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Volcanic mega-eruptions may trigger major cholera outbreaks

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ABSTRACT: Reviewing the results of environmental epidemiology, post-volcanic climatology, and environmental history, we focused exclusively on volcanic eruption-ENSO and ENSO-cholera connections in order to establish a hypothesis that large tropical and Northern Hemisphere volcanic eruptions trigger an environmentally driven cascade process via post-volcanic ENSO anomalies. This cascade process has tended historically to lead to cholera outbreaks in Bengal (i.e. the Ganges-Brahmaputra delta region of modern India and Bangladesh). To test our hypothesis, we set up a dataset from strong tropical and Northern Hemisphere volcanic events that forced the ENSO system, ENSO indices, and historical data for cholera outbreaks. Eight volcanic eruptions (≥ 3.3 W m^{-2}) were accompanied within 2 yr by El Niño events over the past 500 yr. For the 19th–20th century period, all selected volcanic eruptions were accompanied by major cholera outbreaks in Bengal during the examined post-volcanic years. For the past 500 yr, the likelihood of the occurrence of major post-volcanic cholera outbreaks was 75%.

KEY WORDS: ENSO · El Niño · Bengal · Tambora · Samalas · Pinatubo · Environmental cascade

1. INTRODUCTION

1.1. Background

Better understanding of the environmental effects of explosive volcanic activity on society is a highlighted goal behind recent efforts of interdisciplinary Earth system research (e.g. the Volcanic Impacts on Climate and Society [VICS] project, PAGES 2018). Famine and disease are regularly applied test-cases for exploring societal responses to volcanically triggered climatic shocks (Lamb 1995, Luterbacher & Pfister 2015). Recognizing that one of the largest eruptions in recorded history, Mount Tambora (Sumbawa, Indonesia) in 1815, seriously altered precipitation and temperature conditions globally in subsequent years (Humphreys 1913, Lamb 1970, Stothers 1984), post-volcanic climate anomalies and famines have long been seen by researchers as drivers behind the outbreak of the first cholera pandemic in 1817 (Post 1973, Lamb 1995, D'Arcy-Wood 2014).

Cholera is at present one of the most devastating contagious epidemic diseases, causing ~3 to 5 million cases and 100 000–120 000 deaths every year by toxigenic *Vibrio cholerae* (Mutreja et al. 2011). The symptoms of this water-borne gastrointestinal infection, such as intense diarrhoea and vomiting which lead to rapid dehydration, have been amply described since antiquity (MacNamara 1876, Sack et al. 2004). The first pandemic on record broke out in the Ganges Delta in 1817 (Jameson 1820). A more recent outbreak in the fall of 1992 was also first reported among fishermen on temporary islands in the delta region of the Ganges, Brahmaputra, Meghna and Padma rivers in Bangladesh (Colwell 1996). In the search for causes, the earliest interpretations suggested a climatic hypo-

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*Corresponding author: pinkezsolt@gmail.com thesis, arguing that extreme environmental conditions in Bengal may have led to the pandemic in 1817 (Pollitzer 1954). Others suggested drought and starvation following the 1815 Tambora eruption as potential environmental reasons for the outbreak of cholera initially in Bengal (Lamb 1995), but this theory was questioned (Oppenheimer 2003). On the basis of instrumental meteorological data and stock price changes from Madras, Bombay, and New Delhi, research literature dismissed that there had been an occurrence of post-Tambora anomalous climatic events in India for the period of 1815 to 1819, and thus climate as a driver was eventually discredited (Pant et al. 1992). But in fact, there is clear evidence for an extreme post-volcanic Bengali drought in 1816 during the monsoon period, followed by severe floods in September which had never occurred 'within the recollection of the oldest inhabitants' (Jameson 1820, p. XXIV). The drought/flood pattern mentioned by Jameson (1820) bears strong similarities to recognized hydroclimatic factors behind more recent cholera outbreaks (Jutla et al. 2015). The 1992 cholera epidemic broke out in Bangladesh (Bengal) (Colwell 1996) a year after the large volcanic eruption of Mount Pinatubo in the Philippines took place in June 1991. Besides these two examples for post-volcanic cholera outbreaks, there is a much earlier mention of a major cholera-like epidemic described in SW China in the summer of 1259, which devastated the Mongols and their auxiliary troops in Yunnan (Kingdom of Dali) and Sichuan (Song Empire) (Song 1976, Thackston 1999). The epidemic reportedly killed more than 5000 soldiers in a relief army heading from Yunnan to assist the campaign against the Song Dynasty of China, and the subsequent outbreak amongst troops in China claimed the life of Möngke Khan, the last ruler of the unified Mongol Empire. This epidemic was preceded by the eruption of Samalas (Lombok, Indonesia) in 1257 (Lavigne et al. 2013). The observed coincidences between large volcanic eruptions, subsequent global climate anomalies, and historically documented major cholera pandemics in SE Asia invite a closer look into the link between the environmental anomalies induced by great volcanic eruptions and outbreaks of cholera.

