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Review

Observing ocean ecosystem responses to volcanic ash

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ABSTRACT

Volcanic eruptions can be catastrophic events, particularly when they occur in inhabited coastal environments. They also play important roles in climate and biogeochemical cycles, including through nutrient deposition in the ocean. Volcanic ash studies in the ocean have focused on the phytoplankton response, generally quantifying changes in chlorophyll-a concentration. Many gaps remain in addressing fundamental questions regarding why volcanic ash deposition may enhance or limit both phytoplankton growth and/or drive community composition shifts. Here we outline a wide, multidisciplinary vision for monitoring volcanic eruptions near ocean ecosystems from satellites, including considerations for characteristics of airborne volcanic ash and ash geochemistry in seawater. Ultimately, observations beyond chlorophyll-a are needed to quantify phytoplankton communities (including harmful algal blooms) and possible impacts across higher trophic levels. We synthesize relevant research from volcanic studies as well as atmospheric and ocean sciences to identify the 'known unknowns' in ash-ecosystem studies. Our goal is to move toward an improved understanding of how real-time and near-real-time monitoring of volcanic eruptions can help address societally relevant questions.

1. Introduction

Volcanic eruptions are extreme events that have had measurable effects on terrestrial and marine ecosystem function throughout Earth's history (Lee et al., 2018; Schmidt et al., 2012). Modern ocean ecosystem responses are relatively less studied than terrestrial responses, due in part to the challenges of observing volcanic ash (VA) impacts in situ, and because volcanic eruptions are commonly disastrous for society, while their impacts on ocean ecosystems are of secondary importance (Tayag and Punongbayan, 1994). The oceanographic community has only recently – in the last ~15 years – begun to consider whether it is possible to see a biological response to VA deposition using satellites and remote platforms. The focus on coupled volcanic-oceanic events in the literature largely centers on the principal volcanic eruptions that have elicited a profound ocean response through enhanced chlorophyll-a, leading to a general paradigm that volcanic eruptions fertilize the ocean by providing limiting nutrients (e.g., iron or manganese; Hamme et al., 2010, Browning et al., 2014, Wilson et al., 2019, Westberry et al., 2019, Barone et al., 2022). Substantial gaps remain in quantifying the full spectrum of phytoplankton responses to volcanic events, from low to high ash deposition rates across a range of chemical compositions (Fig. 1). Can volcanic eruptions always be expected to fertilize the ocean, or are there situations in which ash in seawater will have no measurable impact, or even a negative effect on marine biota? Answering this question is not only scientifically interesting, but it has societal importance as coastal communities grapple with volcanic disasters and their repercussions on water quality, fisheries, and human health.

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The likelihood of an ocean biological response from phytoplankton (unicellular photosynthetic protists that provide roughly half of the world's net primary production) to ash deposition is a function of several factors (Fig. 2). From the volcanic perspective, the main factors are the VA composition and emission rate across the size spectrum of ash (Zimanowski et al., 2003). From an atmospheric perspective, the properties of the VA (particle size, shape and composition) change as VA is transported from its volcanic source to ocean regions (Langmann et al., 2010). Ash may be dry-deposited (free fall of particles directly from the atmosphere) or wet-deposited (deposition of material mixed with suspended water, e.g., rain, snow, ice, fog in the atmosphere) depending on the presence and phase of water in the atmosphere (Duggen et al., 2010; e.g., Delmelle et al., 2001, Kawaratani and Fujita, 1990). Ash first deposited on land can then be remobilized by winds or runoff, leading to delayed deposition in the ocean (Fig. 2). Once in the ocean, ash vascularity (density) and geochemistry will affect its behavior in seawater, including its buoyancy, sinking, and solubility (Ayris and Delmelle, 2012). In the ocean, the degree to which phytoplankton are nutrient limited will affect any phytoplankton growth response to ash deposition (Hecky and Kilham, 1988), and different groups of phytoplankton respond differently to atmospheric deposition (Mahowald et al., 2017). The residence time and dilution of ash in water will be controlled by physical conditions and water mass circulation, in addition to mixing and resuspension events within the water column. Depending on ash deposition rate, ash layers in the surface ocean may limit light transmission to waters below, and ash may dilute phytoplankton as a food source in the water column, potentially decreasing encounter rates of phytoplankton and zooplankton (their predators). Ultimately, some or none of these characteristics may be available from remote platforms for any given volcanic eruption, due to the optically dense plumes obstructing various signals. Yet, given the episodic nature of volcanic eruptions, satellite remote sensing offers the only way to assess volcanic activities in real time (and synoptically) without physically traveling to the location by plane or ship. The availability of real-time (or near-real-time) observations are important for monitoring events to improve understanding of the role volcanoes play in influencing ocean ecosystems, and also may help provide aid to coastal communities experiencing disaster.

In this review, we introduce a flexible multidisciplinary framework with which to approach future remote sensing studies of volcanic ash in the ocean. We identify primary axes of importance, namely, 'Airborne volcanic ash characteristics,' 'Ash geochemistry in seawater,' and 'Ash impacts on ocean biota.' In order to move toward a predictive understanding of ash effects on ocean biology and biogeochemistry, these axes ideally will be considered in concert. We argue that a multidisciplinary approach is needed, as quantifying ash concentration, describing ash composition and behavior in seawater, and defining pre-existing ocean ecosystem structure are critical and non-trivial components for anticipating ocean impacts. Here, we identify the 'known unknowns,' or those parameters that are not able to be sensed from space but are important to consider (including possible downstream effects on zooplankton and fish). We discuss current progress from the viewpoint of lab-controlled studies and existing observations in situ, as well as uncertainties associated with attributing a remote sensing signal to a biological response to ash in the ocean. The framework presented here aims to move the field toward a diagnostic understanding of how satellite observations can help monitor real-time airborne and marine changes following volcanic eruptions.

2. Airborne volcanic ash characteristics

Volcanic ash (VA) is a broad term referring to the multiphase solid particulate matter emitted into the atmosphere by volcanic activity. VA physiochemical characteristics are critical to its impact on the Earth system because the composition and size of the ash will determine its interactions within the atmosphere. The chemical and mineralogical

