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

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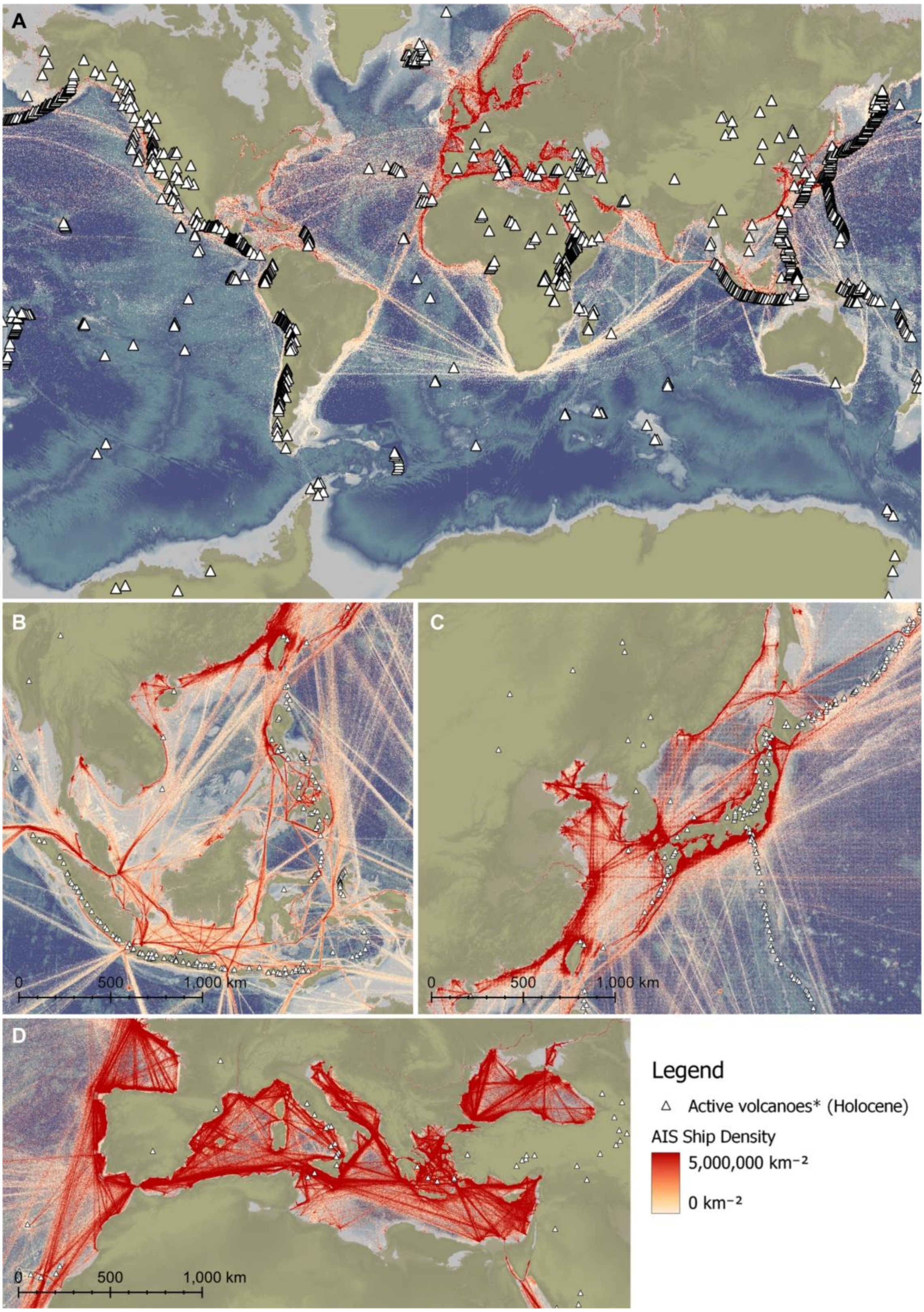
With a global economy dependent on marine traffic there has been little study or recognition of the risk posed to this industry by volcanism. Most major shipping lanes pass close to active volcanoes, or through straits and channels which can be impacted by volcanic debris. In this paper we set out the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

Introduction

Oceangoing shipping is central to our global economy, with approximately 90% of international trade reliant on it, with the volume of shipping forecast to more than double by 2050 (Sardain, Sardain, and Leung 2019). Understanding and quantifying the risks which underlie shipping operations is a critical part of supporting this important sector of our economy, but little work has been done to explore the hazards and risks posed by volcanic eruptions and their by-products. A large portion of the worlds' seaborne trade passes within close proximity of active volcanic systems (Figure 1), such as the Mediterranean Sea, the Aleutian Arc, the Indonesian Archipelago, Japanese volcanic arc and the Caribbean. Volcanic eruptions are common events, with ~1 – 2 dozen active eruptions going on at any given time (GVP 2013).