1.1. The evidence for climate-influenced cholera epidemics

V. cholerae is an aquatic bacterium, usually associated with phyto- and zooplankton, shellfish, and various fish species (Colwell & Huq 1994) occurring in estuaries, river deltas, and coastal zones stretching from tropical to continental zones, e.g. the northern Bay of Bengal (Bangladesh and India), Chesapeake Bay and the Gulf of Mexico in North America (Johnson et al. 2010), and some coasts of Peru and Europe (Vezzulli et al. 2016). The *V. cholerae* species has divided into hundreds of serogroups, but among the strains, the *phylocore* genome clade of *V. cholerae* is responsible for all major cholera outbreaks (Chun et al. 2009). In Bangladesh, where *V. cholera* is endemic, the seasonal peaks for both the abundance of toxigenic serogroups and cholera incidences are the pre- and post-monsoon warm seasons, in spring (March–May) and autumn (September–November) (Sultana et al. 2018). Anomalies in the monsoon system, warming water surface temperatures, river discharge, and socio-environmental human factors may increase the nutrient concentration of coastal zones (Escobar et al. 2015), influencing plankton blooms and subsequent increases in the abundance of zooplankton (e.g. planktonic copepods) which are the main reservoir of the pathogen (Sack et al. 2004). The abiotic environmental drivers of plankton abundance, including ambient temperature, show a close statistical relationship with cholera incidence (Lipp et al. 2002). Thus, two elements of the recent global environmental crisis, fertilization of oceans and seas and above-average temperatures, including intensifying heatwaves seen with recent climate change, increase cholera risk (Rodó et al. 2002, Vezzulli et al. 2016, Carlson & Trisos 2018) both by raising zooplankton abundance and fostering the rapid spread of pathogens in terrestrial ponds, rivers, and surface water (Lipp et al. 2002, Vezzulli et al. 2016). The El Niño/Southern Oscillation (ENSO) is the dominant mode of ocean–atmosphere variability over the tropical Pacific. During El Niño events, sea surface temperature (SST) in the central and eastern tropical Pacific becomes substantially warmer than normal while, during La Niña events, SST becomes cooler than normal in these regions (Wang & Fiedler 2006). These changes can also affect the climatic situation in more distant regions of the globe. For instance, ENSO is one of the main drivers of the hydroclimatic regime in the northern Bay of Bengal, where 6 of the recorded 7 cholera pandemics broke out (Clemens et al. 2017). The El Niño phase of ENSO, probably via its influence on surface water temperatures and river discharge, explains ca. 70% of interannual variance in cholera incidence in Bengal (Pascual et al. 2000, Rodó et al. 2002, Koelle et al. 2005). There is an increase (decrease) in cholera after warm (cold) ENSO events, (Pascual et al. 2000). This coupling is not persistent; it is stronger under extreme ENSO states and vanishes during normal conditions (Pascual et al. 2000).

1.2. Post-volcanic ENSO anomalies in the northern Bay of Bengal following large tropical and Northern Hemisphere volcanic eruptions

Large volcanic eruptions can inject sulfur-rich gases into the stratosphere, triggering a reduction of the incoming solar radiation, perturbing the global energy balance (Robock 2000), causing a decrease in global mean surface temperature, and influencing the oceanic–atmospheric circulation including ENSO (Fig. 1) (Emile-Geay et al. 2008, D'Arrigo et al. 2011, Liu et al. 2018). The post-volcanic ENSO response shows diversity depending on the atmospheric dynamics at the time of the ejection of volcanic gases and the latitude of the volcano. Large tropical explosive eruptions have greater climatic effects globally as the volcanic materials may reach the stratosphere due to the high energy of explosive eruptions and their geographical position in atmospheric circulation (Robock 1981). Tropical volcanic eruptions with higher volcanic forcing than Pinatubo in 1991 could significantly alter the ENSO system, raising El Niño intensity in the post-volcanic years (Emile-Geay et al. 2008). In addition, many reconstructions illuminate a significant impact of large high-latitude volcanic eruptions on ENSO (Pausata et al. 2015, Khodri et al. 2017) or Asian and African monsoon regimes (Oman et al. 2005). Additionally, Liu et al. (2018) laid out the ENSO impact of volcanic eruptions in a tropical, Southern (SH), and Northern (NH) Hemisphere categorization scheme, thereby highlighting that La Niña-like responses exist in the eastern and central Pacific Ocean during the years following large tropical and NH eruptions. The suggested eastern-Pacific ENSO anomalies (Liu et al. 2018) have a significant impact on the precipitation pattern of the Bay of Bengal (Balaguru et al. 2016). By developing polar records and the calibration of ice core information, Crowley & Unterman (2013) presented a new volcanic forcing collection for aerosol optical depth. Finally, using ice core and multi-proxy record-based volcanic forcing timelines (Sigl et al. 2015, Toohey & Sigl 2017), a synthesis by Dätwyler et al. (2019) found 9 tropical and NH eruptions that were followed by El Niño events during the last millennium (Fig. 6 in Dätwyler et al. 2019) and these results were confirmed in 6 cases by at least 2 other independent analyses (Fig. 7 in Dätwyler et al. 2019).