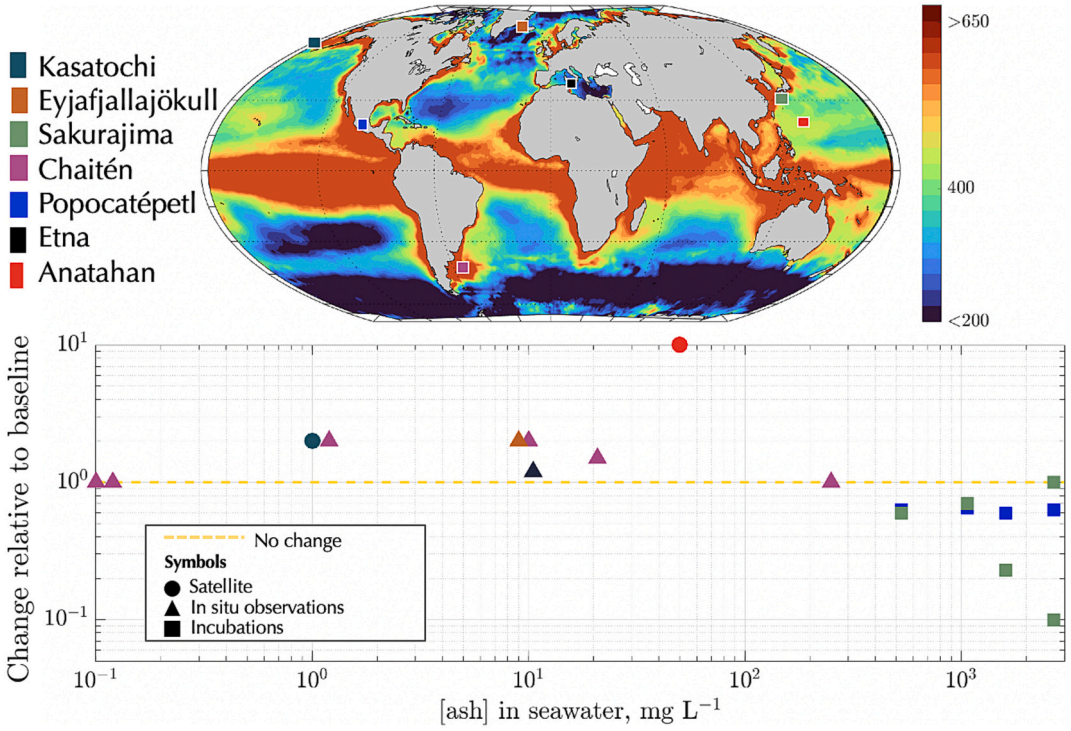

Fig. 1. (top) Climatological average of net primary production, mg C m^{-2} d^{-1} from the carbon based productivity model (Westberry et al., 2008). Locations with volcanic data are in colored boxes. Note that satellite, in situ, and incubation results are all presented as colored squares. (bottom) The relative change in chlorophyll-a concentration (circle and triangle symbols) and growth rate (square symbols) relative to a baseline (i.e., value after ash addition divided by value prior to ash addition) due to different concentrations of ash in seawater Satellite values are taken from Lin et al., 2011. In situ observations are from Mélançon et al., 2014, Browning et al., 2014 (and refs therein), and Achterberg et al., 2013. Incubations (with 2 different phytoplankton compositions) are from Hoffmann et al., 2012.

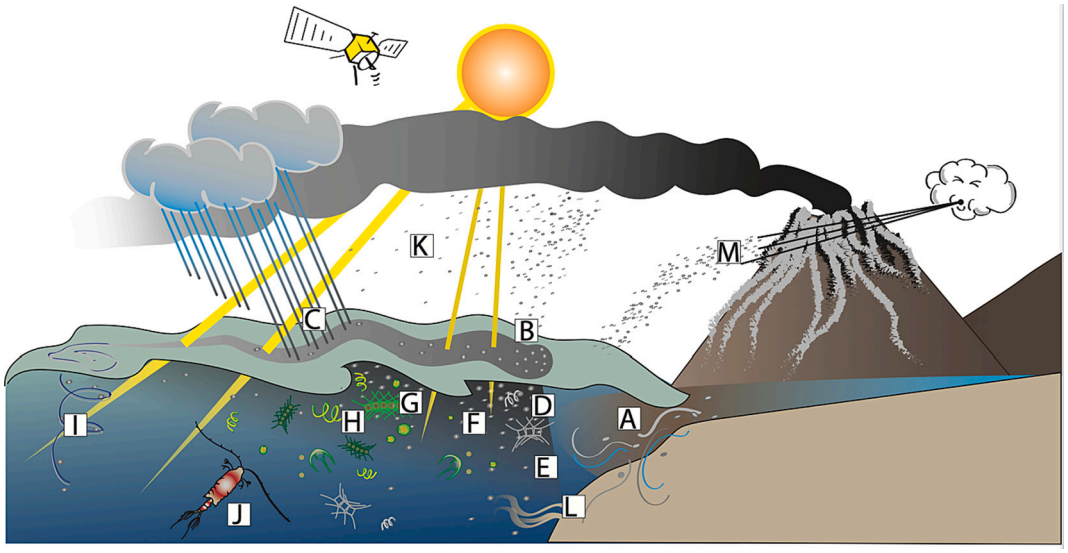

Fig. 2. Conceptual illustration of coastal volcanic eruptions. A. Fluvial input of aged ash and chromophoric dissolved organic matter (CDOM). B. Dry deposition. C. Wet deposition. D. Ash leaching (potential toxicity given by grey phytoplankton). E. Shading due to ash microlayer. F. Organic ligands enhance nutrient leaching. G. Enriched CDOM from increased particulate ash concentration. H. Increased phytoplankton growth and biomass, community changes. I. Vertical mixing enhances ash flux to depth. J. Possible trophic effects (direct or indirect). K. Higher light attenuation in the atmosphere closer to the volcanic source compared to further away. L. Resuspended ash and sediment from continental shelf. M. Remobilized ash.

composition and particle size distribution of VA is complex and may consist of: juvenile, angular volcanic glass shards; crystal fragments derived from multiple mineral phases (e.g., quartz, feldspar, micas, pyroxenes, amphiboles, olivine); and lithic fragments eroded from the volcanic conduit and vent during eruption (Vogel et al., 2017; Heiken, 1974). In volcanic plumes, VA always coexists with volcanic gases (water vapor, CO_2, SO_2, halogens) and liquid or solid hydrometeors (i.e., consisting of liquid or solid water particles) that can influence VA composition, element mobility and lifetime. Ionic and halide salts can also be incorporated into VA as the volcanic plume rapidly cools, and these salts may enhance the reactivity of VA above the plume (Ayris and Delmelle, 2012). VA will sink at different speeds depending on its size and density, and the soluble salt fraction is expected to quickly dissolve once the ash is deposited in seawater. The optical properties of the ash determine its interactions with incoming solar radiation and outgoing long wave radiation, as well as its interactions with clouds (Langmann, 2014).

In general, modeling top-of-atmosphere radiances while accounting for ash is challenging because VA has unknown composition and unknown refractive index, with unknown size and shape distributions (Krotkov et al., 1999a). Discriminating volcanic ash (VA) from metrological clouds (water and ice) and other aerosols (smoke, dust) requires advanced retrieval approaches, e.g., multiangle (MISR), polarization (POLDER, HARP), and spectral extension methods (UV Aerosol Index from TOMS, OMI/OMPS/GOME/TROPOMI). Aerosol layer height can be retrieved using O2 absorption and/or multi-angle stereo techniques. From the inversion point of view, retrieval biases present a major challenge, because there are no good a-priori constraints on the inversion. Wrong a-priori (size, shape, refractive index) results in biased ash optical thickness and mass retrievals. Given all these challenges, there has been reasonable agreement between independent ultraviolet (UV) and infared (IR) ash mass retrievals, as in the case of the Mt. Spurr eruption (Krotkov et al., 1999b). In addition, more comprehensive measurements of the complex refractive index of VA are becoming available (e.g., Deguine et al., 2023; Piontek et al., 2021; Reed et al., 2018), which will assist future VA ash mass retrievals.

The chemical composition of VA is unknown prior to an eruption, and while it can often be constrained based on the prior eruptive history and tectonic setting of a volcano (Rogers, 2015), this is not always the case for all volcanoes. The particle size range and components of VA depend on eruptive processes, and hence are largely unpredictable. Typically, silicic (SiO_2, >63% by weight) ash compositions produce more highly explosive eruptions, higher eruption columns, and finer VA particles (with very fine ash proportions of 30 to >50%, compared to 1–4% of basaltic eruptions, Rose and Durant, 2009), leading to longer atmospheric residence times and wider dispersal of VA, although particle shape also influences the atmospheric lifetime of VA. After an eruption has occurred, some compositional information can be derived from satellite measurements (Gangale et al., 2010; Clarisse et al., 2010a, 2010b, 2013), or in rare cases from direct airborne sampling of volcanic plumes (e.g., Rose et al., 2003). Hyperspectral infrared (IR) satellite measurements can distinguish VA from other airborne particulates (e.g., desert dust, wildfire smoke; Clarisse et al., 2010a; 2013) and can identify VA composition based on silica content (e.g., distinguish basaltic ash from rhyolitic ash; Gangale et al., 2010; Clarisse et al., 2010a). Ultraviolet (UV) satellite observations can potentially provide information on the iron oxide species present in VA (Carn and Krotkov, 2016; Go et al., 2022). However, satellite sensitivity to VA (and aerosol type in general) is limited, so ash plumes usually cannot be tracked very far from the source unless particle concentrations are rather high.