There are many separate volcanic hazards which pose risks to shipping (Table 1, Figure 2), several of which can reach thousands of kilometers from the originating volcano. There is documented evidence of ships that have been affected by eruptive phenomena, for example at the eruptions from Katmai (Griggs, 1922), Krakatau (Simkin and Fiske, 1983), Rabaul Caldera (Johnson and Threlfall, 1985), Montagne Peleé (Tanguy 1994, Scarth 2002, Zebrowski Jr 2002) and Myojin-sho (Morimoto and Ossaka, 1955). In Simkin and Fiske (1983) there are nearly 100 ships mentioned regarding encounters with floating pumice and tephra fall. Outcomes range from delayed arrivals, to damaged engines, ship destruction, and crew fatalities. Despite this clear track record of ship, personnel and economic losses due to volcanism, there is no system currently in place to provide automated warnings to the maritime industry. The Volcanic Ash Advisory Center (VAAC) network provides routine hazard alerts to the aviation industry, and forms part of the daily aviation routing and planning process, whereas seafarers have no routine system to assist in passage planning. Increasing maritime traffic (commercial, private and industrial), economic dependency on global shipping, and more personnel and passengers at sea will only increase the potential risks from volcanic activity in the coming years.

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.

Assessment of volcanic risk in the terrestrial realm has improved markedly in recent decades, and multi-faceted approaches linking field 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, exploration of this risk (e.g. the creation of hazard maps by scientists for civil authorities, first responders, and the general public) rarely reaches beyond the coast, and the limited work exploring hazard propagation offshore has usually focused on tsunami generation, or not considered offshore risk at all (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). The proximal hazards relate to events such as pyroclastic density currents (PDCs) – fast moving (50-200 km/h) hot (>200°C) currents of volcanic ash and gas, which can propagate across the sea surface for tens of kilometers (Sparks 1976; C. J. N. Wilson 1980; Lube et al. 2005; Branney and Kokelaar 2002; Brown et al. 2017). These are devastating on land, and have the potential to be equally devastating for shipping within their reach, not only from the heat and particle abrasion, but also the dynamic pressures they can exert. Other very proximal hazards (<1 km) may include sudden sub-surface explosions (Barberi et al. 1992; Baker et al. 2002), or violent explosions along coastlines when lava flows reach the marine environment (Moore et al. 1973; Mattox and Mangan 1997; Kaneko et al. 2019), both of which can expel hot volcanic bombs in ballistic trajectories up to hundreds of meters from their source.

There are 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 stem from the dispersal of ash and pumice (“tephra”) through fallout from an eruption column, or release to the sea surface from a submarine eruption. These processes result in ash clouds at a wide variety of altitudes and densities, raining out of ash and pumice, and the accumulation of pumice rafts which can survive for weeks or months, drifting across wide areas largely unmonitored, and/or thick turbid suspensions of fine ash within the shallow water column. 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, as seen in Anak Krakatau in 2018, and Hunga Tonga-Hunga Ha’apai in 2022. 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 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.