As for the spatially more explicit reconstructions in terms of Bengal, a study of 14 large tropical eruptions showed a subsequent significant decrease in monsoon intensity and a coinciding increase in SST in the northern Bay of Bengal (Fig. 4 in Wegmann & Brönnimann 2014). The Pinatubo eruption was followed by a strong El Niño event (Predybaylo et al. 2017), and such a co-occurrence entails a modelled decrease of precipitation in Bengal (Trenberth & Dai 2007), causing serious drought in Bangladesh and the Indian states of Bihar and Odisha in 1992 (FAO 1993). Droughts have multiple impacts on cholera as a disease. On the one hand, drought events in offshore regions lead to warming SST, triggering algae blooms and increasing copepod abundance, the main reservoirs of *V. cholerae* (see Section 1.1.). On the other hand, droughts 'seem to promote cholera transmission' (Koelle et al. 2005, p. 699) due mainly to shrinking clean water supplies. As we saw with Pinatubo, the 1815 eruption of Tambora was likewise followed by an El Niño event, and accompanied by an extreme hydroclimatic pattern in Bengal (Raible et al. 2016). Crucially, rain was absent during most of the summer monsoon season of 1816 (Jameson 1820), leading to an uncommon drought, while September, the last month of the monsoon period, saw high rainfall and flooding. A tree-ring based drought reconstruction (D'Arrigo et al. 2011) shows a drought in Myanmar (formerly Burma) in the post-Tambora years. Tree-ring data from the upper water catchment

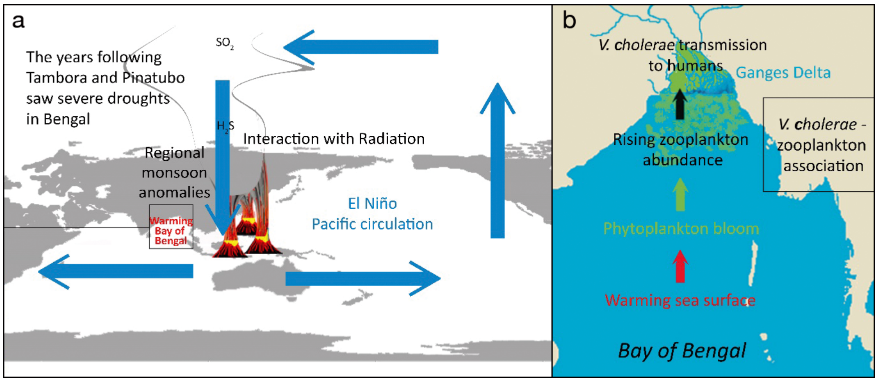

Fig. 1. (a) Post-volcanic response of the hydroclimatic system during El Niño events. Blue arrows indicate the equatorial east–west atmospheric Walker Circulation during El Niño phase (Lau & Yang 2002). (b) Abiotically driven cascade process of cholera transmission in the northern Bay of Bengal

of the River Ganges-Brahmaputra recorded the second warmest July to September period of the past 5 centuries for 1813 to 1822 (Sun et al. 2016). Like the two volcanic eruptions explored above, the post-volcanic years for the earlier Samalas eruption (1257) show an anomalously strong El Niño event during 1258 and 1259 (Emile-Geay et al. 2008, Dätwyler et al. 2019). We have no explicit precipitation reconstructions for the post-Samalas years in the northern Bay of Bengal or in the Ganges-Brahmaputra Delta. The nearest reconstructions from the mountainous regions of Myanmar, Thailand, and Vietnam show that the Samalas eruption was followed by positive precipitation anomalies during the summer monsoon period of 1258 and 1259 in SE Asia (Anchukaitis et al. 2010). This pattern, however, can hardly be projected on Bengal as the ENSO-Indian monsoon system is spatially diverse (Malik et al. 2016, Roy et al. 2019).

1.3. Hypothesis

In the light of the above considerations, we hypothesise that in cases where large tropical and NH volcanic eruptions happened in El Niño years or were followed by El Niño events within 2 yr of the eruption, this pattern may indirectly lead to cholera epidemics through the following causative chain (Fig. 1):

1. Certain large tropical and NH eruptions influence the ENSO system and are accompanied by El Niño events.
2. One of the effects of this is to disturb the Asian monsoon system, causing a positive temperature anomaly over the northern Bay of Bengal and the Ganges-Brahmaputra Delta.
3. The warming sea surface induces phytoplankton blooms, with a subsequent increase in the abundance of zooplankton, several species of which are hosts of *V. cholerae*.
4. This increase stimulates the transmission of pathogens from the cholera reservoirs to the human population living in the coastal zones of the Bay of Bengal.