Critical for this review, the iron and phosphorus in VA has been suggested to impact ocean biogeochemistry (Langmann, 2013; Langmann et al., 2010; Duggen et al., 2007; Olgun et al., 2011, 2013). Studies have also shown that widely varying amounts and forms of bioactive metals (e.g., iron, zinc, cadmium) as well as toxic metals (e.g., lead, copper) and halogens (e.g., fluorine, chlorine) can accompany VA. However, VA composition is highly dependent on both the volcano and the eruption, and more systematic studies of the compositions of ash are required (Langmann et al., 2010; Duggen et al., 2010; Frogner et al., 2001; Vogel et al., 2017; Shkinev et al., 2016; Koffman et al., 2021).

Volcanic eruptions are often difficult to forecast, although eruption 'run up' time and eruption magnitude are broadly correlated. Large-magnitude eruptions are typically preceded by weeks to months of increasing unrest, which can provide a warning of an impending eruption, although forecasting the timing and magnitude of an eruption remains challenging (Passarelli and Brodsky, 2012). The ability to forecast eruptions relies on ground-based monitoring data (seismic, ground deformation, gas emissions), which are not available for the vast

majority of volcanoes (Brown et al., 2015). While the ability of satellite observations to forecast the timing of volcanic eruptions is nascent (Poland and Anderson, 2020), satellite data are routinely used to assess volcanic emissions and impacts shortly thereafter (Poland et al., 2020).

Ideally, an atmospheric assessment of VA should include the following major components: 1) location and timing of eruption; 2) duration of volcanic activity; 3) determination of ash injection height; 4) area covered as the ash cloud disperses; 5) quantification of ash emission

Table 1

Assessment of historical, current, and future satellite missions, their period of performance, spatial and spectral resolution, and applicability to studying atmospheric and marine aspects of VA in coastal ecosystems. Satellites are colored by their capabilities (orange = land/air properties, blue = ocean ecosystem properties) to guide a quick look at what resources are available. Aerosol concentration and particle size can be obtained from aerosol optical depth and the Angstrom coefficient, and aerosol composition or aerosol type (VA versus others) is given by ultraviolet absorption, infrared emissivity, and backscattering polarization. The location of aerosols in the atmospheric column is given by lidar backscattering coefficients, ultraviolet absorption and emissivity in the infrared. In the water column, chlorophyll, particle load, and dissolved material can be retrieved through remote sensing reflectance inversion algorithms in the visible range. Particle load and phytoplankton carbon can be obtained from lidar backscattering coefficients. Acronyms: Advanced very-high-resolution radiometer (AVHRR), Total Ozone Mapping Spectrometer (TOMS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR), Atmospheric Infrared Sounder (AIRS), Spinning Enhanced Visible and Infrared Imager (SEVIRI), Ozone Monitoring Instrument (OMI), Infrared Atmospheric Sounding Interferometer (IASI) on Meteorological Operational Satellite (MetOp), Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation mission (CALIPSO), Global Ozone Monitoring Experiment-2 (GOME-2), Geostationary Ocean Color Imager (GOCI) on the Communication, Ocean, and Meterological Satellite (COMS), Visible Infrared Imagining Radiometer Suite (VIIRS) on Suomi National Polar-orbiting Partnership (SNPP), National Oceanic and Atmospheric Administration satellites (NOAA), Advanced Technology Microwave Sounder (ATMS), Ozone Mapping and Profiler Suite (OMPS), Advanced Himawari Imager (AHI), Earth Polychromatic Imaging Camera (EPIC) on Deep Space Climate Observatory (DSCOVR), Advanced Baseline Imager (ABI) on Geostationary Operational Environmental Satellites (GOES), Ocean and Land Colour Instrument (OLCI), Tropospheric Monitoring Instrument (TROPOMI), Geostationary Environment Monitoring Spectrometer (GEMS) on Geostationary-Korea Multi-Purpose Satellite-2 (GEO-KOMPSAT 2), Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2), Earth, Cloud, Aerosol, and Radiation Explorer (EarthCARE), Ocean Color Instrument (OCI), Spectro-Polarimeter for Planetary Exploration (SPEXone), Hyper-Angular Rainbow Polarimeter-2 (HARP-2) on Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite, Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR) instrument.

Instrument * = geostationary	**Mission** **Timeline**	**Resolution** (pixel length, km)	**Wavelengths** **(bold is hyperspectral,** else multispectral**)**	**Capability**	
AVHRR	1978 - present	1.1	Visible (green, red), NIR to IR		
TOMS (NIMBUS-7, Earth Probe)	1978 - 2005	4.7	UV		
Landsat-5,7,8,9	1984 - present	0.1	Visible, NIR to IR		
SeaWiFS	1997 - 2010	1.1	Visible, NIR		
ASTER (Terra)	1999 - present	0.015	Visible (green, red), NIR, TIR		
MODIS (Terra, Aqua)	1999/2002-present	1	Visible, NIR, IR		
MISR (Terra)	1999 - present	4	Visible, NIR		
AIRS (Aqua)	2002 - present	13.5	**NIR, IR**		
SEVIRI (MSG)	2002 - 2022	3	Visible, NIR, IR		
OMI (Aura)	2004 - present	13 x 24	**UV – Visible**		
MetOp/IASI	2006 - present	1	**IR**		
CALIOP (CALIPSO)	2006 - present	5	Polarized lidar 2 channels: 532, 1064 nm		
GOME-2 (MetOp-A)	2006 - present	40	**UV, Visible**		
GOCI (COMS*)	2010 - present	0.5	Visible and 1 NIR		
VIIRS (SNPP, NOAA-20, NOAA-21)	2011 - present	0.375-0.75	Visible, NIR, IR		
ATMS (SNPP, NOAA-20, NOAA-21)	2011 - present	15.8	Microwave radiances (23.8 – 183.3 GHz)		
OMPS (SNPP, NOAA-20, NOAA-21)	2011 - present	50	**UV**		
AHI (Himawari-8,9*)	2014 - present	0.5-4	Visible (blue, green, red), NIR, IR		
EPIC (DSCOVR)	2015 - present	18	UV, Vis, NIR		
ABI (Goes-16/17*)	2016 - present	2	Visible, NIR, IR		
OLCI (Sentinel 3a,b)	2016 - present	0.3	Visible, NIR		
TROPOMI (Sentinel 5p)	2017 - present	3.5	UV, Visible, NIR		
GEMS (GEO-KOMPSAT 2B*)	2020 - present	0.5 - 2	**Visible, NIR**		
ICESat-2	2018 – present	0.5 -3	Elastic lidar, 532 nm		
EarthCARE	2023 launch date		Polarized UV lidar, Visible, NIR, IR, TIR		
OCI / SPEXone / HARP-2 (PACE)	2024 launch date	1	**UV, visible, NIR, IR,** with polarimeters		
GLIMR	2026/7 launch date	0.3	**UV, NIR, IR**		