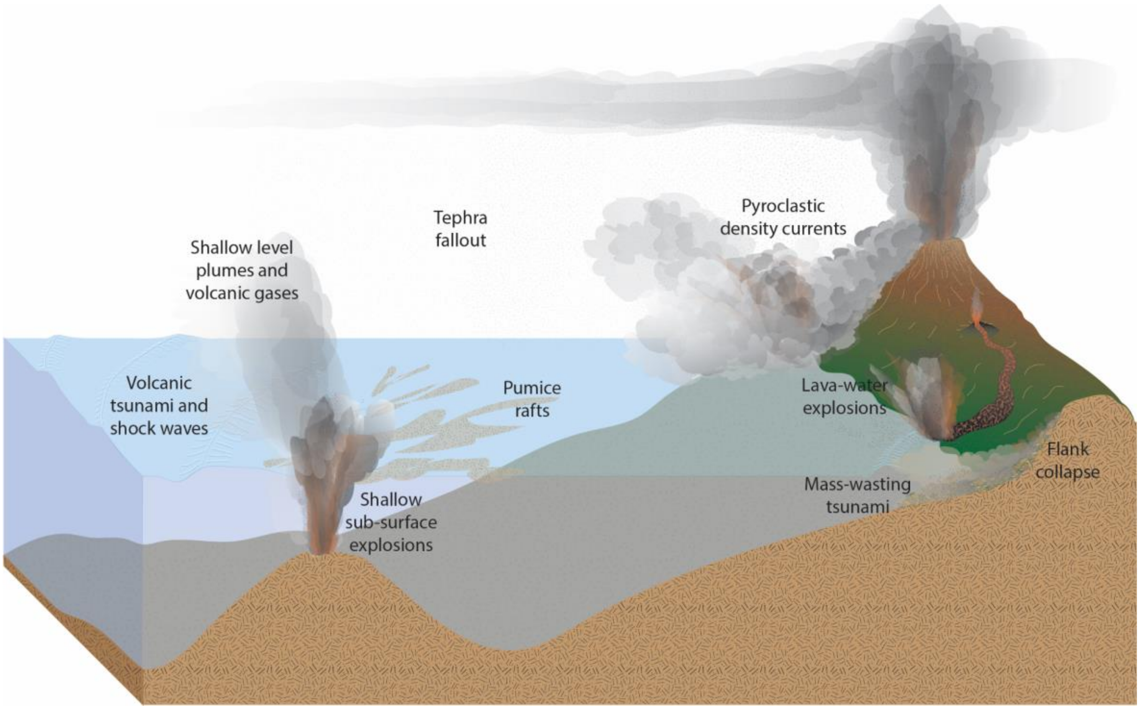
In this paper we outline the primary risks posed to shipping by explosive eruption, explore the level of risk the global shipping industry is exposed to, and outline a series of priorities for consideration by the volcanology and shipping community.

Primary hazards

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.

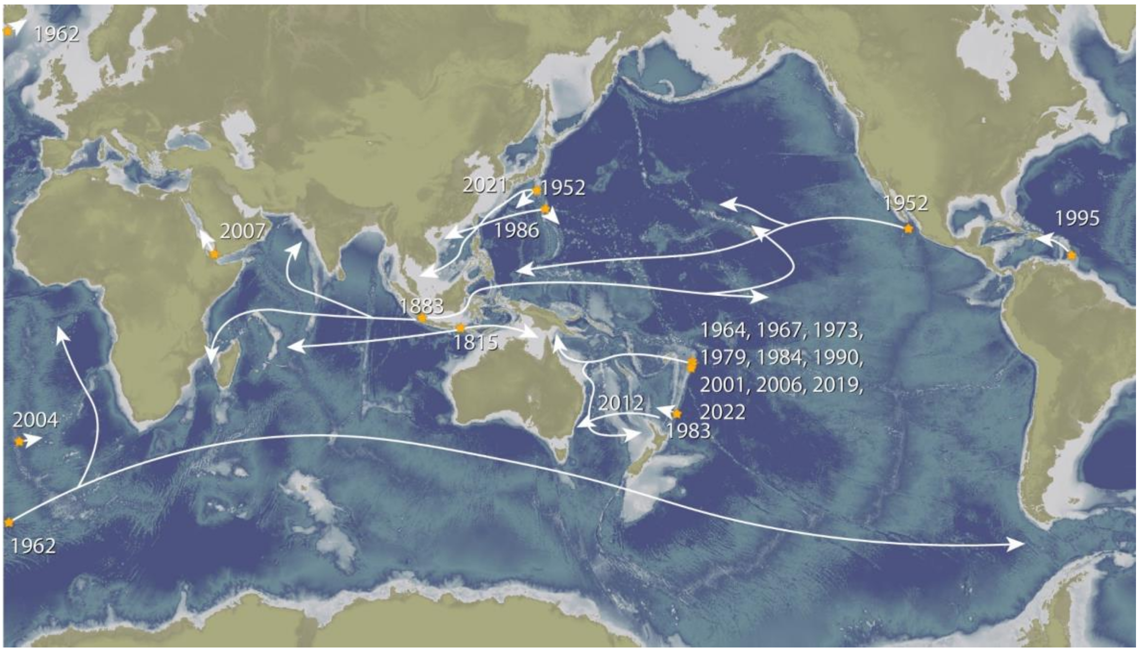
While larger eruptions such as Pinatubo in 1991 (VEI 6) can have regional and even global effects, even eruptions as small as VEI 3 can generate substantial tephra hazards in an area, and are much more frequent; while we might expect one or two VEI 6 eruptions per century, we could expect 5 VEI 5 eruptions in the same time, 70+ VEI 4 eruptions, and over 400 VEI 3 eruptions (Mason, Pyle, and Oppenheimer 2004; Papale 2018). This results in – on average – multiple large hazardous eruptions per year from explosive volcanoes, which are concentrated at oceanic plate margins, providing close proximity to shipping (Fig 1).