2. MATERIALS AND METHODS

To test our hypothesis, we assembled a dataset from strong tropical and NH volcanic events that forced the ENSO system, ENSO indices, and complementary historical data for cholera outbreaks over the past 5 centuries. There is a wide consensus that the Years 3 to 5 after the eruptions saw a significant cooling in the Tropical Pacific, and the appearance of El Niño events is common in the Years 1 and 2 after the eruptions (Dätwyler et al. 2019). Moreover, the above demonstrated temporal pattern of El Niño, following major eruptions, as seen in the cases of Samalas, Tambora, and Pinatubo, and the subsequent epidemic outbreaks show that major cholera or cholera-like events occurred within the first 2 post-eruption years. Therefore, El Niño events and cholera outbreaks in the eruption year and 1 to 2 post-volcanic years were collected and considered in the analysis. El Niño events were selected using the ENSO index based on instrumental data for 1854 to 1991 and paleoclimatic proxies before 1854 (Dätwyler et al. 2019). We used volcanic explosivity indices by Crowley & Unterman (2013) and Sigl et al. (2015) for records of volcanic activity (Table 1).

Table 1. Volcanic forcing values of large volcanic eruptions (≥3.3 W m^{-2}) and ENSO index in the Years 0 to 2 after the eruption. ENSO index: before 1854, proxy-based reconstruction; after 1854, instrumental records (Dätwyler et al. 2019). ENSO index is the average sea surface temperature anomaly in °C (with relation to 1981–2010) over the Niño3.4 region defined as the area from 5° N–5° S and 170°–120° W. A positive ENSO index indicates an El Niño event. (–) No information available

Name of volcano	Year of eruption	Volcanic forcing (W m^{-2})				ENSO index		
		Crowley & Unterman (2013)		Sigls et al. (2015)		Year 0	Year 1	Year 2
		Year 0	Year 1	Year 0	Year 1			
Period 1								
Pinatubo, Philippines	1991	−4.97	–	−6.49	–	0.63	0.67	0.36
Cosigüina, Nicaragua	1835	–	−6.20	–	−6.57	0.30	0.53	0.63
Unknown	1831	–	−3.49	–	−6.46	−0.20	0.23	0.51
Tambora, Indonesia	1815	−17.20	–	−17.20	–	−0.47	0.18	−0.47
Period 2								
Laki, Iceland	1783	–	–	−15.49	–	0.22	0.27	0.47
Komagatake (?), Japan	1694	–	−11.03	–	−10.24	0.68	0.52	−0.26
Melibengoy, Philippines	1640	–	−6.58	–	−11.84	0.63	0.00	1.19
Huaynaputina, Peru	1600	–	−7.08	–	−11.58	0.06	−1.23	0.03

Furthermore, we collected data for major cholera epidemics in the past 5 centuries and for cholera-like outbreaks in Bengal and its wider region in immediate post-eruption years for the period before 1817 (Table 2). The abundance of historical records gradually decreases for India including Bengal as we move further back from the 20th century (Arnold 1986), and the occurrence of reliable figures is incidental before 1817, the year that marks the onset of what is generally called the first cholera pandemic. Occasionally some travelogues shed light on small patches of the entire region over the period of the 15th to 18th centuries, which is the reason why we widened the scope of the collection to the area beyond Bengal. That wider region spans south and SE Asia including South China. We used primary and secondary medical sources, such as contemporary reports, statistical, and historical collections which convincingly distinguish massive cholera events from 'soft evidence' for major cholera events. More precisely, we reviewed reports of the health boards of the British, mainly colonial, administration (Steuart 1819, Jameson 1820), and histories of cholera, based on collections of similar materials, written by MacNamara (1870, 1876), Macpherson (1884, 1888), Peters (1875), and Semmelink (1885).

In view of the conditions of the historical data, we established 2 time windows for selecting volcanic eruptions. Due to the relatively high data abundance and the reliability of the medical reports from the past 2 centuries, we selected volcanic eruptions from the 19th and 20th century (Period 1) for what we expected to be hard evidence of major cholera events (Table 2). Then, another time window was set up for the period of the 16th to 18th century (Period 2). Available historical medical figures from the medical collections listed above mark a horizon of emerging European reports from India and SE Asia from the early 16th century onward (MacNamara 1870, 1876, Peters 1875, Macpherson 1884, 1888). To borrow the wording of Dätwyler et al. (2019), there is no consensus for every aspect of volcanic eruption–El Niño teleconnections and 'how ENSO responds to volcanic events' (Dätwyler et al. 2019, p. 2712). Thus, we focused on the volcanic eruption–El Niño pattern only where volcanic forcing of tropical and NH eruptions with at least the same volcanic forcing as Pinatubo (3.3 W m^{-2}) (Emile-Geay et al. 2008) was evidenced, and where volcanic activity was accompanied by an El Niño event in the eruption year or Years 1–2 after the eruption. For the selection, we used the volcanic forcing timelines of Crowley & Unterman (2013), Sigl et al. (2015), and a dataset of ENSO reconstructions based on a large, updated collection of proxy records (Dätwyler et al. 2019).

