophysical signals produced by the magmatic processes are and how quickly magma rises through the conduit to the surface*. **In the event that the volcano does not provide any precursory signals (i.e. the eruption starts at T=0 min), it will not be possible to issue a pre-eruptive warning.**

In this hypothetical exercise, if the process of magma migration to the surface is quicker than 24 minutes prior to the next eruption at Hekla, there will be no timely warning issued by IMO to support the safety of aviation operations, nor any other mitigation actions operated by Civil Protection.

7 Recommendations to improve early warning system at Hekla volcano

Hekla volcano has demonstrated a very short precursory period, so it is valuable to assess if there are possibilities to improve monitoring at Hekla with new instruments and/or process/analyse the existing data with new methods or algorithms, in order to potentially increase the pre-eruptive warning time.

7.1 Seismicity

The University of Iceland (UI) and IMO were awarded a Rannís Infrastructure grant in 2018 to install a seismic array around the seismic station MJO including 6 broad-band (BB) sensors from DIAS and 5–7 new Raspberry Pi (RP) sensors. These should start to stream data in the summer of 2019 as part of EUROVOLC (European catalogue of Volcanoes, a Horizon 2020 project ID: 731070, funded by the European Union, https://eurovolc.eu/) WP9. The main aim of this array is to detect magma migration from deep within the crust moving towards the surface – movement within a deep channel and also that associated with dike emplacement.

An additional 3 year Rannís funded project grant (IS-NOISE, http://is-noise.earth/) that commenced in 2018, will analyse changes in seismic velocity at Hekla for identifying precursors tof volcanic eruptions. The Hekla seismic network is dense enough in the vicinity of the edifice to compute robust seismic velocity variations and compare them with available parameters to potentially forecast a future volcanic eruption. Similar work has been undertaken at Piton de la Fournaise (La Réunion, France: Brenguier et al., 2008) and Colima (Mexico: Lamb et al., 2017).

During the next few years, it is planned to undertake all the necessary actions required to implement SeisComP software for the detection and the processing of seismic events. This system is widely used internationally at different institutions in charge of monitoring the level of seismicity and triggering alerts based on automatic detection. This will simplify the automatic processing of earthquakes and the determination of their magnitude (once properly tuned). Existing modules will be implemented which are designed to trigger automatic warnings via email, SMS and encrypted messages.

In order to improve the system, it is important to take the necessary steps to make the automatic processing of the seismic system more robust. In particular, in the event of NAM1 disk failure, that NAM2 backup disk replaces it automatically.

7.2 cGPS and tilt measurements

Track processing of cGPS observations

It is planned to setup a GPS early warning system within the next 12–24 months based on data processing utilizing Track software (Grapenthin, 2014a and 2014b) modified for volcano deformation monitoring. This could allow real-time deformation analysis and early warning triggering. Unfortunately, the installation of new equipment at each of the existing near-field cGPS stations, will be required to ensure the long-term success of this system. Currently, no

GPS instruments located around Hekla (within 10 km) are owned by IMO. All of the instruments were installed by Peter La Femina (Penn State) through a National Science Foundation (NSF) grant and the existing equipment is old and in need of replacement.

Real-time high-rate (≥1 Hz) processing of GNSS and other geodetic data (e.g., tilt) will be implemented in order to develop a geodetic based early warning for volcanic eruptions. Analysis of deformation observations acquired during the 2011 at Grímsvötn volcano indicates that warning times on the order of 1 hour, are feasible for this particular volcano. High-rate processing of GPS and tilt data during the 2011 eruption at Grímsvötn revealed that the onset of deformation preceded the eruption by an hour (Hreinsdóttir et al., 2014).

The Berkeley Seismological Laboratory (UC Berkeley), in collaboration with New Mexico Tech, implemented the Geodetic Alarm System (G-larmS) to include real-time GPS data into an operational earthquake early warning system (EEW, Grapenthin et al., 2014a and 2014b). Expansion of G-larmS with application to volcanic systems is straightforward given a robust sensor network and in many ways a simpler problem than EEW. Solving the inverse problem every 1-5 minutes should be sufficient for alerting and forecasting, provided any precursory deformation signal occurs and is large enough to be detected.