and dispersal; and 6) determination of ash plume mineralogical and chemical composition, physical properties, and changes in near-real-time. Current satellite technology can generally supply this information, but observational conditions and sensor limitations frequently work in combination to prevent successful detection. For example, the time of satellite overpass with respect to the eruption stage is critical because the initial plume's vertical extension provides the injection height, which in turn constrains the horizontal extension and dispersal of the volcanic cloud. When determining total aerosols in a satellite pixel using a passive sensor (e.g., MODIS or GOES/ABI, see Table 1), a clear sky view is needed so all the observed radiation can be linked to the aerosol loading. Partially cloudy scenes are frequently unused because of the inability to parse out the cloud from the aerosol contribution to the observed signal (see also Platnick et al., 2003). While geostationary sensors have been operational for a few decades and have been used to monitor historical eruptions (Holasek and Self, 1995; Marchese et al., 2022), these sensors lack adequate spatial and spectral resolution for quantification of fine aerosol loadings (<1 um). The poor sensor resolution of fine aerosols is important because these fine aerosols can travel the farthest, and thus are deposited over a very large area (Fig. 3). The deployment of the latest generation of geostationary sensors has been a clear improvement with respect to this issue as the observations of the Himawari-8 Advanced Himawari Imager (AHI) and GOES-17 Advanced Baseline Imager (ABI, Table 1) enabled an excellent characterization of the vertical extension and evolution of the ash cloud of the 2022 Hunga Tonga eruption (Carr et al., 2022). Furthermore, legacy and improved aerosol detection and retrieval algorithms (Pavolonis et al., 2015; Kondragunta et al., 2020; Gupta et al., 2019) are being ported to geostationary imagery, thus enabling aerosol information suitable for comparison with aerosol transport models. Satellite observations typically record less than 6% of the total erupted ash mass (Rose et al., 2001, their Table 7), and provide a biased sample of the grain size distribution (by preferentially providing measurements of fine sized ash (< 17 μm) compared to what is observed on the ground (> 20 μ, Stevenson et al., 2015; Prata and Lynch, 2019). Satellite radiances may also be saturated by the strong VA signal immediately following an eruption, and satellite observations of VA mass are confounded by the VA composition unknowns (Krotkov et al., 1999a). Both field and satellite measurements are needed to record the mass, distribution, composition, and other characteristics of the ash deposition (Cashman and Rust, 2020).

Regardless of observation sampling frequency, quantifying aerosols in the atmospheric column is an important challenge. Once emitted into the atmosphere, ash is transported horizontally and vertically within the atmosphere similar to any aerosol, and removed through either dry deposition (gravitational settling or turbulent deposition) or by wet deposition (by precipitation) out of the atmosphere (Mahowald et al., 2011a; Stohl et al., 2011). Understanding these transport processes is critical, not only to estimate the fetch of the deposition area, and also to elucidate the compositional chemical changes in the ash cloud during transit. The altitude of the plume is particularly important, because aerosols lofted higher will reside in the atmosphere longer. Particles reaching the stratosphere will have a much longer lifetime, as the stratosphere is more stable and does not have wet deposition processes (Stohl et al., 2011). While volcanic aerosols are present through the column in the immediate vicinity of the volcano, rapid sedimentation within a few hundred kilometers results in a volcanic cloud located in the mid to upper troposphere, on top of a 'cleaner' lower atmosphere. Thus, a significant portion of total aerosols (all aerosols, not just from volcanoes) are in the marine boundary layer immediately downwind from the volcano, where maximum deposition will occur.

Satellite data are commonly used within models to better contextualize and forecast VA dispersion. Generally speaking, the study of volcanic ash transport makes use satellite data in different ways depending on the intended application (climate or biogeochemical or disaster response) and the nature of the model (Lagrangian or Eulerian types). Lagrangian type of transport models are generally preferred for rapid response because they can be quickly initialized with weather forecast information as well as satellite data that can be quickly processed (Gouhier et al., 2022). Thus, for example, initial satellite estimates of volcanic plume height (Chai et al., 2017) and total aerosol mass concentration amounts are used to initialize and constrain the forecast (Pardini et al., 2020). Satellite data are also used for verification and calibration of forecasts (Crawford et al., 2022; de Leeuw et al., 2021). For climate applications, Eulerian modeling approaches are preferred for hemispherical or global simulations that encompass multiple eruptions and/or long time periods. They also either assimilate satellite to constraint simulations or are used to verify or adjust parameterizations assumed in the simulations (Wells et al., 2023; Bruckert et al., 2022; Muser et al., 2020).

In addition to the unknown composition of the material initially released to the atmosphere, the uncertainty of simulated aerosols in Earth system models are primarily due to: 1) the altitude of the volcanic plume, which depends on the eruption explosivity, ejected material density, entrainment, and gas temperatures; and 2) the particle size of ash falling out of the plume (Stohl et al., 2011). Note that there is a difference in language between volcanologists and the aerosol community, where the aerosol community uses 'fine' and 'coarse' for aerosols less than 2.5 μm and 10 μm in diameter respectively (Mahowald et al., 2011b), while the volcanic community considers 'fine ash' to be ash less than ~100 μm in size (e.g., Osman et al., 2020). In all cases, relatively larger ash particles will be removed much more quickly from the atmosphere due to gravitational settling (Petroff and Zhang, 2010). Consequently, as the plume moves downwind, the particle size distribution and relative composition of ash will change (Fig. 3). The higher

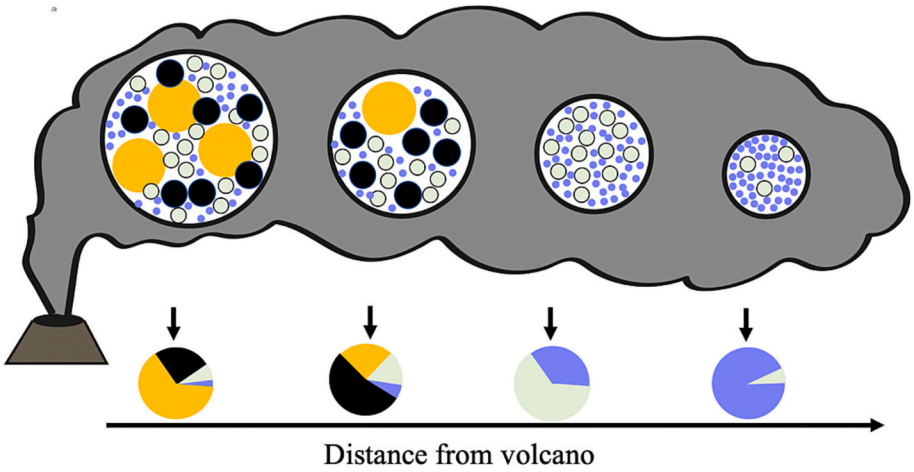

Fig. 3. Conceptual diagram of 4 ash sizes (largest in yellow, followed by black, light green, and purple) with increasing distance from the volcano. Larger ash will be deposited in the immediate vicinity, and possibly dominate the mass flux of ash types compared to farther from the volcanic source where fine-sized ash and smoke remains. The pie charts represent the relative composition of ash in the ocean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deposition of VA near a coast does not necessarily mean that open ocean areas are unaffected, particularly if VA is carried by strong offshore winds (Hamme et al., 2010).

3. Ash geochemistry in water

3.1. Deposition and dissolution

There are a number of known processes that can impact the spatio-temporal variability of phytoplankton response, including wet and dry deposition to marine surface waters, fluvial inputs of terrestrial ash, sinking of ash particles in the water column, composition of ash leachates, and the role of organic compounds in facilitating elemental transfer and solubility (Fig. 2). Taken together, these processes will direct future work to permit a detailed understanding of when and where VA inputs will have the greatest effect on marine primary productivity, and whether these inputs will be advantageous or deleterious to phytoplankton growth. Ultimately, satellite remote sensing offers very little in the realm of aqueous ash geochemistry, but understanding the pathways of ash dissolution in seawater can help improve and contextualize satellite observations, especially when ancillary in situ observations may be available.