With regard to the above hypothesis, we assume that although sporadic cholera outbreaks do occur naturally and frequently in Bengal, the number of cholera cases or cholera-caused deaths should be higher within 2 yr following an eruption event (≥3.3 W m^{-2}) than the average number of cholera cases or cholera-caused deaths within other years. In the age of statistically explicit data collections (1870–2019), only one big volcanic eruption occurred which was followed by positive ENSO anomaly within the next 2 yr: Pinatubo (1991). Thus we used normally distributed data of the percentage of cholera cases (Fig. A1 in the Appendix) registered among the patients visiting the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B), in Dhaka for 1980 to 1997 (Pascual et al. 2000) (Fig. 2) to test (one sample Welch *t*-test) the significance of the differences of annual percentage of cholera cases registered in ICDDR,B for the years of 1991,

Table 2. Volcanic eruptions that significantly forced the ENSO regime, and cholera outbreaks in immediately following years

Volcano, country, year	Cholera outbreak	
	Location, year	Source
Period 1		
Pinatubo, Philippines, 1991	Bengal, 1992	Colwell (1996)
Cosigüina, Nicaragua, 1835	Bengal 1837	MacNamara (1876, p. 125–128)
Unknown, 1831	Bengal, 1833	MacNamara (1876, p. 117–121)
Tambora, Indonesia, 1815	Bengal, 1817	Jameson (1820)
Period 2		
Laki, Iceland, 1783/4	India, 1786	Macpherson (1884, pp. 144–145, 232)
Komagatake (?), Japan, 1694	Surat (India), 1695	(Soft evidence) Semmelink (1885, p. 116–117), Macpherson (1884, p. 113)
Melibengoy, Philippines, 1640	Java (Indonesia), 1641–42	(Soft evidence) Peters (1875, p. 524)
Huaynaputina, Peru, 1600	Arracan Islands (Bangladesh, Myanmar), 1602	Macpherson (1888, p. 47)

1992 and 1993, compared with the average of the period. Moreover, we used Simpson's (1887) dataset for the annual number of cholera deaths registered in Calcutta between 1871 and 1885 (Table A1 in the Appendix), which covers the year of the eruption of Krakatau (Indonesia, 1883). Although Krakatau was not followed by a reconstructed positive anomaly within 2 yr, using one-sample Welch *t*-test we also tested the significance of the differences of annual number of cholera deaths registered in Calcutta for the years of 1883, 1884 and 1885, compared with the average of the period of 1871–1885.

Finally, we estimated likelihoods, over the past 500 yr, for major cholera outbreaks within 2 yr following an eruption event that might have affected and modified the ENSO regime.

3. RESULTS

On the basis of the figures provided by Crowley & Unterman (2013) and Sigl et al. (2015) for volcanic forcing, and the ENSO timeline of Dätwyler et al. (2019), 8 'volcanic eruptions with a radiative forcing greater, in absolute value, than ~3.3 W m^{-2}, (Emile-Geay et al. 2008, p. 3144) were accompanied within 2 yr by El Niño events over the past 500 yr (Table 1). Only 2 eruptions (≥3.3 W m^{-2}), an undefined eruption in 1809 and Krakatau (in 1883), were not accompanied by positive ENSO events in any year within 2 yr after the eruption. As to the explosive eruptions of Mount Gamkonora (Indonesia, 1673) and Mount Agung (Indonesia, 1963), their volcanic forcing value was lower in Sigl et al. (2015) as well as in Crowley & Unterman (2013) than the threshold (≥3.3 W m^{-2}). Owing to this discrepancy between the reconstructed values of their volcanic forcing, Gamkonora and Agung have not been included or listed among the analysed cases.

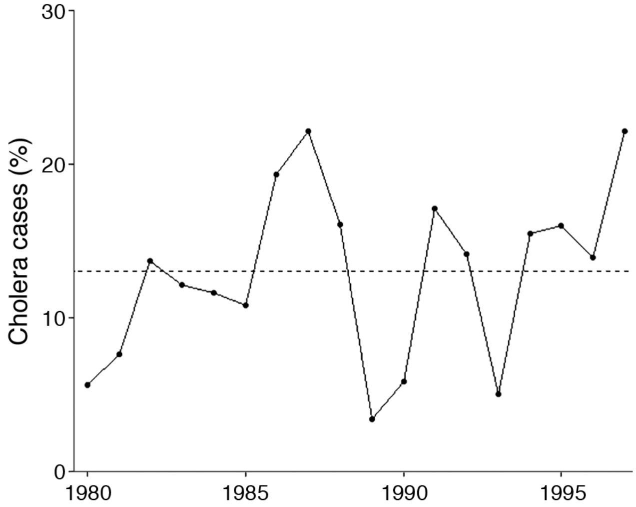

Fig. 2. Annual percentage of cholera cases registered among patients visiting the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B), in Dhaka for 1980–1997 (Pascual et al. 2000) and their average (dashed line)