Tilt measurements

Electronic tiltmeters are high precision instruments capable of recording continuous tilt measurements with a high temporal resolution. The apparatus consists of a glass vial containing a bubble immersed in a conducting fluid (Westphal et al., 1983). Ground displacements result in a shift in the location of the bubble with respect to two electrodes. This shift produces an electric current which is amplified and converted to a tilt measurement in microradians. Due to their sensitivity to changes in temperature and pressure they are often installed in boreholes on the flanks of volcanoes. Tiltmeters have recorded remarkable deformation measurements at a series of volcanoes providing insight into diverse volcanic processes, including dyke emplacement prior to the July 2001 eruption at Mt Etna (Bonaccorso et al., 2002), an episode of aseismic slip on the south flank of Kilauea volcano in November 2000 (Cervelli et al., 2002) and tilt cycles related to magma pressurisation at the Soufrière Hills volcano from 1996–1997 (Voight et al., 1998).

Volcano observatories often use tiltmeters, to monitor ground deformation in the vicinity of a volcano. In Iceland only one tiltmeter is currently in operation at Grímsvötn volcano, which showed valuable observations during the 2011 eruption in Grímsvötn as mentioned above. Since the 70’s, campaign tilt measurements have been undertaken each year in the vicinity of Hekla. The results showed an inflation pattern prior the last two eruptions and an on-going inflation signal is detectable since after the 2000 eruption (Sturkell et al., 2006; 2013). This suggests that a network of continuous tiltmeters may by useful as an additional data stream for detecting precursory signals related to either an increased rate of magma migration or the opening of a conduit. It is recommended that a feasibility study be undertaken to model potential tilt signals associated with these processes and to determine optimal installation site locations.

7.3 Strainmeter observations

Automated correction of strain measurements

Borehole strain measurements are influenced by local variations in atmospheric pressure and by Earth tides caused by the effect of the sun and moon on the Earth's crust. For near real-time monitoring of Hekla, uncorrected borehole readings are adequate as the scale of ground deformation immediately ahead of an eruption would be hundreds of times larger than background atmospheric and geophysical influences. However, for long-term detection of subtle deformation signals ahead of an eruption, a corrected time-series is needed. Displacements of the Earth's surface due to air-pressure changes can be accounted for using measurements from a barometer housed aboveground at each strain station. Earth tides can be predicted using various established geophysical techniques, resulting in corrections for a given location. Atmospheric and tidal corrections have been combined at IMO to produce a simple, automated procedure to eliminate extraneous signals. As mentioned previously, automated corrections will not necessarily increase the detectability of a Hekla eruption, but they will yield more accurate measurements, allowing long-term changes to be considered.

Strain-rate detector for eruption warnings

Borehole deformation is monitored at IMO using an online graph that displays the rate-of-change (ROC) for each of the five strainmeters in the network. The ROC is the speed at which borehole deformation changes over a specific interval. Prior to the onset of the next Hekla eruption, the ROC is expected to increase significantly over several minutes. In other words, the typically flat signal – indicative of no change – would transform into a steeply sloping line, with the polarity of the line defined by the location of the strainmeter relative to the source of deformation. To ensure that a pre-eruptive signal is detected as quickly as possible, an automated strain-rate detector is needed for warning purposes at IMO. A simple moving-average approach has been tested, whereby the last three minutes of measurements are compared to the last 21 minutes. If the ROC exceeds a given value, then a warning could be issued to IMO's monitoring staff. Further work is needed to calibrate the detector and to deploy it operationally. In terms of the early detection of precursory signals, the automated detector should be prioritised for development. An immediate, early warning would allow IMO staff to validate the alert with other monitoring data.

Improvements in strain-data handling

Strain data are recorded on-site at both 1 and 50 SPS. The 1 SPS data are used for monitoring purposes, whereas the 50 SPS data are archived at IMO without being visualised. Monitoring files are routinely sent from each station at three-minute intervals; all other files are sent at hourly intervals. The incoming 1 SPS data are added to a strain-rate graph, which updates every five minutes and is available online. Accounting for both the lag of the data transfer and the creation of the graph, the latest monitoring results could be eight minutes behind real-time. With computer processing time included, the delay is closer to ten minutes. There are two possibilities for reducing the delay: data-handling improvements and on-site modifications. To minimise data latency, 1 SPS files could be sent from each strain station in Seismic Analysis Code (SAC) format directly to SeisComP software on Sandur (IMO in-house server) bypassing NAM, then converted to mseed format. This would allow the files to either be incorporated into SCREAM (an acquisition and monitoring interface for seismic data from Guralp Systems) or plotted directly in the monitoring room using SeisComP plotting software. This improvement could reduce the delay to around four minutes and it is technically feasible. The second option involves hardware changes to the acquisition system at each station. Possibilities include the installation of a seismic digitiser to enable high-rate telemetry in the same way as a SIL seismic station. This solution would require extensive development work with CIW and the timescale for the modifications is unclear. Of the two solutions, it is recommended that the data-streaming option is explored first, with the aim of making improvements by December 2019.

