Assessing the magnitude of volcanic risk to global shipping

Paul Cragg[1], Pete Rowley[2]*, Sam J. Mitchell[2]

* Corresponding author. Pete.rowley@bristol.ac.uk

[1] Unaffiliated

[2] School of Earth Sciences, University of Bristol, Bristol UK. BS8 1RJ

ORCiD:

Pete Rowley 0000-0002-8322-5808

Sam Mitchell 0000-0002-3224-5833

This manuscript has not undergone peer review. It has been submitted for publication at the WMU Journal of Maritime Affairs. Subsequent versions may have slightly different content. If accepted, the final version of this manuscript will be available via the "Peer reviewed publication DOI" link to the right on the website. We welcome comments or questions.

Assessing the magnitude of volcanic risk to global shipping

Paul Cragg[1], Pete Rowley[2]*, Sam J. Mitchell[2]

* Corresponding author. Pete.rowley@bristol.ac.uk

[1] Unaffiliated

[2] School of Earth Sciences, University of Bristol, Bristol UK. BS8 1RJ

Abstract

With a global economy dependent on marine traffic, there has been little study or recognition of the risk posed to the shipping industry by volcanism. Most major shipping lanes pass close to active volcanoes, or through straits and channels which can be impacted by volcanic debris. In this paper we set out the main hazards presented by volcanoes to shipping, and reflect on the magnitude of risk that these pose.

There is a demonstrated track record of losses and damages caused by volcanic events in the past, and as shipping volumes increase, the exposure to similar events in the future also increases. As remote sensing techniques and observation of active volcanism improves, the occurrence of marine volcanic events has clearly been under-reported. We suggest there is a dangerous lack of recognition of the scale of the risk posed to the marine transport industry, and to the supply chains it feeds.

Abstract

With a global economy dependent on marine traffic, there has been little study or recognition of the risk posed to the shipping industry by volcanism. Most major shipping lanes pass close to active volcanoes, or through straits and channels which can be impacted by volcanic debris. In this paper we set out the main hazards presented by volcanoes to shipping, and reflect on the magnitude of risk that these pose.

There is a demonstrated track record of losses and damages caused by volcanic events in the past, and as shipping volumes increase, the exposure to similar events in the future also increases. As remote sensing techniques and observation

of active volcanism improves, the occurrence of marine volcanic events has clearly been under-reported. We suggest there is a dangerous lack of recognition of the scale of the risk posed to the marine transport industry, and to the supply chains it feeds.

Keywords: volcanic hazard, risk to shipping, pumice rafts, submarine volcanism

Introduction

Approximately 90% of international trade is reliant on marine shipping, with the volume forecast to more than double by 2050 (Sardain, et al. 2019). A large portion of the worlds' maritime trade passes within 100 km of active volcanic systems (Figure 1), but little work has been done to explore the related hazards or risks.