Ash constituents can become solubilized or otherwise available to phytoplankton communities through several pathways: 1) dissolution of dry ash particles that are deposited directly to surface waters (dry deposition), 2) dissolution of ash aerosols in clouds or humidity prior to deposition via rain or snowfall to surface waters (wet deposition, and note that wet deposition does not always include ash dissolution), or 3) redistribution of 'fossil' ash that was previously deposited on terrestrial landscapes via either wind remobilization or rainfall-runoff processes and riverine transport. Leaching experiments (to solubilize away materials with water) conducted over the last few decades indicate that VA is a consistent and significant source of nutrients, essential elements, and trace metals, including Fe, Al, P, F, Mn, Zn, Cl, Ca, K, Mg, Na, and SO_4 (Witham et al., 2005; Duggen et al., 2010; Stewart et al., 2020). Similar enrichments of metals have been observed immediately post-eruption in ash-impacted seawater (Censi et al., 2010) and dissolution is suggested to occur fast enough to support enhanced primary production in surface waters prior to sinking of ash particles (Frogner et al., 2001). Although it has not been measured directly, VA may be reemitted from surface waters to the overlying atmosphere, as has been observed for dust (Cornwell et al., 2020).

Chemical composition, solubility, and particle size of VA vary widely (Duggen et al., 2007; Olgun et al., 2013; Hoffmann et al., 2012; Mahowald et al., 2018). Fresh, dry VA hosts myriad soluble elements, most notably Fe for nutrient-limited seawater, that quickly dissolve in water vapor (humid environments) or are washed away by meteoric water (rainfall, rivers, etc.) upon initial water-ash interactions (Duggen et al., 2010). Some of these elements may be in the form of sulfate and halide salts, which may form at magmatic temperatures (600–1200 °C), through chemisorption near the condensation temperature of sulfuric acid (~200 °C) in plumes, or possibly through partial dissolution of ash in contact with sulfuric and halogen acids at lower temperatures (Delmelle et al., 2018). While the formation of Fe-sulfate salts has not been observed, their existence has been invoked to explain the rapid release of Fe upon contact with water (Ayris and Delmelle, 2012). Since the dissolution of volcanic salts in clouds and water vapor occurs at a lower pH than seawater, the solubility and potential bioavailability of some elements, such as Fe, may be significantly enhanced during wet deposition compared to dry deposition (Duggen et al., 2010). Finally, larger VA aggregates, which are promoted by high humidity, enhance deposition of ash particles in surface waters closer to the eruption site because atmospheric residence time and distance traveled are a function of particle size (Duggen et al., 2010; Colombier et al., 2019).

During volcanic eruptions, a portion of ash is deposited on terrestrial landscapes. Due to the physicochemical nature of deposited ash (e.g., organo-metallic complexes, low pH, presence of toxic metals), VA soils have been shown to stabilize large stocks of organic carbon (Eswaran et al., 1993; Tonneijck et al., 2010). The reaction of volcanic gases with ash and water vapor results in soluble salts from freshly deposited ash, and could lead to acute effects in proximal freshwater environments (Smith et al., 1982; Modenutti et al., 2013), as well as potentially chronic impacts on coastal environments over the long term. Although fossil volcanic ash has lost most of its salt coating during first contact with water, the disaggregation of previously deposited ash particulates (during river or wind transport, debris flows, human activity, etc.) has been shown to enhance the release of elements such as Ca, Na, Al, K, and Si to exposed waters (Genareau et al., 2016). On a macroscale, volcanic eruptions significantly alter watershed hydrology and geomorphology via soil destabilization, accumulation of dead woody debris, and deposition of new ash layers (Pierson and Major, 2014). Taken together, these hydrogeomorphic changes result in massive and stochastic delivery of organic carbon and pyroclastic material to coastal regions (Mohr et al., 2017; Umazano and Melchor, 2020). The legacy effects of volcanic events can persist for decades to centuries after the eruption occurs (Pierson and Major, 2014; Steinman et al., 2019; Major, 2020). This phenomenon is recorded in sedimentary records, which indicate that deposited ash enhances organic carbon burial and preservation in coastal sediments on historic and geologic timescales (Lee et al., 2018; Longman et al., 2019). These impacts result from a combination of fertilization and enhanced primary production in surface waters, oxygen depletion in ash-affected sediments, and direct organo-mineral associations (Haeckel et al., 2001; Hembury et al., 2012; Longman et al., 2021).

Regardless of whether VA enters marine surface waters fresh or aged, and via wet or dry deposition, previous studies agree that the presence of adsorbed organic ligands (any molecule or atom that binds to a receiving molecule) during transport further enhances the solubility and mobilization of some elements from VA (Duggen et al., 2010; Censi et al., 2010). It is suggested that these organic ligands may derive from phytoplankton, cell lysis, and/or bacterial decomposition of organic matter in surface seawater or originate from burnt vegetation or volcanic gases in eruption plumes (Randazzo et al., 2009; Baker and Croot, 2010; Taylor and Lichte, 1980; Capaccioni and Mangani, 2001). Although organic ligand-metal interactions appear to be a major factor in VA solubility and bioavailability, very little is known about how organic carbon may adsorb onto fresh VA during transport (Weinbauer et al., 2017), let alone its leachability and contribution to dissolved organic carbon in ash-affected seawater. A water quality study of the effects of a volcanic eruption on Patagonian lakes showed up to an 8-fold increase in total suspended solids concentration, but no change in dissolved organic carbon concentration (Modenutti et al., 2013), which suggests that bulk dissolved organic carbon inputs from ash deposition may be negligible in marine environments. Further research on the content and composition of organic carbon associated with VA is needed.

The aging of VA between initial eruption and subsequent deposition to surface seawater appears to be a major control on the potential beneficial, harmful, or neutral impacts on marine phytoplankton and higher trophic levels. Several studies have shown that the composition of ash collected immediately following an eruption can change during laboratory storage, such that older (unhydrated) samples release less Fe during leaching experiments than fresher samples from a similar volcanic setting (Jones and Gislason, 2008; Duggen et al., 2010; Olgun et al., 2011). This decreased Fe solubility over a period of 10–25 years has been attributed to the loss of soluble salt coatings on ash grain surfaces, although this loss has not been observed directly.

In contrast, the environmental aging of VA, wherein ash remains on the land surface for years to centuries following an eruption and interacts with meteoric and groundwater subsequent to remobilization by wind or water, also impacts ash geochemistry and may enhance the bioavailability of Fe and other metals in ways unrelated to salt coatings.

For instance, in the high-precipitation environment of southern Alaska, environmental aging processes resulted in 5× higher Fe solubility and 10× higher easily-reducible Fe compared to fresh, dry-deposited ash (Koffman et al., 2021). Changes in Fe-bearing phases may relate to soil formation processes and the migration of Fe through the ash/soil profile through time (Koffman et al., 2021), and thus aging processes are likely to differ depending on climate regime. Wind remobilization events in volcanically-active regions (Flower and Kahn, 2017) have been documented following eruptions in Iceland, Alaska, Kamchatka Peninsula and Patagonia (Bullard et al., 2016, Meinander et al., 2022 and references within), so further work is needed to determine the role of ash remobilization events in providing nutrients to ocean ecosystems, particularly considering how aging processes may enhance or reduce the solubility of Fe and other bioactive metals.