A typical subaerial explosive eruption, and many submarine eruptions, will produce a plume of tephra which is injected into the atmosphere. The height of this plume will vary with the eruption conditions, but can be anything from a few hundreds of meters to many tens of kilometres. This material will be sifted and transported by the local wind conditions, which can vary significantly by altitude (e.g. between the lower troposphere and stratosphere, Figure 2), resulting in the fallout of coarser material and the transport of finer over wide areas. Ash plumes from eruptions are routinely monitored, and have durations of hours to days.



The material sedimented from these plumes can range from several (up to tens of) centimetres diameter (pumice), to fine micrometre diameter ash particles 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. Fresh pumice and ash can therefore be quite fragile, buoyant, and even capable of acidifying local water as the captured sulphur oxides react with the water (Santana-Casiano et al. 2013).

Pumice rafts can accumulate as a result of this buoyancy of the material and rapid sedimentation (or ascent to the surface) of tephra. While wetting of pumice can result in substantial portions of it sinking, there is a fraction of the material which can remain buoyant for weeks up to years. These rafts are relatively poorly understood, and their accumulation, transport, and eventual break up are a focus of ongoing work. 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 (Fig. 2). They have been tracked traversing hundreds or thousands of kilometres from their source (Figure 3) over a period of weeks or months. Hazards they pose to shipping and shoreline infrastructure are documented (Asano and Nagayama 2021), as well as their ability to cause months of disruption thousands of kilometres from the volcano from which they erupted,.Pumice-engulfed ports in Okinawa, Japan, needed to be cleared by hand following the 2021 Fukutoku Oka-No-Ba eruption over 1200 km away (Yoshida et al. 2022).



Risk to shipping – mechanical hazards

Loss of propulsion

Nearly all marine engines rely upon seawater cooling systems to regulate their running temperatures. Older vessels may be able to operate with 50% reductions in cooling water volume, but newer vessels are known to have lower design overheads, and can experience issues at as little as 30% loss of volume of cooling water (Personal communications with Rolls Royce Marine Engineer technicians during building of a new vessel. Ulsan Shipyard, South Korea. May 2003).

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 should be kept clear of larger pumices allowing the small through. Sand-mud grade particles 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 will quickly block the internal strainers. Depending on the piece of machinery in question, the coarse filter size in these strainers may be as little as 3 mm mesh.

Main engine cooling water coarse filters are generally 10-15 mm mesh. There are two separate filters so the duty engineer can clean one while the engine is still being cooled via the second. Cleaning a filter is not necessarily a quick operation and, on larger vessels especially, may take two or three men a few hours to complete. Where the rate of intake of pumice is rapid enough, there may not be time to clean one filter while the other is still functioning.

In a well-designed main engine cooling system, with the vessel on reduced speed, it is likely that the main engine cooling water flow will be maintained. Recounting personal experiences, Lund (2001 to 2002, personal communication) found that, even working flat out, the coolers could not be kept clear and the vessel would only be able to make headway for 15 to 20 minutes at a time before she would black out again and have to drift with the pumice field while the cooling system was again cleared. Separate intakes for the auxiliary machinery (generator motors, refrigeration plant, air conditioning etc), where fitted, will have finer filters and are likely to quickly become blocked. Keeping these clear will be an added burden to the ship’s crew. It is likely that at least some machinery will have to be sacrificed so the main engine and generator motor cooling systems can be maintained.