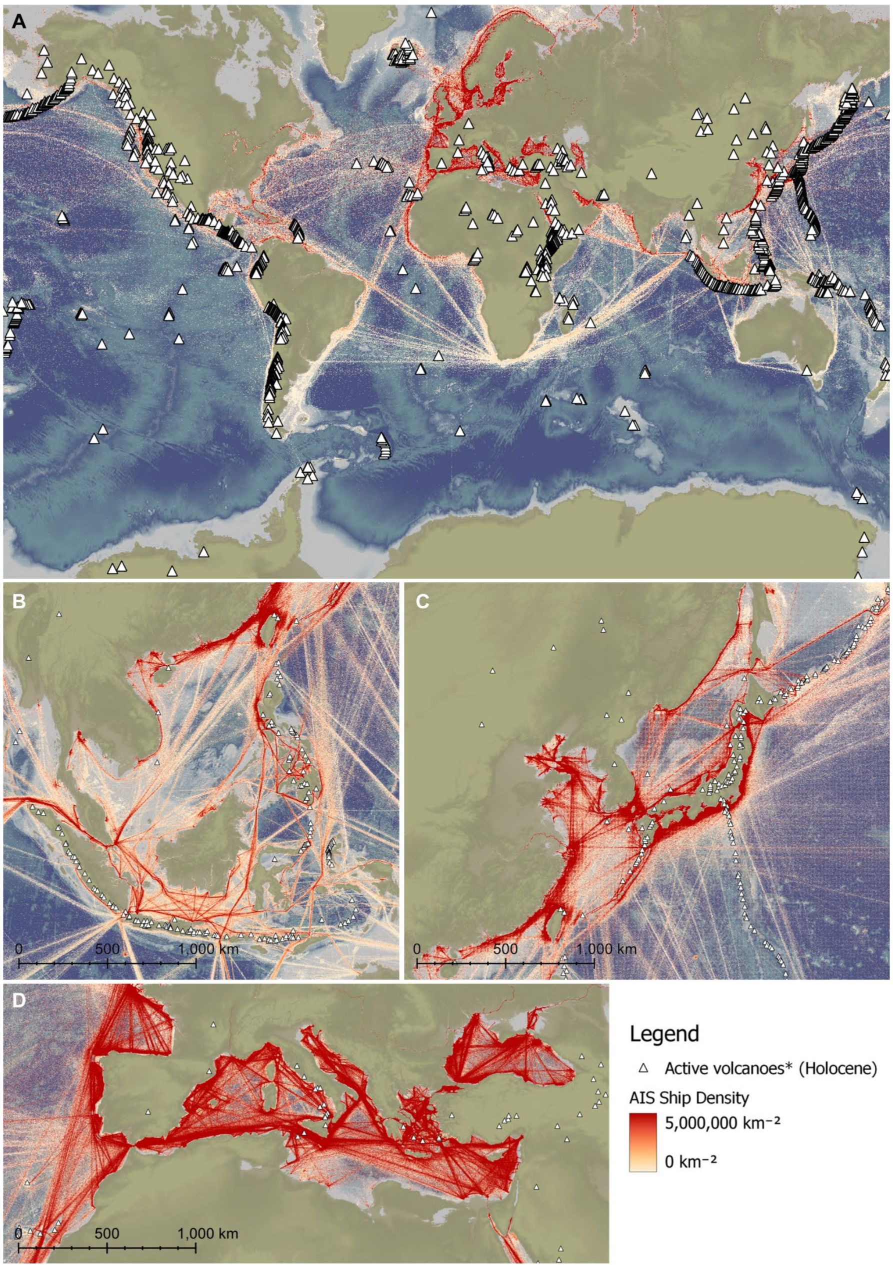

Figure 1. (A) Global map of active volcanoes (white triangles), shipping density (orange-red), and observed pumice rafts over the last 200 years.highlighting substantial overlaps in key areas including (B) the Mediterranean, (C) the Sea of Japan and (D) the Andaman and Java Seas. The shipping density data (World Bank 2021) is derived from hourly Automatic Identification System (AIS) positions received between Jan-2015 and Feb-2021. The AIS positions may have been transmitted by both moving and stationary ships within each grid cell, therefore the density is analogous to the general intensity of shipping activity.

There are many separate volcanic hazards which pose risks to shipping (Table 1, Figure 2), and there is a long history of volcano-related shipping losses, disruptions, and damages, for example at the eruptions from St Pierre, Martinique (Guibert et al 2018), Rabaul Caldera (Johnson and Threlfall, 1985), and Myojin-sho (Dietz and Sheehy, 1954). Despite this, there is no system currently in place to provide automated warnings of nearby activity to the maritime industry.

Table 1. Risks to shipping from individual volcanic hazards based on ship proximity.

Type of volcanic hazard	**Proximity to source**	***Risks to shipping**
Lava-water coastal explosions	< 1 km	Ship destruction/severe damage; potential loss of life/critical injuries; large ballistics in hull side
Shallow sub-surface explosions	< 1 km	Ship destruction/severe damage; potential loss of life/critical injuries; ship instability from wave action
Volcanic gases	Up to 10's km	Crew inhalation and respiration; possible metalwork corrosion from acidic vapours
Pyroclastic density currents	Up to 10's km	Ship destruction/severe damage; potential loss life/critical injuries; large ballistics in hull side
Terrestrial and submarine flank collapses	Up to 10's km	Ship destruction/severe damage; potential loss life/critical injuries; large ballistics in hull side
Tephra (ash/pumice) fallout	Up to 100's km	Damage to electronic equipment; inhalation/respiration of fine ash; instability from wet tephra accumulation; navigation loss; radar attenuation
Volcanic plumes in atmosphere	Up to 100's km	Disruption to navigation and position fixing; reduced visibility; radar attenuation
Oceanic pumice rafts	Up to 1000's km	Loss of propulsion in engines; need to redirect shipping traffic; damage to turbines
Tsunamis and shockwaves	Up to 1000's km	Wave damage; flooding; instability or capsizing; potential loss of life; pressure waves dangerous to hearing and health close to source

*The level of risk for each impact is variable and dependent on a number of parameters such as distance from source, magnitude and intensity of hazard, number of personnel, vessel type, age and speed.

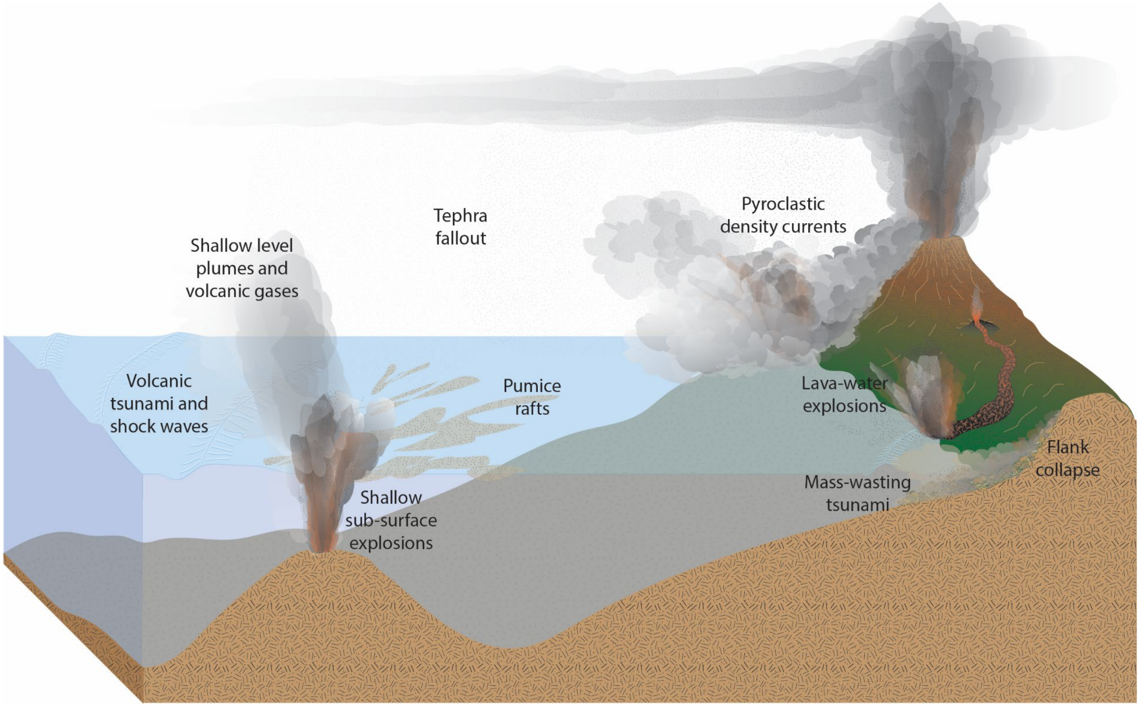

Figure 2. Marine hazard processes at and around active volcanoes.

Assessment of volcanic risk in the terrestrial realm has improved markedly in recent decades, and multi-faceted approaches linking field data and observations, experimental modelling, and numerical simulation have enabled us to explore the exposure to different hazards for a wide range of settings and eruption types. However, mapping and reporting of this risk rarely reaches beyond the coast, and the limited work exploring hazard propagation offshore has usually focused on tsunami generation (Legros and Druitt 2000; Milia, Torrente, and Zuppetta 2003; le Friant et al. 2009; Cas and Giordano 2014).