4. Ash impacts on ocean biota

4.1. Toxicity

In addition to fertilization impacts on ecosystems, VA has the potential to deliver toxic quantities of trace metals and halogens to the environment (Kockum et al., 2006) and may also scavenge anthropogenic organic compounds such as dioxins, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) (Ayris and Delmelle, 2012, and refs therein). Phytoplankton toxicity has been reported for Cu concentrations of 11–200 ppm in seawater (Mann et al., 2002), for Pb concentrations of 20–465 ppb, and for Cd of 0.23–500 ppb (Echeveste et al., 2012). Other trace metals found in VA may also be toxic at high concentrations. While desert dust is recognized as the largest natural source of Cu to the ocean surface (Lopez et al., 2019) and has been found to cause toxic effects (Paytan et al., 2009), explosive volcanic eruptions can deliver much greater quantities of Cu and other metals to relatively small geographic areas, thus increasing concentrations above toxic thresholds. For instance, using measurements from Aleutian Arc volcanoes, Koffman et al. (2021) estimated that an eruption with a similar magnitude to Kasatochi (in 2008) could deposit ~1400–2600 metric tons of Pb, ~9000–18,000 metric tons of total Cu, and 400–800 metric tons of soluble Cu in nearby waters. These estimates are somewhat higher than those for the 2008 eruption of Chaitén, likely reflecting differences in volcanic composition (Ruggieri et al., 2012). While it seems plausible that VA deposition could have widespread negative impacts on marine ecosystems, to our knowledge this effect has not been observed, perhaps due to rapid physical transport (dilution) in ocean waters.

Toxicity depends on the amount of free, uncomplexed metal available; as organic ligand concentrations increase, metal uptake by transport proteins decreases (Sunda and Huntsman, 1998). Therefore, toxicity can only occur once available chelators (chemical compounds binding to metal ions) are saturated (Moffett et al., 1997). In terms of Cu toxicity, cyanobacteria are the most sensitive, dinoflagellates and coccolithophores have intermediate tolerance, and diatoms have the highest tolerance (Lopez et al., 2019). Toxicity sensitivity scales with cell size (where larger cells have higher tolerance), possibly due to diffusion rate differences (e.g., Behrenfeld et al., 2022) across cell sizes. Elevated trace metals from VA deposition can impact phytoplankton species differently, and these differing responses can lead to shifts in community composition (Hoffmann et al., 2012). It may be expected that ongoing ash inputs in volcanically active regions play a role in driving community structure, and future satellites with higher spectral resolution like NASA's PACE (Plankton, Aerosols, Clouds, and ocean Ecosystem; Werdell et al., 2019) mission may help in observing community composition changes following ash deposition due to the improved information about phytoplankton communities found in hyperspectral data (e.g., Chase et al., 2017; Kramer et al., 2022).

As well as delivering large quantities of metals to the environment, volcanoes emit halogens such as Br^- and F^- that are known to cause severe toxic effects to humans, livestock, and both terrestrial and aquatic ecosystems. Emissions of hydrofluoric acid from the 1783–1784 Laki eruption (Iceland) decimated livestock and caused long-term health problems such as fluorosis (Thordarson and Self, 2003), which is a skeletal and dental disease arising from overexposure to fluoride. Fluorosis in both wild and domesticated herbivore populations has been observed following recent eruptions in Chile (Flueck, 2016). Fluoride can be toxic to aquatic organisms at high concentrations (Camargo, 2003), but little is known about the impacts of volcanic fluoride emissions on marine ecosystems. Additional work is needed to understand the potentially toxic impacts of volcanic eruptions. Satellite imagery cannot directly observe toxicity, but satellites could, for instance, observe the impact of toxicity via low phytoplankton concentrations compared to what is expected for similar light, nutrient, and zooplankton levels.

4.2. Phytoplankton

The observed impacts of VA on marine organisms are scarce and while the response of phytoplankton is the most commonly reported, these results vary (Fig. 1). As previously discussed, while VA in seawater may provide limiting and co-limiting nutrients needed for phytoplankton to grow, VA may also contain toxic metals that inhibit phytoplankton growth. Diffusion rates of nutrients or metals from VA into seawater will vary with VA characteristics, namely size and solubility. VA may have no effect whatsoever on phytoplankton growth; the ash can be diluted in seawater depending on local physical conditions, there may be a lack of nutrient availability in the ash, and/or the phytoplankton may not be nutrient-limited, all of which could lead to no change in phytoplankton growth rate. Regardless of the nutrients contained in ash, the addition of highly absorbing material (both particulate and dissolved ash) can alter the light environment, reducing the light available for photosynthesis. In all cases, some phytoplankton groups may have advantages that allow them to perform better than others in ashen seas (Hoffmann et al., 2012; Kramer et al., 2020). One case study, which analyzed stream water quality during and after the 2011 eruption of Mount Bulusan (Philippines), showed a 2-fold increase in mean silica concentration that is thought to have caused an observed shift toward a diatom-dominant community in the estuary into which the streams drain into (Siringan et al., 2018). Changes in phytoplankton community composition following VA input may also alter the structure of the marine food web across trophic levels (see the following sections). High concentrations of ash can also dilute the food source for zooplankton and/or clog fragile mucous membranes (see Drazen et al., 2020 and refs therein), which could relieve top-down grazing pressures on phytoplankton and allow cells to accumulate. The challenge of distinguishing such biological responses becomes even more complex when the uncertainty of satellite observations used to derive phytoplankton properties is taken into consideration.

Methods to assess the biological response to different ash additions include both in situ bottle incubation studies as well as remote sensing methods (e.g. Hoffmann et al., 2012 vs. Duggen et al., 2007). It is difficult to time a research cruise to be simultaneous with an extreme and unpredictable event such as a volcanic eruption in order to assess the ash effect directly (Bisson et al., 2020a), and thus remote sensing is an excellent tool for looking at ocean responses. A primary challenge of assessing biological effects of ash from satellite remote sensing is that no satellite offers direct observations of phytoplankton. Rather, ocean color satellites measure top-of-atmosphere reflectance, which requires appropriate atmospheric correction to uncover the ocean signal (remote sensing reflectance), and remote sensing reflectance covaries with phytoplankton, non-algal particles (ash, detritus, sediment), and colored dissolved organic matter that may be enhanced by ash leachate. For most of the ocean, satellite chlorophyll-a is derived from empirical algorithms using remote sensing reflectance. In these waters, phytoplankton (and co-varying constituents) drive the ocean color signal.

However, phytoplankton alone do not drive the ocean color signal when ash is present, and ash is optically complex, as it spans different sizes, solubilities, and composition (Kramer et al., 2020). In these waters, the standard chlorophyll-a algorithm likely does not perform accurately. Several studies have explored an oceanic response to ash using satellite observations of chlorophyll-a (a pigment common to all phytoplankton; Duggen et al., 2007, Hamme et al., 2010, Henson et al., 2013, Browning et al., 2015, Westberry et al., 2019) because chlorophyll-a can be derived from remote sensing reflectance. However, chlorophyll-a is an imperfect metric for phytoplankton biomass, as pigment concentration and expression vary with changes in phytoplankton physiology (by up to a factor of ~3, see Behrenfeld et al., 2005 and data therein), and the presence of VA in the ocean and atmosphere affects the performance of satellite algorithms used to obtain accurate chlorophyll-a estimates. Westberry et al. (2019) also considered the response of chlorophyll-a fluorescence and phytoplankton carbon to study changes in growth/physiology for two volcanic eruptions, but these products (and any products derived from remote sensing reflectance inversions, including phytoplankton absorption) may also be sensitive to ash in the water and/or atmosphere. Ultimately, chlorophyll-a, fluorescence or phytoplankton carbon may not be the most useful metric to quantify planktic ecosystem changes because changes in chlorophyll cannot be explicitly linked to different types of phytoplankton (including harmful algal species, which are of particular concern for human health and fisheries). To develop a holistic perspective on volcanic ash impacts, remote sensing observations coupled with shipboard measurements are needed.