7.4 Gas measurements

Surveillance of gas composition and flux provides insights into how volcanoes work and valuable information for assessing volcanic hazards. Variations in gas compositions are valuable elements to determine the presence of magma at shallow depth when volcanic unrest starts. Many examples exist worldwide, where SO_2 and CO_2 flux measurements, combined with seismic and deformation data, helped scientists to evaluate correctly the nature of the unrest, the state of the volcano, and to anticipate the eruption (e.g. Pinatubo 1991 (Daag et al., 1996), Redoubt 2009 (Werner et al., 2013), Merapi 2010 (Jousset et al., 2012).

Expanding our geochemical monitoring to include more frequent campaign style surveys and additional gas sensors will improve our capability to forecast volcanic eruptions and possibly will allow us to detect the shallow movement of magma when other instruments are not detecting changes or are inconclusive.

At present, two types of continuous subaerial instruments are installed at Hekla: the DOAS and MultiGAS instruments. In addition, subaerial gases are collected at Hekla once a year for analysis. The area with the highest temperature is identified using a thermocouple then gas is collected from this location into evacuated flasks. The samples are sent for lab analysis of major and minor components and isotopic analysis.

Field campaign measurements for pre-eruptive monitoring need to be undertaken regularly, to build a time series of background, non-eruptive conditions, so that changes in the system can be identified.

Radon emissions

Within a month prior to the 1980-81 eruptions at Hekla, anomalous radon spikes were observed in a time series of measurements undertaken on samples collected from a geothermal borehole at Fluðir, ~35 kilometres northwest of the volcano (Jónsson & Einarsson, 1996). A campaign style survey of radon soil-gas measurements was undertaken in summer 2018 to determine whether or not significant amounts of radon could be detected on the summit. The measurements indicated that elevated levels of radon are being emitted in the same region with the highest CO_2 emissions and that a permanent radon detector would be an option for improved early warning. A second soil gas survey is planned during the summer of 2019 to identify a potential site for the installation of a continuous radon detector, potentially on the flanks of Hekla, to avoid the challenges of operating a continuous station at the summit.

Radon has successfully been used at other volcanoes outside Iceland to detect precursory eruptive signals. At El Hierro (Canary Islands) increases in both radon and radon/thoron ratio were observed prior to the 2011–2012 submarine eruption (Padilla et al., 2013). Increases in radon were also observed during the 2011–2012 unrest at Santorini volcano (Parks et al., 2013), associated with a shallow magmatic intrusion (Parks et al., 2012). In both cases concurrent increases in CO_2 emissions were also observed. The hypothesis is that these observed increases in radon are likely related to rock fracturing processes during the intrusion/migration of magma beneath these volcanoes.

CO_2 in water instruments

Another possibility is to modify an instrument used for measuring CO_2 dissolved in fresh water. The instrument was first developed by project partners at the Palermo branch of the Istituto Nazionale di Geofisica e Vulcanologia in Italy (INGV-Palermo) in 2008. It operates successfully within human-constructed underground water drainage structures on the flank of Etna, but until now, has been fraught with environmental problems operating in Iceland.

The instrument is composed of a probe containing a conductivity and temperature sensor and a coiled PTFE membrane tube that allows dissolved gas to enter it from the water it is immersed in. Following pressure equalization, between the gas inside the tube and that dissolved in the water (approximately three hours, related to the geometry of the device and type of membrane), the gas in the PTFE tube is pumped into an infrared gas analyser (IRGA).

Two instruments have been tested in springs on the flanks of Hekla as part of the EU-funded FUTUREVOLC project for the monitoring of Hekla. The first of these Italian-designed instruments was installed in Iceland in July 2013 with the participation of both project partners from IMO and INGV-Palermo. The instrument was installed in a small spring that flows into Selsundslækur. This spring is known historically for being affected by Hekla, with spring water levels decreasing prior to eruptions. This initial installation ran for two months until larvae and algae blocked the PTFE tube and water condensation inside the box damaged the electronics. In 2014, improvements were made to the instrument. It was made more resistant to the cold by including a heater and additional insulation inside the box and by modifying the electrical board. This station ran for four months, until the blockage problems recurred. In June 2015, two instruments were installed in Selsund and Rangárbotnar, but one failed due to high voltage supply from the solar panel, so now the instruments include an electrical filter to protect the electrical boards; the second station was destroyed in a flood in spring 2016.