The range of hazards posed by explosive volcanoes to shipping can broadly be divided into proximal (within ~20 km of the volcano) and distal (>~20 km from the volcano) (Table 1). Proximally, pyroclastic density currents are one of the major concerns – fast moving (50-200 km/h) hot (>200°C) mixtures of volcanic ash and gas which are capable of propagating offshore (e.g. Trofimovs et al 2009). Other very proximal hazards (<1 km) may include sudden sub-surface explosions (Barberi et al. 1992; Baker et al. 2002), exposure of personnel to volcanic gases, shockwaves from submarine explosions, or violent explosions along coastlines when lava flows reach the marine environment (e.g. Mattox and Mangan 1997, and a tourist vessel damaged and over 20 injured from a coastal lava bomb ejection during the 2018 Kīlauea eruption, Hawai´i).

There are also a number of speculated but poorly understood hazards which are possible in the proximal zone. These include buoyancy reductions due to gas bubbling from submarine vents, and the impact of volcanic gases on corrosion. These require substantial further work and are not considered here.

The distal hazards often stem from the dispersal of tephra (volcanic ash and pumice) through fallout from an eruption column, or release to the sea surface from a submarine eruption. The impact of each of these events can cover areas of tens of thousands of square kilometers or more.

A well recognised distal hazard are tsunami generated by the collapse of a volcanic edifice. These types of flank collapses are relatively common in the geological record, and the resulting tsunami can produce a globally significant hazard – particularly to inshore shipping as the wave heights build. This was seen most recently following the Hunga Tonga-Hunga Ha´apai event in 2022, with dozens of boats sunk or capsized around the Pacific rim, and extensive damage to some coastal infrastructure (Aquino 2022; Reuters 2022; Marine Industry News 2022). However, tsunami risk is not dealt with in this work, as tsunami modelling and warning systems are well established.

In this paper we highlight the primary risks posed to shipping focusing on tephra dispersal in the distal area, and suggest some priorities for improving our understanding of these risks, and developing policy to manage them.

Eruption magnitude and frequency

Volcanic eruptions are classified using a Volcanic Explosivity Index (Newhall and Self 1982), where VEI 0 is a gentle, small-scale eruption emitting no more than a few hundred cubic meters of material, VEI 4 eruptions erupt up to a cubic kilometre of material (equivalent to Mt St Helens in 1980, or Eyjafjallajökull in 2010), up to VEI 8 which are the very rare super eruptions emitting up to thousands of cubic kilometres of material.

Eruptions as small as VEI 3 can generate substantial tephra hazards in an area of thousands of square kilometers, while VEI 6 eruption impact wide regional areas and can have global short term impacts. In a century, we can expect 70+ VEI 4 eruptions, and over 400 VEI 3 eruptions (Mason, Pyle, and Oppenheimer 2004; Papale 2018). These hazardous events are concentrated at oceanic plate margins, providing close proximity to shipping (Fig 1).

Tephra dispersal processes

A typical subaerial explosive eruption, and many submarine eruptions, will produce a plume of tephra over hours or days (Figure 2), which is injected into the atmosphere. The height of this plume will vary with the eruption conditions, but can range from hundreds of meters to stratospheric altitudes. Ash plumes from eruptions are routinely monitored due to the risk to aviation. High altitude ash can distribute globally, and accumulations of sediment from these clouds pose a risk to vast areas of active shipping lanes globally (Figure 3).