Little research has been conducted to quantify the optical influence of ash on remote sensing reflectance, but available work suggests that rhyolitic ash in seawater biases satellite chlorophyll-a by more than an order of magnitude for oligotrophic waters, and by less than a factor of 2 for environments with >0.5 mg chlorophyll-a m^{-3} (Browning et al., 2015). A recent study found different inherent optical properties (enhanced absorption by dissolved material in particular) during Thomas Fire ash deposition (Kramer et al., 2023). There are substantial knowledge gaps in understanding how VA affects inherent optical properties of seawater. One reason for the knowledge gap is in part because remotely sensed inherent optical properties are retrieved from apparent optical properties, and quantifying the latter is highly uncertain during VA deposition. The ash particles present in the atmosphere act as strong light-absorbing aerosols, and the standard ocean color atmospheric correction algorithms may not fully remove this component, resulting in an enhanced water-leaving signal that translates to an augmented chlorophyll-a signal (Gordon and Wang, 1994; Nobileau and Antoine, 2005; Ahmad et al., 2010). More work in this area is needed, especially because the relative uncertainties associated with satellite-derived chlorophyll-a concentrations are a function of both the ocean environment and the ash type. Despite these challenges and those mentioned above, satellite remote sensing remains an important tool for studying the biological effect of ash in situ, because satellite observations can provide time-series context while also resolving spatial heterogeneity in the ocean signal. Improved quantification of uncertainties in the remote sensing signal will undoubtedly improve interpretation of any biological response in the ocean to VA input.

4.3. Zooplankton and Fish

One blind spot of remote sensing is the quantification of VA impact on zooplankton, which feed on phytoplankton and are a link to higher trophic levels, including fish. Although detecting zooplankton through remote sensing platforms is in development (e.g., Behrenfeld et al., 2019; Basedow et al., 2019), existing satellite observations can be coupled with in situ zooplankton observations to be used in food-web models for improved prediction of herbivory rates (e.g., Bisson et al., 2020b). At the time of writing, there are no studies that characterize the effects of VA on marine zooplankton. An analogy may be found in lake zooplankton, where one study in the Andean North-Patagonian lakes found that filter feeders (mainly cladocerans) did not reach adulthood when VA concentration exceeded 8 mg L^{-1} (Balseiro et al., 2014), and in general, survival and fecundity decreased following ash exposure. This study noted the resurgence of zooplankton in the year following the eruption, implying a short-term effect. Parallels may also be drawn from the deep-sea community, through studies of nepheloid layers and sediment resuspension events. Increased sensitivity of zooplankton to ash concentration with distance from the coast might be expected, as these open ocean organisms are likely adapted to water without high sediment concentrations. Physiological distress can be caused by ash clogging the respiratory and olfactory membranes of these animals, and sediment can reduce the buoyancy of gelatinous plankton if it adheres to them (Drazen et al., 2020; Robison, 2009). Filter feeders may experience bottlenecks within their fragile mucous nets as well as dilution of food due to ash in seawater. More work is needed to quantify the extent to which ash affects zooplankton based on the expected range of ash concentrations and the associated zooplankton response, especially to inform coastal communities of possible ecological changes in the nearshore environment.

Light is a primary factor in structuring the distribution of marine organisms in the upper ocean, including zooplankton and fish, and light moderates predator-prey interactions between the two (Hansen and Visser, 2016). Remote sensing reflectance, photosynthetically available radiation (PAR), and light attenuation are all measured routinely from satellites. Ash deposition onto the ocean surface has the potential to decrease light levels (i.e., lower PAR, higher light attenuation) by increasing turbidity, a factor known to alter predator-prey dynamics due to its impact on visual predators (Utne-Palm, 2002; Pangle et al., 2012). Diel vertical migration is a ubiquitous behavior during which many zooplankton and fish species migrate from the surface ocean, where they feed at night, to deeper, darker waters during the day, thereby decreasing the likelihood of predation by such visual predators. This substantial migration of biomass is controlled largely by modulations in surface light levels (Cohen and Forward, 2019) and results in the active transport of carbon and other nutrients from the sea surface to depth - an important part of the ocean's biological carbon pump (reviewed in Steinberg and Landry, 2017). A strong negative relationship has been documented between zooplankton vertical migration depth and light attenuation; in this case, increased turbidity led to a shallower migration depth (Ohman and Romagnan, 2016). Similar effects were found in Lake Tahoe, when wildfire smoke and ash increased turbidity and decreased migration depth (Urmy et al., 2016). While untested for ocean systems, we hypothesize that the deposition of VA would alter vertical migration behavior, thereby temporarily impacting predator-prey dynamics, and the active transport of carbon by migrating biota. Future work with lidar satellites in combination with ocean color measurements may help address these predator-prey dynamics from space (Behrenfeld et al., 2019).

Most of the studies of VA and higher marine trophic levels (e.g., fish) come from just two eruptions: Mt. St Helens in 1980, and Kasatochi in 2008. Experiments using the ash from the Mt. St Helens eruption on juvenile and salmonid smolts (Newcomb and Flagg, 1983) and Pacific herring larvae (Boehlert and Morgan, 1985) reached different conclusions. While VA was found to be detrimental to salmon smolts at high concentrations (Newcomb and Flagg, 1983), it increased the feeding rate of Pacific herring larvae (Boehlert and Morgan, 1985). Both studies indicated that the particulate component of the ash impacted the fish, rather than any toxicity imparted from soluble components (Newcomb and Flagg, 1983; Boehlert and Morgan, 1985). These studies only considered the short-term effects of ash addition, over scales of less than a day. In contrast, studies of the impacts of the 2008 Kasatochi eruption focused on interannual timescales. The eruption of iron-rich ash over normally iron-depleted marine waters led to a phytoplankton bloom visible in satellite data, which was then used to explain higher salmon numbers the following year (Parsons and Whitney, 2012), although this result has been contested (McKinnell, 2013) and subsequently defended (Parsons and Whitney, 2014). The impact of ash on fish will also vary

depending on the life stage of the affected species, as smaller juvenile fish are more vulnerable to toxins or dampened growth.

Beyond fish, VA deposition can impact other marine organisms. For instance, iron enrichment can favor phytoplankton species that are detrimental to coral reefs (Schils, 2012). Thick ash deposition can also directly obliterate coral reefs (Vroom and Zgliczynski, 2011) or lead to the loss of shallow water habitat (Zimmermann et al., 2018). Further work, including ongoing remote sensing developments for coral reefs (Hedley et al., 2016) is needed to determine the range of beneficial, negative, or neutral impacts on higher trophic levels and on other aspects of marine ecosystems.

5. Recommendations for future work

Future volcanic eruptions and other VA ash deposition events in coastal areas need to be monitored from a multitude of perspectives, and remote sensing data can contribute in a number of different ways. Here we summarize six key considerations, pointing to future research directions that will make the most of satellite data for exploring biological signals in the wake of VA deposition. First, the remote sensing reflectance used to derive chlorophyll-a is only as good as the atmospheric correction algorithms used to produce it, and even routine errors in atmospheric correction can influence the magnitude of derived chlorophyll-a (e.g., Siegel et al., 2000; Feng and Hu, 2016; Bisson et al., 2021). Ash plumes introduce strongly absorbing aerosols into the atmosphere, and the standard ocean color atmospheric correction methods are not as accurate when such aerosols are present. Thus, an improved understanding of how ash affects atmospheric correction and the satellite chlorophyll-a product is urgently needed, especially to properly interpret satellite chlorophyll-a observations during and after volcanic eruptions. Examining the impacts of ash in seawater on remote sensing reflectance and on the inherent optical properties derived from satellite measurements will also improve the estimates of chlorophyll and other in-water properties from space.