Every selected volcanic eruption was accompanied by a significant cholera event in the Years 0 to 2 after the eruptions (Table 2), but information on 2 of the 8 cases did not explicitly support that the number of cholera cases/deaths would have rendered the event as extraordinary. Chronologically, the major cholera outbreak of the post-Pinatubo years (1992–1994) has been clearly reconstructed (Colwell 1996). Cholera-caused disease and death figures are generally scarce for Bengal before the 1870s (Arnold 1986, Malik et al. 2016), with the exception of the first pandemic (1817–1824), which was reconstructed with high accuracy and completeness by the colonial administration (Steuart 1819, Jameson 1820). Nonetheless, we came across well-founded medical reconstructions for severe cholera outbreaks that happened in various places of the Indian subcontinent, including Lower Bengal in 1833–1834 (MacNamara 1870), and 1837–1838 (MacNamara 1876) (Table 2). In 1833, a medical superintendent's description reported on a local outbreak of cholera in Bengal during March that surpassed anything he had ever seen in severity, and which then spread everywhere in India (MacNamara 1876). In 1837, the same area and the east Bengal districts, Chittagong and Assam, suffered from a severe wave of cholera in 1837 which rapidly spread to Inner and SE Asia in the subsequent years (MacNamara 1876). Moreover, cholera and starvation killed at least 2 million people just in the Madras Presidency during 1833 (Arnold 1986). As for the post-Laki years (1783–1785), a massive pilgrimage expanded the range of the pathogen in 1783 when cholera killed an estimated 20 000 victims in a week — though whether this was simply a sporadic local outbreak that was aggravated by the public gathering or something tied to the eruption is unclear (Macpherson 1884). Only a temporally less explicit description preserves the memory of an outbreak, indistinctly defined as 'pest' ('some say cholera Asiatic'), that depopulated the Bacaim settlement in Surat (W India) 'some years after 1695' (Semmelink 1885, p. 117). In the Bombay region, however, a world-travelling physician recognized that cholera was prevailing there in 1695 (Macpherson 1884). For the post-volcanic years following the explosive eruption of Melibengoy (1640–1641, Philippines), 2 pieces of soft evidence were discovered in Indonesia;

a Dutch traveller described the danger of cholera on the coast of India in 1641, and a physician in Flanders gave an unambiguous description of a local case of cholera in 1643 (Macpherson 1884). Likewise, an unambiguous European description has survived of cholera symptoms on the Arracan Islands (Chattogram District, Bangladesh and Rakhine State, Myanmar; Macpherson 1888) 2 yr after Huaynaputina erupted in Peru in 1600 (Table 2).

Results of one sample Welch tests showed that the percentage of cholera cases registered in Dhaka was significantly higher in the year of the eruption of Pinatubo (1991) ($t = -7.1364$, $p < 0.01$) and in 1992 ($t = -1.9945$, $p < 0.05$) than the average of the examined period (1980–1997). In the case of Krakatau, the annual number of cholera deaths registered in Calcutta for the years of 1883 ($t = -4.4782$, $p < 0.01$) and 1884 ($t = -6.0366$, $p < 0.01$) were significantly higher than the average in the period of 1871–1885.

In the case of the 19th and 20th century (Period 1), all selected volcanic eruptions were accompanied by major cholera outbreaks, and thus the likelihood of the development of major cholera outbreaks in Bengal during the years of examined volcanic eruption-El Niño pattern is practically 100%. On the basis of the collected 17th and 18th century figures, the likelihood for the occurrence of major cholera outbreaks in the Years 0 to 2 after the volcanic eruptions is 50%. For the examined 500 yr, 6 out the 8 extreme volcanic events were followed by major cholera outbreaks, and thus the likelihood for the occurrence of major cholera outbreaks within 2 yr after the eruption is 75%.

4. DISCUSSION AND CONCLUSIONS

Out of the 8 selected explosive volcanic eruption–El Niño pattern episodes of the past 500 yr, 6 were accompanied by major cholera outbreaks in Bengal (and before the 19^{th} century, in the wider Indian Ocean region). Focusing on the 19^{th} and 20^{th} century period when the validity and abundance of data are relatively good, the likelihood of the coinciding occurrence of a large tropical/NH volcanic eruption–El Niño pattern and a major cholera outbreak within 2 yr after the eruption is 100% (Table 2). These results support the hypothesis of the study that in cases where large tropical and NH volcanic eruptions happened in El Niño years or were followed by El Niño events within 2 yr, this pattern appears to indirectly lead to cholera epidemics. Although the available sample set is quite small, it represents almost the total collection of explosive volcanic eruptions with at least 3.3 W m^{-2} radiative forcing that occurred over the past half-millennium (Crowley & Unterman 2013, Sigl et al. 2015). In the age of statistically explicit data collections (1870–2019), only 1 big volcanic eruption occurred which was followed by positive ENSO anomaly within the next 2 yr: Pinatubo (1991). The observation of a significantly higher than average percentage of cholera cases registered among patients of ICDDR,B (Dhaka, Bangladesh) in the year of the Pinatubo eruption and in 1992 than in the examined period (1980–1997) also supports our hypothesis.

We have to emphasize that the historical sources from the 19^{th} century and even earlier document sporadic, often localized, outbreaks of cholera as common experiences. It would be impossible to document every instance of cholera even in the 19^{th} century, and we have not attempted to argue that cholera outbreaks require a large volcanic eruption to take place. Rather, what we observe in detailed historical records is that above-average, unprecedented or 'raging' cholera outbreaks (to borrow the wording of the superintendent surgeon of the British army at Sagar in central India, who witnessed such an event in 1834; MacNamara 1876) tended to follow major eruptions. As an example, the cholera-caused deaths in Bombay among European troops were 35 in 1831, but 263 in 1834 (MacNamara 1876) when a major epidemic, originating in Bengal in 1833, spread westward across India following the huge eruption of an unknown volcano in 1831.