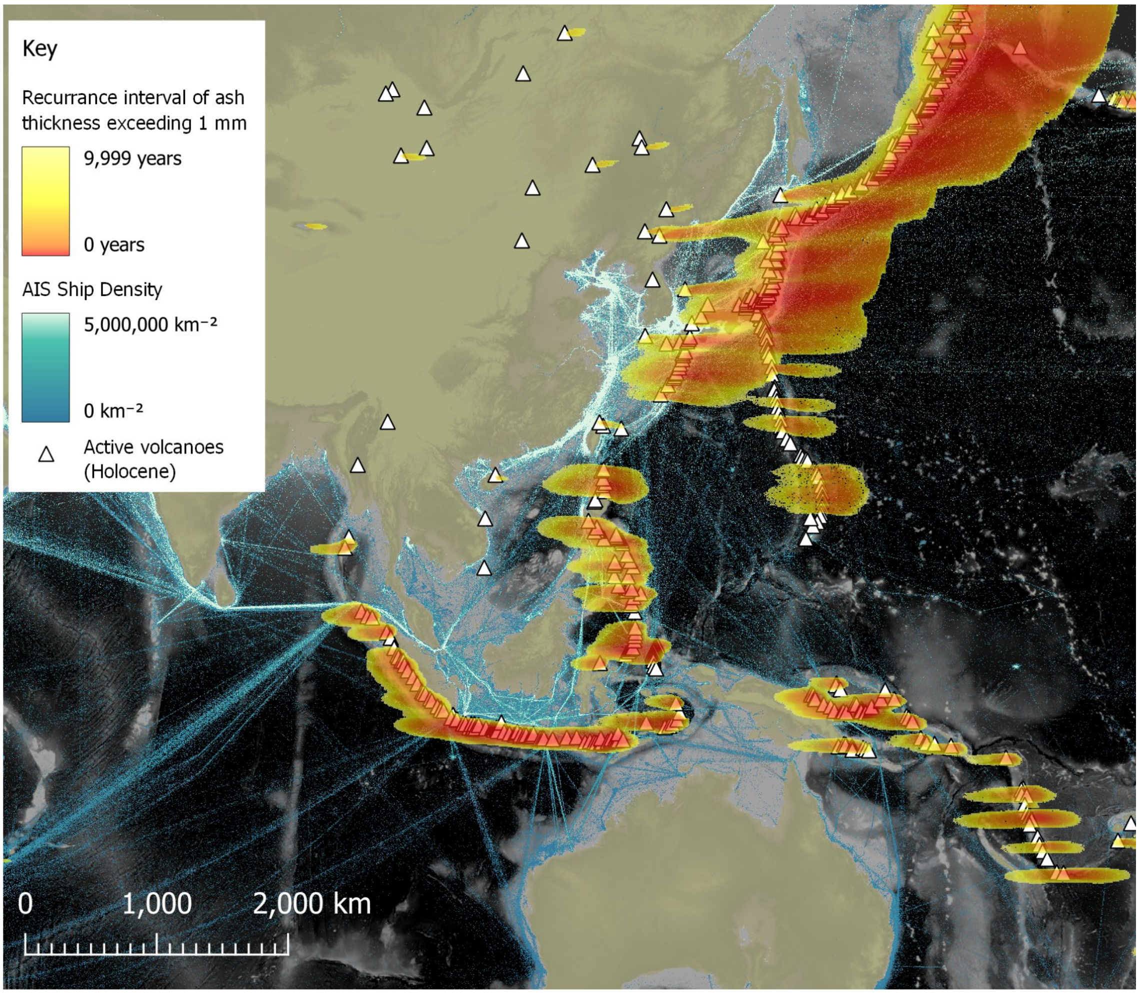

Figure 3. Regional map of SE Asia showing the recurrence interval (in years) for ash accumulation of greater than 1 mm thickness (from Jenkins et al. 2015), and how that interacts with AIS-derived shipping densities (World Bank 2021).

The material sedimented from these plumes can range from relatively localised centimeter-scale particles, to fine micrometer-diameter ash, which can take days or weeks to settle out over much wider areas. These tephra particles are foam-like structures, comprising volcanic glass inflated by the gases which drove the eruption.

This buoyant material can form floating rafts of pumice with lifetimes of weeks to months. The accumulation, transport, and eventual break up of these is poorly understood. They can reach hundreds of kilometres in length, strung out through a combination of wind and ocean currents, with sediment packs tens of centimetres or more thick. They have been tracked traversing hundreds or thousands of kilometres from their source (Figure 1A) over a period of weeks or months.

Risk to shipping – mechanical hazards

Loss of propulsion

Nearly all marine engines rely upon seawater cooling systems to regulate their running temperatures. A typical main sea inlet grating for the cooling system restricts the diameter of ingested particles sucked up into the sea chest to about 15 mm across the minor axis but could be much greater than this along the major axis. Providing there is a flow of water along the hull, from the vessel moving or a strong current, the inlet grating would be kept clear of larger pumices, allowing a constant supply of smaller particles through. Sand-mud grade particles (such as volcanic ash) would initially pass through the system but may eventually start to coat the pipe work (Johnson and Threlfall 1985) and cooling plates. Gravel-sized material (coarse ash and pumice) will quickly block the internal, finer mesh strainers.

Also essential for the operation of diesel engines is airflow sufficient to ensure a flammable mixture within the combustion chamber. This air comes from the engine room atmosphere which, in turn, is provided by high-capacity ventilation fans. A fine (<1mm) mesh filter is generally installed at the air intake to remove solid particles before the air is exhausted into the engine room. This filter would soon become clogged with entrained tephra (ash sedimentation within the atmosphere) and would need to be removed and cleaned at regular intervals. While in areas of light tephra fall, this should not pose a problem to the ship's crew who will have to venture onto deck to do this. During heavier fall this would become challenging, while also exposing deck crew to further hazards (decreased visibility, slip hazards, and respiratory issues associated within inhaling fine ash and volcanic gases; Stewart et al., 2022). At some stage, these filters may have to be removed completely allowing tephra to be blown direct into the engine room. Marine diesel engine operating temperatures (up to 350°C, e.g. Lu et al 2013, Korczewski, 2016) are below that typically required to fully melt primary volcanic material (400-800°C, Giordano, Nichols, and Dingwell 2005), but this ignores instantaneous internal temperatures within cylinders (Lu et al 2013) and there is no work exploring the potential for sintering within the cylinder and exhaust. Additionally, abrasion of the inner surfaces and valves may lead to degradation of the engine.

Marine turbine engines are powered by steam from a dedicated boiler and there is little chance of the external atmosphere getting into the system and damaging the turbine blades. Some naval vessels are powered by gas turbines, and these would suffer similar problems as experienced by aircraft (Song et al 2016). As ash passes into a turbine engine, the particles become heated, pass through the fan and compressor, begin to melt in the combustion chamber, and can accumulate as a glass on the turbine blades. This can result in erosion of blades and other engine components, deposition of glass which restricts airflow, and the deposition of carbon on the fuel nozzles (Davison and Rutke 2014). These can result in a requirement for maintenance or complete overhaul, and engine shutdown (Chen and Zhao 2015; Wylie et al. 2017; Vogel et al. 2019).

Electronic equipment

Sophisticated electronic management systems are increasingly common on board ships, and exposure to tephra is weakly explored. Some research indicates that, in the short term at least, electronic components may not suffer too much (Gordon et al. 2005) and 'stand-alone' air conditioning equipment has been shown to be reasonably resilient to the effects of tephra entrainment into condenser equipment in other settings (T. M. Wilson and Cole 2007).

The combination of moisture and tephra has been shown to cause serious problems to electrical distribution systems on land (Bebbington et al. 2008). Although vessels do not have an open distribution system, the wet environment and potential for tephra entrainment into switchboards and breaker panels is a hazard which should be explored. Radio aerials, especially those used for high frequency transmissions, can be similarly affected by shorting across insulators.

Stability

The International Maritime Organization lays down a set of minimum allowances in terms of ship's loadability. Additional allowances for ice build up need to be applied if the ship is expected to encounter ice accretion during the voyage. In the case of encountering a volcanic plume there is potential for ships to gain substantial mass from tephra accumulation. Accumulation close to the volcano may reach meters of thickness in a few hours; more distally this can reduce to centimetres or millimetres. However, tephra is hydrophilic, and will gain mass which can lead to it achieving densities of 1500-2500 kg m^{-3}. At these densities, accumulation of 10-20 cm of tephra will exceed the ice loading limit of 30 kg m^{-2}. These thicknesses are commonplace at even fairly small eruptions (Bebbington et al. 2008; Bonadonna and Costa 2013). With the tendency of tephra to easily drift in prevailing winds, it is likely that any loading on a moving ship will be asymmetrical. Accumulated tephra thicknesses exceeding this loading limit may be found up to 10's km from source during larger, but still frequent, explosive eruptions, or eruptions with a very strong downwind ash dispersal.