On many large, modern vessels, their velocity through the water is enough to restrict the amount of cooling water that would enter a normal sea chest that is flush with the ship's hull. These vessels often utilize a scoop system when in deep water to aid the flow of water into the sea chest. These are not normally fitted with a coarse grid and all pumices meeting the scoop will be entrained into the sea chest thus exacerbating the problem. The presence of water promotes the aggregation of ash-sized tephra into larger particles (van Eaton et al. 2012), which would promote greater filter blocking.

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 will soon become clogged with entrained tephra (ash sedimentation within the atmosphere) and will 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. However, as the tephra fall gets heavier it may be impossible to keep these filters clean both through the rate at which they clog up and the hazards to the crew on deck (decreased visibility, slip hazards, and respiratory issues associated within inhaling fine ash; 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. In itself, this should not affect the operation of the engines, as any ash entrained into the combustion chamber will be expelled again in the exhaust as marine diesel engine operating temperatures (up to 350°C, e.g. Lu et al 2013, Korczewski, 2016) are below that required to melt primary volcanic material (400-800°C, Giordano, Nichols, and

Dingwell 2005). Abrasion of the inner surfaces and valves may eventually lead to degradation of the engine performance but should not be critical in the short term.

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 all result in outcomes ranging from changes in engine efficiency, to a requirement for maintenance or complete overhaul, through to engine shutdown (Chen and Zhao 2015; Wylie et al. 2017; Vogel et al. 2019).

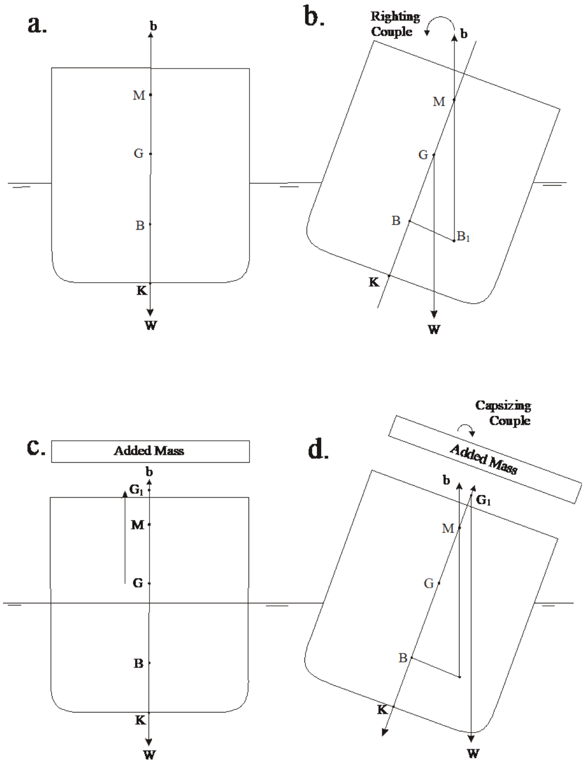
Electronic equipment

Modern marine diesel engines and other shipboard machinery are increasingly controlled by sophisticated electronic management systems which can be as complex as any found ashore or in an aircraft. Entrainment of tephra into the engine room may affect the electronics, although some research indicates that, in the short term at least, electronic components may not suffer too much (Gordon et al. 2005). Likewise, ‘stand-alone’ air conditioning equipment has been shown to be reasonably resilient to the effects of tephra entrainment into the condenser (T. M. Wilson and Cole 2007). Although their work was regarding a condenser for milk cooling equipment on a dairy farm both types work on the same principle and can be considered interchangeable.

The electric distribution system on land may be seriously affected by accumulation of only a few millimetres of tephra, especially if it is damp (Bebbington et al. 2008). Although vessels do not have an open distribution system, similar to that used on land, entrainment of tephra into switchboards and breaker panels may cause shorting and tripping of breakers. Radio aerials, especially those used for high frequency transmissions, can be similarly affected by shorting across insulators.