We are arguing for a difference in degree rather than kind when it comes to the presence of cholera infections in Bengal following an eruption. In the very short historical window for which we have good records available, we see an ever-present situation of sporadic cholera on the Indian subcontinent, but we also observe a significant increase in the numbers of cholera deaths (Table A1), frequency of cases (Fig. A1), and wider geographic distribution of the disease following major volcanic eruptions. This striking pattern seems to be related to the eruptions themselves. Dealing with historical records from the 16^{th} to the mid-19^{th} century, we cannot provide exact parameters for what constituted a major cholera outbreak, nor would a precise quantitative definition be useful to demonstrate our hypothesis. However, Charles MacNamara, one of the keenest observers of cholera in Bengal in the 19^{th} century, used terminology that helps illustrate the relationship for which we are arguing, of course without attempting to draw any connection to volcanic eruptions. For instance, he noted that 'In 1835 epidemic cholera was at a very low ebb throughout Bengal' (MacNamara 1876, p. 124), and that the prisoners and troops in central and northwest India were 'well nigh free' of cholera, though he noted some localized and limited outbreaks. 'The year 1836 was another year of rest as regards cholera', he observed (MacNamara 1876, p. 125), but it still broke out with great severity among a single regiment, affecting 113 men of which 21 died, most frequently in old barracks rather than new ones — suggesting issues of sanitation and clean water were pertinent in this isolated case. However, regarding the year 1837 (when according to our hypothesis, we should expect a serious cholera epidemic within the 2 yr following the 1835 eruption of Cosigüina), he noted that cholera 'raged' through Bengal causing 'a great mortality,' and that during 'the year 1837 cholera was very prevalent throughout the whole of Lower Bengal' (MacNamara 1876, p. 128). In 1838, this cholera epidemic radiated throughout western India, reaching Kabul, Afghanistan in 1839 (MacNamara 1876, p. 129).

Following major eruptions, we regularly note a distinct type of 'phenomenon' which MacNamara attempted to describe and which supports our hypothesized connection: 'We have therefore in the history of cholera in Bengal during 1837 a repetition of the phenomena of 1817, 1826, and 1833; a vast outburst of the disease occurring throughout the whole of Bengal gradually advancing to the west and northwest as far as the line corresponding to 78° east longitude; then halting for the cold season but in the meantime throwing forward its feelers into the provinces beyond the invaded area' (MacNamara 1876, p. 128). Though he did not know it, we are aware that 3 out of 4 of these major, extreme cholera episodes, which unfolded along a very similar and noticeable pattern, followed neatly within the 2-yr aftermath of a major volcanic eruption (Tables 1 & 2), as we would expect to see with our proposed hypothesis. It is also notable that according to reconstructions, the years 1832 and 1833 saw positive ENSO anomaly, as did the years 1836 and 1837, following major eruptions (Dätwyler et al. 2019).

Due to the high risk it poses and the high adaptivity of the pathogen, the complex social and environmental factors behind cholera have been widely examined (Boucher et al. 2015). Large-scale volcanic activity alters global biochemical and climatic circulations, affecting various aspect of ecological interactions in coastal marine ecosystems where *V. cholerae* is endemic. Reviewing the results of environmental epidemiology, post-volcanic climatology, and environmental history, we focused here exclusively on the volcanic eruption–ENSO and ENSO–cholera connections and built up a hypothesis that large tropical and NH volcanic eruptions via post-volcanic ENSO anomalies (Emile-Geay et al. 2008, Predybaylo et al. 2017, Liu et al. 2018) may alter the Indian monsoon (Trenberth & Dai 2007). This in turn causes a positive temperature anomaly over the northern Bay of Bengal, triggering an environmentally driven cascade process which leads to cholera outbreaks (Lipp et al. 2002). Potentially, there are further indirect post-volcanic impacts on the ecosystems of *V. cholerae* which may alter the abiotic and biotic environment of the pathogen or might contribute to the genetic transformation of *Vibrios* (D'Arcy-Wood 2014). For one possibility, monsoon anomalies apparently cause increasing variability in river discharge, one of the observed drivers behind plankton blooms which play an important role in the described cascade process leading to cholera outbreaks in the Bay of Bengal (Rodó et al. 2002, Koelle et al. 2005, Pascual et al. 2008). Concerning this point, only a hypothesis can be raised, as we do not have spatially and temporally precise flood reconstructions or simulations for the lower Ganges-Brahmaputra catchment. After the eruption of Kasatochi (2008, Alaska, USA), volcanic ash fed a plankton bloom that was observed in the NW Pacific (Hamme et al. 2010). Regarding the relevance of this to our hypothesis, it must be noted that 'phytoplankton responses to ash deposition should be anticipated to be (...) complex' and this biochemical process has not yet been clarified (Browning et al. 2015, p. 3). Testing cholera's response to direct contact with volcanic ash has refuted the idea that inorganic iron would have positive impact on the growth of *Vibrios*, but the addition of Saharan dust was shown to significantly increase their population (Zhang et al. 2019).