Hazards to navigation

Position fixing

In recent years, weather radars have been used extensively to track tephra clouds from a volcanic eruption (Lacasse et al. 2004; Donnadieu et al. 2016; Marzano et al. 2016; Syarifuddin et al. 2021) due to the opacity of volcanic ash to radar emissions, with the ability to cause radar white-out. Weather radars generally operate in or around the 'C' (5 cm) or 'L' (28 cm) bands whereas Marine radar operates in either the 'S' (10 cm) or 'X' (3 cm) bands. The reflectivity of a radar target composed of small, distributed particles, such as tephra, varies inversely with the fourth power of the radar wavelength used (Collin 1985; Harris et al. 1981). The S band radar wavelength lies between those for the C and L band radars. We would expect the S band radar to be affected by attenuation and reflection to a degree somewhere between these two end-points. The X band wavelength is shorter than the other radars and will be more susceptible to attenuation than the C band. The broad vertical swath of marine radar results in a particular susceptibility to overhead low-level ash plumes, even if the tephra remains suspended rather than falling.

As particles rain out through the lower atmosphere, the haze produced reduces visibility. A density of dust that would only lead to a very fine coating on a horizontal surface can reduce visibility to less than one nautical mile. This level of visibility is low enough to cause serious navigation problems, especially in busy shipping lanes or confined waters. Horizontal visibility in an area of tephra fall can be expected to reduce proportional to the density of the fallout. This visibility problem may be worsened by volcanic gas emissions resulting in plumes of sulphate rich volcanic fog (vog).

Pumice raft inundation

Due to their long lifetime and ability to be moved by both ocean currents and wind, pumice rafts pose a risk across large swathes of ocean basin even far from active volcanic centers (Figure 4). They pose a hazard to shoreline infrastructure (Asano and Nagayama 2021), and can cause months of disruption requiring substantial recovery effort (Yoshida et al. 2022).

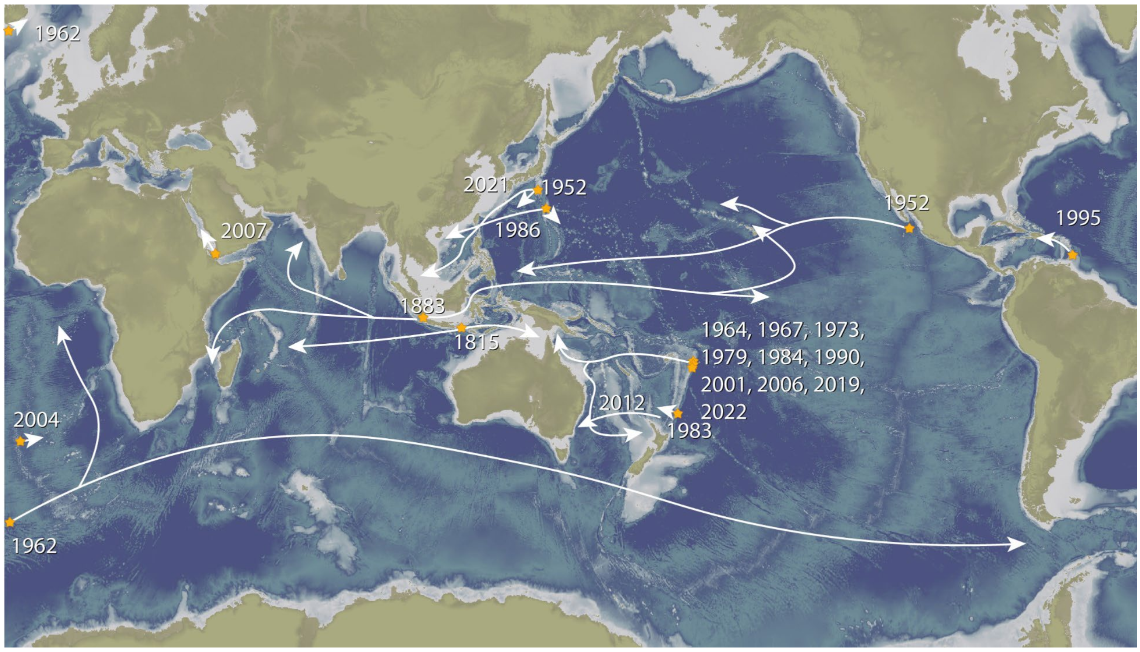

Figure 4. Observed pumice raft tracks over the last 200 years, modified after Bryan et al. (2012), with additional observations from Jutzeler et al. (2014; 2020) and Yoshida et al. (2022).

The outcomes of the M/V Ever Given blockage of the Suez Canal in 2021 made clear the scale of risk when critical shipping lanes and routes are shut down or restricted (J.

M. Lee and Wong 2021) – a situation which could easily be replicated through volcanic activity, or pumice raft inundation in the wrong place. While much recent pumice raft activity (Figure 3) has mainly occurred in low traffic areas of the Pacific ocean, there is a clear hazard in higher traffic areas such as the Mediterranean, Red Sea, Caribbean, and the various straits and narrows in South East Asia.

Hazards to health

Respiration of volcanic ash has been shown, in general, to have little long-term effect on the health of a fit adult (Martin, Wehner, and Butler 1986; Horwell and Baxter 2006; Stewart et al. 2022). This is dependent upon the length of exposure and quantity of silica present in ash particles <4µm. Irritation and bronchial tract problems are the most likely scenario following short term exposure to tephra particles <100µm in size, but PM-2.5 face masks can significantly reduce the risks from inhalation of volcanic ash, in the eventuality of prolonged exposure. For a vessel caught in an area of tephra fallout, any exposure to passengers or crew is likely to be short term, but ships do not routinely carry appropriate personal protective equipment (PPE). Additionally, prolonged downwind exposure to volcanic gas (carbon dioxide, sulfur dioxide, and halogen species) may put ship personnel at significant health risk (Horwell and Baxter, 2007; Hansell and Oppenheimer, 2004); these risks may also be reduced through appropriate PPE usage.