Stability

For a vessel to float upright the centre of buoyancy (B), centre of gravity (G), keel (K), and the metacentre (M) must be in a vertical line on the centreline of the vessel, with KM > KG > KB (Figure 4). In this case, she is said to have a positive metacentric height (+GM).



When a vessel is built, the position of her initial metacentre is determined by an inclining experiment and the height of the metacentre above the keel (KM) is tabulated for different draughts. To ensure all vessels are stable enough to meet all expected conditions during a voyage, a minimum set of criteria are laid down by legislation, including the minimum GM that a vessel must have at all stages of her voyage. In practice, most seafarers will keep well above these minimum criteria. However, as the GM can also affect the sea-keeping properties of a vessel, it must not be too large.

Where masses of unknown quantity (both total mass and location) are added to the vessel (e.g. tephra fallout), they must be allowed for when determining that the ‘departure/arrival’ and ‘at sea’ conditions for the ship meet the minimum legal requirements. These conditions are frequently encountered with either excess water or ice loading. Excess water mass is generally limited by the catchment area and is allowed for both in the minimum criteria mentioned above and particular features within the ship’s construction. Icing, however, is a different problem and much more like the situation that may arise from tephra accumulation.

Most vessels experience icing from meeting extreme temperature conditions in moderate to heavy weather. Water spray from the sea hits the cold steelwork of the vessel and deck cargo where it freezes and ice accretion occurs. As well as accumulating on the deck and other horizontal surfaces ice may also build up asymmetrically on vertical surfaces causing the vessel to list as well as loose stability. The International Maritime Organization lays down the minimum allowances required:

(1) All exposed horizontal surfaces are assumed to carry 30 kg m^{-2} of ice

(2) Vertical surfaces are assumed to be the lateral area of both sides of the ship above the waterplane and carry 7.5 kg m^{-2} of ice.

(3) Other surfaces not included in the above are accounted for by increasing the total of 1 and 2 by 5% and the calculated moments (mass x Distance from Keel or Centreline) of these weights by 10%.

(4) In this condition the vessel must never become overloaded.

(International Maritime Organization 2002)

Where vessels are to operate in locations where ice accumulation rates have historically been higher than the above, then additional allowances must be made.

The magnitude of loading by tephra lies within a broad window of values; while accumulation close to the vent 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 amounts 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. This footprint increased so by strong wind advection, and especially so by katabatic winds that drive air downslope from high elevation, such as in mountainous volcanic terrain to coastal regions and water.

Hazards to navigation

Position fixing

Attenuation and reflection of radar waves by precipitation is a well-known and documented phenomenon and is due to water being a lossy dielectric medium (Collin

1985). The reflective ability of water droplets is utilized in weather forecasting for tracking cloud and rain. For a seafarer, the greatest problem is that radar returns from rain tend to mask a target by scattering and reflection of the radar signal which, in heavy tropical showers and squalls, can lead to 'White-out' of the Radar screen. This makes identification and monitoring of returns from a vessel, navigation mark or coastline difficult although electronic modification of the received signal does help in overcoming this problem. Attenuation of the signal is not normally of concern at the ranges used for marine navigation and anti-collision work.

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. 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.

When dust or pollution particles are suspended in air, 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. Global Navigation Satellite Systems are unlikely to be strongly impacted unless wet tephra accumulate on the aerial.

Redirecting traffic

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 in the wrong place. This event lasted just 6 days, yet disrupted supply chains globally, delaying shipments, imposing substantial route diversions, and costing the global economy untold amounts in resulting knock-on effects. Pumice rafts are frequently observed to have lifetimes measured in months, and there are numerous bottlenecks to major shipping lanes which not only pass within short distances of active volcanic centres (Figure 1), but also that have already seen pumice raft activity (e.g. the Sunda Strait, the Red Sea, the Torres Strait, and others - see Figure 2)

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; Buist et athe Red Sl. 1986; S. H. Lee and Richards 2004; 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. For a vessel caught in an area of tephra fallout, or rendering assistance during or after a volcanic crisis, any exposure of the seafarer is likely to be short term. Due to the health restrictions placed upon serving seafarers most, if not all, will be of reasonable health; chronic asthma sufferers, for example, are not allowed to work on board ship. Irritation and bronchial tract problems are the most likely scenario following short term exposure, for tephra particles <100µm in size, but a healthy individual should be able to cope with this and the respiratory tract should clear soon after inhalation ceases. Use of PPE for crew and passengers, especially high graded PM-2.5 face masks can significantly reduce the risks from inhalation of volcanic ash, in the eventuality of prolonged exposure.