We propose 1) redesigning the instrument, so that it is small and responsive to water levels and can be installed in cold fresh water boreholes, 2) developing the infrastructure surrounding the instrument to give it a stable environment, and 3) digging wells next to the natural springs where the instruments would be installed so they are not vulnerable to seasonal floods, sunlight, etc. In addition to significantly modifying the instrument for reliable use in Iceland, we would also develop and implement software for retrieving and storing the data in a properly indexed database, and automate real-time data display and warnings of threshold exceedances. The final result will be an instrument with three options for installation depending on environmental conditions: 1) the current design which is suitable for stable, protected environments; 2) a more compact model that can be used in fresh water wells or boreholes; and 3) infrastructure built around the current design which allows it to be operated in remote, undeveloped locations. All of these options will utilize specialized software to facilitate real-time monitoring of the measurements. The instruments will provide one reading every four hours and near real-time display of these measurements will be monitored 24-hours/day by the natural hazards specialists on duty at IMO for the purpose of pre-eruptive volcano monitoring. Background levels of CO_2, utilizing the months of data already collected, will be used to define the thresholds that would trigger automatic alarms.

All of the gas sensors are sensitive to changes in external temperature (weather) and internal temperature as well as other factors, so that the data should be "detrended" to remove these instruments and environment-imposed signals on the data. Presently this is done manually, and work is in progress to automate this.

Soil temperature probe

A temperature probe could be installed inside the hut where the MultiGAS is installed on the summit of Hekla. This consumes very little power so it could be run continuously, and it is much simpler than gas measuring instruments thus less vulnerable to breaking down. This would provide an indirect measurement of the flux of gases reaching the summit. At Vulcano Island, strong correlations were observed between fumarolic temperatures and gas flux (Tedesco et al., 1991). At Merapi volcano, correlations were also observed between temperature variations and earthquake activity (Zimmer & Erzinger, 2003). Thus a temperature probe on the summit of Hekla may provide information indicative of changes in volcanic activity that may be precursory to an eruption.

7.5 Webcams

As part of the ICAO Joint Financing Agreement with Iceland, an additional project, "ANALYZING AND MODELLING REMOTE SENSING DATA TO IMPROVE VOLCANIC ASH DISPERSION MODELS", is planning to develop the webcam network. Hekla is one of the five target volcanoes considered in this project. Each volcano will be equipped with two more webcams for surveillance. Locations will be identified considering pre-existing infrastructure (co-location with other instrumentation) and to fulfill a geometry requirement to obtain the best view. Data from the web-cams will be processed, calibrated and tested for those volcanoes for which the potential for future and significant explosive eruptions is known, i.e. Hekla, Katla and Grímsvötn. The algorithm to estimate plume height will be developed, given the web-cams geometry and wind field. This will result in quantitative estimates of plume height from web-cams complementary to those produced regularly, each 10 minutes, by the radars. Algorithms aimed to estimate the exit velocity of the volcanic mixture will also be tested. The exit velocity assessment will help in quantifying the mass flow rate. Web-cam referenced plume heights will be available in the monitoring room. The web-cam derived plume height estimations will be processed in a similar way as the radar data via the Volcanic Eruption Source Parameter Assessment (VESPA, brunnur.vedur.is/radar/vespa) system to provide additional constraints to the eruption mass flow rate computation.

7.6 Infrasound

Within the same project mentioned in the previous section, the infrasound data processing will be automated and improved. The data from the infrasound system will be processed automatically in house in order to locate the direction of provenance of the signal and identify the erupting volcano. This will constrain the position of the eruptive source and the time of the onset of the eruption, i.e. when the volcanic mixture starts to interact with the atmosphere. This aspect is very important to consider in Iceland where volcanic systems might extend over hundreds of kilometres. Being able to identify with confidence, the location of the source, will help in reducing the uncertainty of the ash cloud injection coordinates. This automatic process will be linked to an early warning signal that will be sent to the monitoring room, allowing the duty-officers to respond in a timely manner to the event. The detection of a location belonging to selected known volcanoes will trigger automatically the activation of that volcano in VESPA. In this way, the plume height assessment and the mass flow rate inversion will be performed in near real-time after the activation.