Suggested risk reduction actions

- *Improving training and onboard reference materials* – Ensuring that manuals and training are provided with guidance regarding how to respond to nearby volcanic activity, including training on appropriate PPE, ship management protocols, and awareness of hazards to the ship and navigation.

- *Establishing of temporary exclusion and risk zones during eruption watches and warnings* – Implementing pre-determined restrictive zones to maritime traffic, seen with the active submarine volcanoes, Kick 'em Jenny (Lesser Antilles) and Home Reef (Kingdom of Tonga).
- *Formalising new networks and communications to notify ships of potential hazards* – There is currently only a limited system in place to routinely notify and advise maritime traffic to all nearby volcanic hazards. A system similar to the Volcanic Ash Advisory Centres (VAACs) for aviation traffic system could allow pre-emptive and more appropriate actions in response to developing volcanic crises.
- *Expansion of volcanic hazard and risk maps to offshore* – Some hazards can be easily mapped offshore due to little change in the physics and processes controlling their distribution, e.g., ashfall and advection of volcanic gases. Other high-risk hazards, such as pyroclastic density currents (PDCs), have poorly constrained interactions with water and require detailed numerical models and experimentation.

Conclusions

The risks posed to shipping around volcanic centres are varied, and generally poorly understood. Of the hazards discussed here, the risk of a total loss to shipping is relatively low. However, the potential for delays, diversions and mechanical failures is probably high. Given the increasing dependence on global shipping freight, the time sensitivity of many deliveries, and the costs related to the running of shipping operations, volcanic activity should be a greater subject of concern.

Considerable work must be done in establishing baseline values for risk in the offshore setting, and in exploring the wider hazards not explored here. However, there is already sufficient knowledge in many areas for policy to start addressing some of these hazards, in advance of a more substantial crisis.

Given the myriad hazards which may be associated with explosive eruptions, we suggest that a collaborative and meaningful effort is prioritised toward the establishment of a shipping-oriented alert system which runs similarly to, in parallel with, or as part of the Volcanic Ash Advisory Centres designated under the International Civil Aviation Organization.

Acknowledgements

We are very grateful to S. Jenkins for providing the original ashfall recurrence shapefile data which enabled us to produce Figure 3.

Statements and Declarations

Competing Interests: The authors declare no competing interests.

References

Aquino, M. (2022). Peru Opens Probe of Oil Spill Blamed on Tonga Volcano and Tsunami. Reuters. https://www.reuters.com/business/environment/peru-opens-probe-oil-spill-blamed-tonga-volcano-tsunami-2022-01-19/.

Asano, T., and Nagayama, A. (2021). Analysis of Workload Required for Removal of Drifting Pumice after a Volcanic Disaster as an Aspect of a Port Business Continuity

Plan: A Case Study of Kagoshima Port, Japan. International Journal of Disaster Risk Reduction 64 (August): 102511. https://doi.org/10.1016/j.ijdrr.2021.102511.

Baker, E. T., Massoth, G.J., de Ronde, C.E.J., Lupton, J.E, and Mclnnes, B.I.A. (2002). Observations and Sampling of an Ongoing Subsurface Eruption of Kavachi Volcano, Solomon Islands, May 2000. Geology 30 (11): 975–78. https://doi.org/10.1130/0091-7613(2002)030<0975:OASOAO>2.0.CO;2.

Barberi, F., A. Bertagnini, P. Landi, and C. Principe. (1992). A Review on Phreatic Eruptions and Their Precursors. Journal of Volcanology and Geothermal Research 52 (4): 231–46. https://doi.org/10.1016/0377-0273(92)90046-G.

Bebbington, M., S.J. Cronin, I. Chapman, and M.B. Turner. (2008). Quantifying Volcanic Ash Fall Hazard to Electricity Infrastructure. Journal of Volcanology and Geothermal Research 177 (4): 1055–62. https://doi.org/10.1016/j.jvolgeores.2008.07.023.

Bonadonna, C., and A. Costa. (2013). Plume Height, Volume, and Classification of Explosive Volcanic Eruptions Based on the Weibull Function. Bulletin of Volcanology 75 (8): 1–19. https://doi.org/10.1007/s00445-013-0742-1.

Branney, M., and P. Kokelaar. (2002). Pyroclastic Density Currents and the Sedimentation of Ignimbrites. 27th ed. London: Geological Society of London Memoir. https://doi.org/10.1144/GSL.MEM.2003.027.

Bryan, S.E., A.G. Cook, J.P. Evans, K. Hebden, L. Hurrey, P. Colls, J.S. Jell, D. Weatherley, and J.Firn. (2012). Rapid, Long-Distance Dispersal by Pumice Rafting. PLoS ONE 7 (7). https://doi.org/10.1371/journal.pone.0040583.

Cas, R.A.F., and G. Giordano. (2014). Submarine Volcanism: A Review of the Constraints, Processes and Products, and Relevance to the Cabo de Gata Volcanic Succession. Italian Journal of Geosciences 133 (3): 362–77. https://doi.org/10.3301/IJG.2014.46.

Chen, W. R., and L. R. Zhao. (2015). Review - Volcanic Ash and Its Influence on Aircraft Engine Components. Procedia Engineering 99: 795–803. https://doi.org/10.1016/j.proeng.2014.12.604.

Collin, R.E. 1985. Antennas and Radiowave Propagation. McGraw-Hill Book Company.

Davison, C. R., and T. A. Rutke. (2014). Assessment and Characterization of Volcanic Ash Threat to Gas Turbine Engine Performance. Journal of Engineering for Gas Turbines and Power 136 (8): 1–10. https://doi.org/10.1115/1.4026810.