Second, the timing of the eruption and availability of 'clear' (cloud-free) skies must be considered. Depending on the local ocean circulation patterns, ash may be retained or detrained from the system, and the relevant time and spatial scales of dispersion may need to be resolved more frequently in some systems than others (e.g., compare the California Current ecosystem with the North Pacific). Geostationary satellites can observe hourly changes in water characteristics, but they do not provide global coverage. There are two planned geostationary missions that will provide increased temporal (and spectral) coverage for US waters: NASA's GLIMR satellite and NOAA's GEO-XO satellite. It is also important to consider the long-term after-effects from volcanoes, including intermittent pulsing events (e.g., heavy rains that wash material into the ocean), or the slow flux of winds carrying terrestrially deposited VA into the ocean over time. Increasing the scales of observation over both space and time will allow for higher-resolution sampling of the surface ocean following an ash deposition event, and ideally improve estimates of the impacts of VA on the system.

Third, passive remote sensing is limited in its ability to quantify the effect of ash on marine ecology and biogeochemistry because ash plumes and clouds associated with volcanic eruptions block the ocean radiance signal from detection by passive ocean color satellites, necessitating clear sky days for observing any ocean change. Active (lidar) satellites (e.g., CALIOP, ICESat-2) have a smaller footprint (~10–100 m, Magruder et al., 2020, Markus et al., 2017) to detect ocean signals in gaps between and within thin clouds, making them useful tools for monitoring the marine response to ash deposition when passive ocean color satellites (typically 1 km pixel size) cannot retrieve a signal due to ash or cloud cover. However, lidar satellites do not measure chlorophyll-a, and instead measure particulate backscattering, which is an optical quantity that covaries with both phytoplankton and VA particles (and/or other ocean particulates). As such, lidar satellites will be useful to detect change, but it may be difficult to discern whether the change is due to the ash concentration or the phytoplankton concentration. Further in situ observations of the relationships between particle backscattering and VA particles in seawater may be useful for improving these relationships from space, especially by incorporating polarization properties (Collister et al., 2020, 2018) when available.

Fourth, VA needs to be sampled in near-real time, with a combination of close-to-vent fallout sampling with distal and in situ sampling inside the plume. Only through in situ sampling in real time will there be a complete analysis of the physicochemical properties needed for atmospheric modeling and satellite interpretation. Our understanding of volcanic events may be greatly enhanced by a planned and coordinated field response to the next large eruption, with efforts similar to the Nearshore Extreme Events Reconnaissance program (NEER, https://neerassociation.org) and the COmmunity Network for Volcanic Eruption ResponSE (CONVERSE, https://volcanoresponse.org).

Fifth, further work is needed to reconcile satellite and ground-based observations of ash dispersal, which may be accomplished by matching known eruptions with available data from satellites (Table 1). Satellite retrievals sometimes provide smaller ash particle sizes than are observed in the field, and estimates of the location and amount of ash deposited differ between satellite measurements of ash clouds and tephra (fragmented material from volcanic eruption) mapping (Cashman and Rust, 2020). In order to resolve this discordance, one could focus a small pilot study on volcanoes with recurring activity, or those with available field data. In all cases, two major limitations are when 1) coastal volcanic eruptions do not coincide with offshore winds which would send ash over the ocean, and 2) satellite data are not available due to cloud cover or thick plumes. When satellite data are not available, additional remote sensing tools can help study the biological response of ash in situ, including Argo floats equipped with biological sensors (e.g., Mittal and Delbridge, 2019). Argo observations provide water column measurements that extend beyond what a satellite can 'see,' allowing the structure of the water column and changes to the mixed layer depth to be quantified (and occasionally euphotic layer depth for floats equipped with downwelling irradiance sensors). Other remote technologies can help, including gliders and drones equipped with radiometers, particularly if they are deployed downwind of active volcanoes.

Sixth, satellite observations can be used within models to extract more information than what is available from satellite data alone. For example, contextualizing satellite observations within atmospheric transport models can enable quantification of ash deposition rates. Thereafter, running regional physical ocean mixing models may help constrain residence times and dilution rates of VA in seawater. Satellite observations used to drive ecological models may also be used to test hypotheses and diagnose whether derived rates are realistic or not, given prior information about the environment (Bisson et al., 2020a). Better quantifying the first-order impacts of VA on an ocean ecosystem will also allow for modeling studies to probe the cascading effects of a volcanic eruption, such as the implications for higher trophic levels or for carbon export via the biological pump.

Thanks to the increased satellite monitoring around the world in the last ~10 years, there is a better understanding of volcanic activity globally. While monitoring is still inadequate particularly at high latitudes, there are regions of interest where certain volcanoes exhibit frequent activity, making them candidates for increased monitoring or, if possible, dedicated intensive observational campaigns. A number of high latitude volcanoes in the Northern Hemisphere (e.g., Semisopochnoi, Great Sitkin, Gareloi, Cleveland, Pavlof, Sheveluch, Bezymianny, Chirinkotan, Kudryavy) exhibit frequent minor activity and are located upwind of ash sensitive ecosystems, so these volcanoes are possible candidates for enhanced monitoring. There are less active volcanoes of interest in the in the high latitude Southern Hemisphere, chiefly Mt. Michael in the South Atlantic (emitting a plume nearly constantly over the last decade) and Piton de la Fournaise in Reunion Island. Autonomous platforms like Argo floats (equipped with optical sensors) operating downwind from these locations are a possibility for

opportunistic studies.

At lower latitudes, there are volcanoes with frequent low activity and with visible low altitude plumes. These volcanoes include Kilauea, Nishina-shima, Etna, Barren Island, and several Andean and Galapagos islands volcanoes. Accessibility to these volcanoes is better than those at high latitudes, and clear sky views needed for satellite observations are more likely. The lower latitude waters associated with these volcanoes may have different nutrient regimes than those of the high latitudes, enabling a spectrum of ash studies across environmental conditions. Finally, we also mention Icelandic volcanoes, as while they do not exhibit as frequent activity as the volcanoes listed, they are located in an area with very high surveillance and have the potential to be rapidly studied in situ due to their proximity to urban centers. Another interesting feature is the frequent and almost predictable blowout of aged ash in the southern Icelandic shores. This process deposits VA hundreds of kilometers into the open ocean. In general, Iceland presents a number of interesting logistical and scientific features that could be used to better understand the concept of aeolian deposition impacts in marine ecosystems.

To facilitate data synthesis as the remote sensing and ground truthing of satellite data continues to evolve, we encourage researchers to clearly state their assumptions (as different fields have different conventions), publish all relevant raw data calculations/codes following FAIR principles (i.e., Findability, Accessibility, Interoperability, Reuse), and scaling parameters used so measured fluxes, concentrations, rates, etc. can be refined over time instead of requiring a new eruption to conduct a new experiment. These approaches will promote data synthesis within and among disciplines as research on VA deposition and effects in the marine realm continue to evolve. Progress can also be made by looking outside volcanic eruptions into other types of stochastic environmental events that affect material transfer and ecological effects at the land-air-ocean interface (e.g., atmospheric deposition of dust and wildfire ash to surface waters). Although the geochemistry of material exported to coastal margins will not be the same as VA, in situ and remote sensing efforts to capture the environmental response to these events is similar to that of volcanic eruptions.

Description of author's responsibilities

KMB led the writing with input from all authors. SG, NM, SW, BK, and SAC were leaders of different subgroups. KMB produced Fig. 1, Fig. 3, and Table 1. KS produced Fig. 2. SD, EG, SK, NK, CM, MEP, KS, and CW contributed writing and final edits on the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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