7.7 Automated check of monitoring status

It would be highly informative to implement an automated alert based on the status of the various monitoring streams. This could be a ranked alert level warning system, initially based on data streams that have in the past enabled early warning prior to the onset of an eruption at Hekla volcano (e.g. seismic and strainmeter data). This would be undertaken by ranking the various seismic and strainmeter stations based on their ability to detect eruption precursors and also the minimum number of stations required to interpret pre-eruptive activity. An alert system could then be put in place based on the functionality of this equipment/status of data streaming regardless the level of activity of the volcano and for example could be imagined as relying on three levels: normal status; compromised status and unreliable status. If either of the strainmeters BUR or HEK is not functioning, then perhaps the instrument alert issued would be a “compromised network” level warning. But for example, if both BUR and HEK (or multiple seismic stations) are not streaming data to the monitoring room then the instrument alert level would be at “unreliable network”. This alert could also be sent to stakeholders to inform them of IMO’s current capacity to detect precursory activity at Hekla, based on these observations.

A similar type of analysis was performed earlier this year, when a severe disruption affected the entire monitoring network at IMO. At that time the main internal system crashed and caused the failure of most of the automatic system used currently in the monitoring room. For several days an assessment of the monitoring capability was done by checking the status of the different monitoring data and processing systems. Based on their functionality, the decision to contact and inform Civil Protection and Isavia was considered and discussed internally. On the 10 of January 2019, IMO informed its main stakeholders about the poor monitoring capacity. An example of such an assessment is displayed in Tables 16 and 17.

Table 16. Overview of the monitoring status on the 10.01.2019, including the data streaming and data processing.

Network	***Status***	***Note***
SIL-seismic	• 20 stations are out • Data streaming has been stable for most of the day	As coming from the monitoring system Icinga
Strain	• 4 stations are out • Data streaming is regular	3 stations have been out for several weeks. BUR station is out as of today at 14.30 (following the energy distribution interruption in South Iceland). Nobody is responsible for maintaining the system.
Infrasound	• 1 station is out • Data streaming is regular	The infrasound analysis on the web page from University of Florence is up and running
Tiltmeter	• The station is out	The station is at Grímsfjall
Webcam	• 4 webcams have not been streaming since yesterday • 3 stations are streaming regularly	The analysis is done only for those webcams looking at volcanoes/rivers
Gas	• No DOAS working • No MultiGAS working • 3 gas sensors are out	DOAS and MultiGas have been out for several weeks
Hydro	• Data are streaming into vmkerfi • No update of the plots used for the monitoring on hnik	Audio warning for floods might be malfunctioning
Radar	• All radars are up and running • Data are coming in-house • The VESPA system for the automatic estimate of plume height is not working	
Lidar	• Real-time streaming of data is working	Web-site is down

Table 17. Monitoring level assessment performed on the 10.01.2019 when IMO's internal system went through a severe disruption.

	Hekla-Vatnafjöll	Katla	Grímsvötn	Öræfajökull	Bárðarbunga
Seismic					
Deformation					
Hydro	NA				
Gas					NA
Borehole strain		NA	NA	NA	NA

8 Summary

Hekla volcano poses a significant threat to aviation as a result of the extremely limited (or no) warning time provided prior to previous eruptions. The consequences could be catastrophic if an eruption occurs at Hekla, with insufficient warning time and an aircraft is within close proximity to the volcano.

The capability to provide a timely warning prior to an eruption depends on 1) the presence of geophysical signals, 2) the capability to detect geophysical signals indicating a change in the volcanic system, 3) an expert, rapid and confident, interpretation of the monitoring data and 4) an effective way to communicate pertinent information about the situation to the official stakeholders, e.g. aviation authorities and airline companies. A delay in any of these four factors will result in a delay in issuing a warning, which is essential to reduce the risk of volcanic ash encounter or any other hazards to overflying aircraft (such as the initial shock wave and turbulence) posed by the initial violent phase of an unexpected eruption.

This project focused on investigating the current capabilities in place at IMO to provide an early warning for Hekla volcano. It has been undertaken by investigating 1) the current monitoring system and its reliability, 2) the automatic system for the data processing and alert and 3) the procedures in place for responding to alerts and communication protocols. The analysis has been undertaken for the seismic, deformation (cGPS and strainmeters) and geochemical networks. It reveals that the current setup of the monitoring network is fulfilling the minimum requirements designed for a high-risk volcano, and also that the level of reliability is quite satisfactory for the different systems as calculated as the downtime of the whole network around Hekla over the last three years. This represents how often the real-time monitoring data were not available in the monitoring room.