Dietz R.S., Sheehy M.J. (1954). Transpacific detection of Myojin volcanic explosions by underwater sound. GSA Bull 65:941–056. https://doi.org/10.1130/0016-7606(1954)65[941:TDOMVE]2.0.CO;2

Donnadieu, F., P. Freville, C. Hervier, M. Coltelli, S. Scollo, M. Prestifilippo, S. Valade, S. Rivet, and P. Cacault. (2016). Near-Source Doppler Radar Monitoring of Tephra Plumes at Etna. Journal of Volcanology and Geothermal Research 312: 26–39. https://doi.org/10.1016/j.jvolgeores.2016.01.009.

Eaton, A. R. van, J. D. Muirhead, C.J.N. Wilson, and Corrado Cimarelli. (2012). Growth of Volcanic Ash Aggregates in the Presence of Liquid Water and Ice: An Experimental Approach. Bulletin of Volcanology 74 (9): 1963–84. https://doi.org/10.1007/s00445-012-0634-9.

Friant, A. le, C. Deplus, G. Boudon, R. S.J. Sparks, J. Trofimovs, and P. Talling. (2009). Submarine Deposition of Volcaniclastic Material from the 1995-2005 Eruptions of Soufrière Hills Volcano, Montserrat. Journal of the Geological Society 166 (1): 171–82. https://doi.org/10.1144/0016-76492008-047.

Giordano, D., A. R.L. Nichols, and D. B. Dingwell. (2005). Glass Transition Temperatures of Natural Hydrous Melts: A Relationship with Shear Viscosity and Implications for the Welding Process. Journal of Volcanology and Geothermal Research 142 (1-2 SPEC. ISS.): 105–18. https://doi.org/10.1016/j.jvolgeores.2004.10.015

Gordon, K. D., J. W. Cole, M. D. Rosenberg, and D. M. Johnston. (2005). Effects of Volcanic Ash on Computers and Electronic Equipment. Natural Hazards 34 (2): 231–62. https://doi.org/10.1007/s11069-004-1514-1.

Guibert A.J, Guérout M., Past L.S. (2018). Past and Present Research in the Underwater
Archaeology of Saint-Pierre, Martinique (FWI). ACUA. Underwater Archaeology Proceedings, 2018. Pp149-154.

GVP. 2013. Volcanoes of the World v. 4.11.0. Smithsonian Institution. (2013). https://doi.org/https://doi.org/10.5479/si.GVP.VOTW4-2013.

Hansell, A. and Oppenheimer, C., (2004). Health hazards from volcanic gases: a systematic literature review. Archives of Environmental Health: An International Journal, 59(12), 628-639.

Harris, D. M., Jr W. I. Rose, R. Roe, and M. R. Thompson. (1981). Radar Observations of Ash Eruptions. In The 1980 Eruptions of Mount St. Helens, edited by P.W. Lipman and D.R. Mullineaux, 323–33. Geol Survey Professional Papers 1250.

Horwell, C.J., and P.J. Baxter. (2006). The Respiratory Health Hazards of Volcanic Ash: A Review for Volcanic Risk Mitigation. Bulletin of Volcanology 69 (1): 1–24. https://doi.org/10.1007/s00445-006-0052-y.

Horwell, C. and Baxter, P., (2007). The health hazards of volcanic ash--A guide for the public (pp. 1-14). International Volcanic Hazards Health Network.

International Maritime Organization. (2002). Code on Intact Stability for All Types of Ships Covered by IMO Instruments. Amersham, Bucks. UK: Halstan & Co. Ltd.

Jenkins S.F., Wilson T.M., Magill C. R., Miller V., Stewart C., Marzocchi W., Boulton M. (2015). Volcanic ash fall hazard and risk: technical background paper for the UNISDR 2015 global assessment report on disaster risk reduction. Global Volcano Model and IAVCEI.

Johnson, R.W., and N.A. Threlfall. (1985). Volcano Town : The 1937-43 Eruptions at Rabaul. Bathurst, N.S.W.: Robert Brown and Associates.

Jutzeler, M., R. Marsh, R.J. Carey, J.D.L. White, Peter J. Talling, and Leif Karlstrom. (2014). On the Fate of Pumice Rafts Formed during the 2012 Havre Submarine Eruption. Nature Communications 5: 1–10. https://doi.org/10.1038/ncomms4660.

Jutzeler, M., R. Marsh, E. van Sebille, T. Mittal, R.J. Carey, K.E. Fauria, M. Manga, and J. McPhie. (2020). Ongoing Dispersal of the 7 August 2019 Pumice Raft From the Tonga Arc in the Southwestern Pacific Ocean. Geophysical Research Letters 47 (5): 1–9. https://doi.org/10.1029/2019GL086768.

Korczewski, Z. (2016). Exhaust Gas Temperature Measurements in Diagnostics of Turbocharged Marine Internal Combustion Engines Part II Dynamic Measurements. Polish Maritime Research 23 (1): 68–76. https://doi.org/10.1515/pomr-2016-0010.

Lacasse, C., S. Karlsdóttir, G. Larsen, H. Soosalu, W. I. Rose, and G. G.J. Ernst. (2004). Weather Radar Observations of the Hekla 2000 Eruption Cloud, Iceland. Bulletin of Volcanology 66 (5): 457–73. https://doi.org/10.1007/s00445-003-0329-3.

Lee, J.M., and E.Y.Wong. (2021). Suez Canal Blockage: An Analysis of Legal Impact, Risks and Liabilities to the Global Supply Chain. MATEC Web of Conferences 339: 01019. https://doi.org/10.1051/matecconf/202133901019.

Legros, F., and T.H. Druitt. (2000). On the Emplacement of Ignimbrite in Shallow-Marine Environments. Journal of Volcanology and Geothermal Research 95 (1–4): 9–22. https://doi.org/10.1016/S0377-0273(99)00116-X.

Lu, X., Q. Li, W. Zhang, Y. Guo, T. He, and D. Zou. (2013). Thermal Analysis on Piston of Marine Diesel Engine. Applied Thermal Engineering 50 (1): 168–76. https://doi.org/10.1016/j.applthermaleng.2012.06.021.