Possible risk reduction actions

A lack of fully comprehensive understanding of many of these hazards and risks (Table 1) necessitates exploring preventative and mitigative measures, as well as simultaneously improving process understanding. From improved monitoring and technology, to marine area management, to establishing new international communications networks, there are a number of methods that could be introduced to reduce the risk to mariners and maritime traffic from volcanic hazards. We note that the methods below are listed as possible suggestions for future study, and are not yet fully explored:

- *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, especially for ships frequenting areas with known or historical volcanic activity (Figure 1).
- *Establishing of temporary exclusion and risk zones during eruption watches and warnings* – Reducing the risk to maritime traffic by implementing pre-determined restrictive zones to maritime traffic, as is done for many volcanoes on land anyway. For example, this was applied following the eruption of Soufriere Hills Volcano, Montserrat, and ongoing with the active submarine volcanoes, Kick ‘em Jenny (Lesser Antilles) and Home Reef (Kingdom of

Tonga). We also see annual shipping traffic significantly reduced by the imposing of shipping restrictions in protected marine reserves around areas of ecological and biological interest e.g., Islas Galapagos and the Hawaiian Island Chain.

- *Formalising new networks and communications to notify ships of potential hazards* – There is currently no system in place that would routinely notify and advise maritime traffic to all nearby volcanic hazards, such as is currently done by the global Volcanic Ash Advisory Centres (VAACs) for aviation traffic. A similar system in place between volcano observatories and shipping traffic management could allow ships and traffic lanes to be better informed, educated, and to react quicker to approaching volcanic hazards in the event of an eruption.
- *Expansion of volcanic hazard and risk maps to offshore to incorporate coastal-proximal shipping traffic* – 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), require further physical modelling first, as the physics of their propagation changes at the coastline (traveling over land vs. over (and within) water).

Conclusions

The risks posed to shipping around volcanic centres are varied, and the scope of some of these hazards is relatively poorly constrained at present due to a lack of study. The frequency and distribution of volcanic eruptions globally has been an area of ongoing study, and there are unquestionably biases in the record which mean an underestimate of global volcanic activity has been systematically part of our assumptions for much of the last 50 years. These biases result from a lack of observation in remote areas, and this is particularly true of activity from submarine volcanoes. Satellite-based remote sensing is improving our ability to record and track these eruptions, but estimates of the magnitude of their threat to shipping is only likely to increase as we improve our ability to spot these events.

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 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 needs to become a subject of concern.

The bulk of the discussion in this paper has focussed on tephra fall, as these are processes which are well studied in the terrestrial realm. The formation, longevity and mechanics of pumice rafts is a nascent science, and much more work is required to understand how these form, travel, and disperse, and what the implications might be for ships and coastal infrastructure which might find themselves engulfed. The physics of pyroclastic density currents (PDCs) across and within water also requires much more study to explore the propagation and runout distances in the event of large explosive eruptions.

Considerable work must be done by the volcanological community in establishing baseline values for risk in the offshore setting, and with recent advances in remote sensing and monitoring this is now becoming a viable target for work. However, there is substantial space for the shipping industry to take steps based on what is already known, which we have highlighted. There is an opportunity to pre-empt the possibility of future crisis, and thus begin the work required, rather than waiting for an impactful event that encourages future work.

Given the myriad hazards which may be associated with explosive eruptions, we suggest that a collaborative and meaningful effort is focussed on 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.

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Figure 1. Global map of active volcanoes (white triangles) and shipping density (orange-red), 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.

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

Figure 3. Observed pumice raft tracks over the last 200 years, modified after (Bryan et al. 2012), with additional observations from (Jutzeler et al. 2014; 2020; Yoshida et al. 2022).

Figure 4. (a) For a vessel to be stable, the centres of Buoyancy (B) and Gravity (G) must be on the centerline with the Metacentre (M) above G. (b) When the vessel is inclined by an external force a righting couple will form and return the vessel to the upright. (c) If sufficient mass is added high up G will rise to G_1 above M. (d) When inclined by an external force a capsizing couple will form.