An analysis of the hypothetical time to deliver necessary information related to an impending eruption to Isavia today reveals that, under optimal circumstances, a first pre-warning might be issued (via phone call) between 18–34 minutes after the first detection of unusual seismicity at Hekla. This time delay may be compared with the 41 minutes required by IMO prior the eruption in 2000. The reduced delay today would primarily result from the increased availability of a specialist, 24 hours a day in-house, to respond promptly to any unusual signals coming from the monitoring network. This analysis suggests that a final alert would be triggered between 24–53 minutes after the first detected sign of unrest. This would represent the minimum amount of time required, prior to the alert being triggered and this number should be put into the context of the volcano timeline, i.e. the time passed from the beginning of the unrest to the onset of the eruption. As in the past, this period has varied between 23 to 79 minutes; *the capability to issue a timely warning strongly depends on the magmatic processes and how quickly magma rises through the conduit to the surface*.

Unfortunately, it is impossible to anticipate when along this timeline the eruption will start, as we do not know at which stage of the unrest the first detectable geophysical/geochemical signal will be recorded. This is why it is crucial to deliver a confident alert as soon as possible. In the scenario outlined above, if the process of magma migration to the surface is quicker than 24 minutes prior to the next eruption at Hekla, there will be no timely warning issued by IMO to support the safety of aviation operations. In addition, in the event that the volcano does not provide any precursory signals, it will also not be possible to issue a pre-eruptive warning. Once the eruption starts, the atmospheric monitoring network will determine the location and assess the onset of the eruption. This means that the infrasound may detect the eruption onset with a delay of 2.5 minutes, the radar and webcam after 10 minutes.

As already stated, the ability of the scientist on duty to make a rapid, confident assessment of any ongoing activity, will be greatly facilitated by **multi-parametric evaluation**. Consequently, additional near real-time measurements (e.g. cGPS displacements, tilt measurements, radon activity, soil temperature) that could potentially support the interpretation of an on-going event in the temporal gap between seismic and strain observations, should be seriously considered as an important addition to the current monitoring network at IMO. The primary recommendations from this study are displayed in Table 18 and outlined below.

The **highest-priority recommendations concerning the existing monitoring system** emerging from this study are as follows (not listed in order of priority):

- Implement strain corrections and automatic alert based on strain-rate calculations
- Implement automated alerts based on the currently available geochemical data
- Implement the Track processing of the cGPS data aimed at the creation of an automatic alert
- Tune the existing early warning system considering the sensitivity of the current seismic network in order to reduce the occurrence of false positives
- Contact Síminn regarding serious concerns on the vulnerability of the mobile network
- Improve power supply to MultiGAS on Hekla summit
- Implement an automatic alert based on the status of the monitoring network at Hekla
- Implement a reliable backup system for all monitoring networks

The **highest-priority recommendations concerning additions** to the existing monitoring network are:

- Install a soil temperature probe in hut on the summit of Hekla and set-up continuous data streaming of measurements to IMO
- Undertake campaign measurements this summer (2019) to identify suitable locations for the installation of a permanent radon detector along with a feasibility study regarding operational requirements
- Pursue the redesign and installation of CO_2 in water instruments

The **longer-term strategy** would include:

- Feasibility study to assess the added value of implementing a tiltmeter network
- Purchase additional MultiGAS and DOAS instruments
- Upgrade all cGPS instruments within 10 km of the summit
- Implementation of SeisComP software
- Evaluation of performance of temporary seismometers

Table 18. Schematic view of the suggested modifications to the existing monitoring and early warning system, along with suggestions for additional equipment.

	Data availability			Data interpretation		Communication
	Instrument	Data streaming	Internal IT system	Automatic data processing	Automatic early-warning	Protocols
Seismic	If additional temporary seismometers prove to be valuable, add new instruments as part of the basic network	Diversify communication methods	Reliable backup system and IT support for all monitoring networks	• Tune existing early warning system • Implementation of Seiscomp software		• Automated daily assessment of monitoring system health
cGPS	• Upgrade all instruments • Feasibility study for installation of tiltmeter network	Diversify communication methods		Implementation of Track processing with the potential to trigger warning based on deformation rate		
Strainmeter		• Convert data into miniseed format • Diversify communication methods		Implementation of the data corrections	Creation of script for early warning based on strain rate	
Geochemical	• Installation of soil temperature probe, radon detector, CO_2 in water instruments • Additional MG in-house • 2 additional DOAS	• Improve the power supply on site (Hekla summit) • Diversify communication methods			Creation of scripts for early warning (thresholds for gas concentration already exist)	

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Cover photo: Hekla eruption, August 1980
Photo: Conny Park