Marine Industry News. 2022. Aftermath of Powerful Tsunami as 50+ Boats Damaged and Dozens Sunk. Marine Industry News. (2022). https://marineindustrynews.co.uk/watch-aftermath-of-powerful-tsunami-as-50-boats-damaged-and-dozens-sunk/.

Martin, T.R., A.P. Wehner, and J. Butler. (1986). Chapter 7: Evaluation of Physical Health Effects Due to Volcanic Hazards: The Use of Experimental Systems to Estimate the Pulmonary Toxicity of Volcanic Ash. American Journal of Public Health 76 (Suppl): 59–65. https://doi.org/10.2105/AJPH.76.Suppl.59.

Marzano, F.S., E. Picciotti, S. Di Fabio, M. Montopoli, L. Mereu, W. Degruyter, C. Bonadonna, and M. Ripepe. (2016). Near-Real-Time Detection of Tephra Eruption Onset and Mass Flow Rate Using Microwave Weather Radar and Infrasonic Arrays. IEEE Transactions on Geoscience and Remote Sensing 54 (11): 6292–6306. https://doi.org/10.1109/TGRS.2016.2578282.

Mason, B. G., D.M. Pyle, and C. Oppenheimer. (2004). The Size and Frequency of the Largest Explosive Eruptions on Earth. Bulletin of Volcanology 66 (8): 735–48. https://doi.org/10.1007/s00445-004-0355-9.

Mattox, T.N., and M.T. Mangan. (1997). Littoral Hydrovolcanic Explosions: A Case Study of Lava-Seawater Interaction at Kilauea Volcano. Journal of Volcanology and Geothermal Research 75 (1–2): 1–17. https://doi.org/10.1016/S0377-0273(96)00048-0.

Milia, A., M. M. Torrente, and A. Zuppetta. (2003). Offshore Debris Avalanches at Somma–Vesuvius Volcano (Italy): Implications for Hazard Evaluation. Journal of the Geological Society 160 (2): 309–17. https://doi.org/10.1144/0016-764902-045.

Newhall, C. G., and S. Self. (1982). The Volcanic Explosivity Index (VEI): An Estimate of Explosive Magnitude for Historical Volcanism. Journal of Geophysical Research 87 (C2): 1231–38. https://doi.org/10.1029/jc087ic02p01231.

Papale, P. (2018). Global Time-Size Distribution of Volcanic Eruptions on Earth. Scientific Reports 8 (1): 1–11. https://doi.org/10.1038/s41598-018-25286-y.

Reuters. (2022). Japan Sees Meter-High Waves and Tsunami Warning after Massive Tonga Eruption. The Japan Times. The Japan Times. https://www.japantimes.co.jp/news/2022/01/16/national/japan-tsunami-tonga-volcano/.

Sardain, A., E. Sardain, and B. Leung. (2019). Global Forecasts of Shipping Traffic and Biological Invasions to 2050. Nature Sustainability 2 (4): 274–82. https://doi.org/10.1038/s41893-019-0245-y.

Song, W., Y. Lavallee, K.U. Hess, U. Kueppers, C. Cimarelli, and D.B. Dingwell. (2016). Volcanic Ash Melting under Conditions Relevant to Ash Turbine Interactions. Nature Communications 7: 1–10. https://doi.org/10.1038/ncomms10795.

Stewart, C., D.E. Damby, C.J. Horwell, T. Elias, E. Ilyinskaya, I. Tomašek, B.M. Longo, et al. (2022). Volcanic Air Pollution and Human Health: Recent Advances and Future Directions. Bulletin of Volcanology 84 (1). https://doi.org/10.1007/s00445-021-01513-9.

Syarifuddin, M., S.F. Jenkins, R.I Hapsari, Q. Yang, B. Taisne, A.B. Aji, Nu. Aisyah, H.G. Mawandha, and D.Legono. (2021). Real-Time Tephra Detection and Dispersal Forecasting by a Ground-Based Weather Radar. Remote Sensing 13 (24): 5174. https://doi.org/10.3390/rs13245174.

Trofimovs, J., Amy, L., Boudon, G., Deplus, C., Doyle, E., Fournier, N., Hart, M. B., Komorowski, J.C., Le Friant, A., Lock, E.J., Pudsey, C., Ryan, G., Sparks, R.S.J. & Talling, P.J. (2006) Submarine pyroclastic deposits formed at the Soufrière Hills volcano, Montserrat (1995-2003): What happens when pyroclastic flows enter the ocean? Geology 34, 549–552.

Vogel, A., A.J. Durant, M.Cassiani, R.J. Clarkson, M. Slaby, S. Diplas, K. Krüger, and A. Stohl. (2019). Simulation of Volcanic Ash Ingestion into a Large Aero Engine: Particle-Fan Interactions. Journal of Turbomachinery 141 (1): 1–12. https://doi.org/10.1115/1.4041464.

Wilson, T.M., and J.W. Cole. (2007). Potential Impact of Ash Eruptions on Dairy Farms from a Study of the Effects on a Farm in Eastern Bay of Plenty, New Zealand; Implications for Hazard Mitigation. Natural Hazards 43 (1): 103–28. https://doi.org/10.1007/s11069-007-9111-8.

World Bank. (2021). Global Shipping Traffic Density Data Catalog. 2021. https://datacatalog.worldbank.org/search/dataset/0037580/Global-Shipping-Traffic-Density.

Wylie, S., A. Bucknell, P. Forsyth, M. McGilvray, and D.R.H. Gillespie. (2017). Reduction in Flow Parameter Resulting from Volcanic Ash Deposition in Engine

Representative Cooling Passages. Journal of Turbomachinery 139 (3): 1–13. https://doi.org/10.1115/1.4034939.

Yoshida, K., Y. Tamura, T. Sato, T. Hanyu, Y. Usui, Q. Chang, and S. Ono. (2022). Variety of the Drift Pumice Clasts from the 2021 Fukutoku-Oka-no-Ba Eruption, Japan . Island Arc 31 (1): 1–17. https://doi.org/10.1111/iar.12441.