As for the potential post-volcanic effects of large ($\geq$3.3 W m^{-2}) eruptions without El Niño transmission, the narrowing condition of the hypothesis that an El Niño event follows in the Year 0–2 post-eruption period excluded 2 eruptions from the analysis: Krakatau (1883, Indonesia) and an unknown volcano (1809). We have relatively strong evidence that Krakatau and the unknown eruption in 1809 were followed by major cholera outbreaks. The celebrated epidemiologist, Robert Koch, arrived in Calcutta in 1883, the year of Krakatau's eruption, and identified the pathogen of the disease as cholera, which was raging in Bengal at the time (Lippi & Gotuzzo 2014). On the basis of cholera deaths in Calcutta (1871–1885), 1884 saw an exceptionally strong spread of the pathogen (Simpson 1887) when the number of victims was significantly higher than the average of the listed 16 years (see Table A1 and Fig. A2 in the Appendix). British medical records in 1808 and 1809 (related exclusively to European troops) reported 5 and 3 cholera cases, respectively, across all military stations, but at least 79 were reported from a single station, Chunar, on the Gangetic Plain (NE India) between 1811 and 1813 (MacNamara 1870). The quick arrival of cholera to that part of Uttar Pradesh is a common pattern of later outbreaks (1817−1819, 1833−1834, 1837−1838). Another eruption, Agung in 1963, was just at the cusp of the assigned forcing threshold; it could be considered influential based on the estimate of forcing by Sigl et al. (2015), but it is below the threshold in the estimate of forcing by Crowley & Unterman (2013). However, that eruption happened in an El Niño year, and 2 yr after the eruption, ENSO still showed a positive anomaly (Dätwyler et al. 2019). Furthermore, the same post-volcanic years of Agung's eruption have outstanding importance in the history of cholera, since the seventh (most recent) cholera pandemic that started in Indonesia in 1961 invaded Bengal in 1963 (McCormack et al. 1969) and the whole of India in 1964, to spread over the world by the 1970s (Fig. 2 in Mutreja et al. 2011). As for Gamkonora (1673), the possible first English reference to cholera in Asia was made by physician John Fryer, who reported witnessing cholera in Surat in 1674 (Fryer 1698). A Dutch author, Willem Ten Rhijne, writing in 1679 likewise reported as an eyewitness that cholera was prevailing particularly in Bengal (Macpherson 1884). His and other statements confirm cholera cases in Java in the same period, and a French author writing of his eyewitness experience (in 1677) confirms that cholera was widespread in India and Goa (Dellon 1685).

The scarcity of observable large-magnitude explosive eruptions (PAGES 2018) means historical and paleoclimate evidence of past post-volcanic effects should be used to clear up uncertainties regarding the mechanisms of volcanically-forced climate variability and post-volcanic impacts on living communities including those of humans (Anchukaitis et al. 2010). In exploring hydroclimatic responses to volcanic eruptions, the reliability of general and regional circulation model simulations could be evaluated using multiple proxy-based reconstructions. Seasonally and annually resolved proxy-based paleoclimatic data are currently sparse or unavailable in the broader region of the Bay of Bengal. Therefore, we could deepen the scientific basis of this hypothesis through the development of proxy-based and historical reconstructions, while additionally scrutinizing instrumental meteorological data. Besides tree-ring-based reconstructions, which provide some annually resolved information on past climatic conditions (Anchukaitis et al. 2010), other potential archives, such as varve records (Sun et al. 2016), still await exploitation in the region.

Although numerous historical records of past pandemics exist, the present study points to the necessity of spatially and temporally explicit historical collections of cholera occurrences before and after the first well-documentated modern pandemic (1817−1824) — something which is lacking at present. Historical data collection for the post-volcanic hydroclimatic patterns in the hotspots of cholera outbreaks, primarily for the northern region of the Bay of Bengal and, ostensibly, the Irrawaddy Basin, might help us to learn more about the environmental context of past episodes of cholera. All of these points highlight that historical evidence should be more heavily involved in 'planetary health conversations' underlining the necessity of integrated research (Carlson & Trisos 2018). Examination of long-term figures for environment−cholera−society linkages will support a deeper understanding of many aspects of recent environmental crises such as global warming, rising ocean temperatures, intensifying hydroclimatic extremes, and drought vulnerability, which significantly increase the statistical likelihood of cholera occurrences (Koelle et al. 2005). Integrated assessment of documentary records for historical cholera epidemics, instrumental meteorological data, and multiproxy paleoclimate information might reveal a regular lag for cholera outbreaks following highly explosive tropical volcanic eruptions which take place at a critical threshold of ENSO state. As a conclusion based on the results of this study, we suggest the following: there is a demonstrated likelihood of cholera outbreaks following strong volcanic eruptions which could force the ENSO regime, causing El Niño events in the Bay of Bengal or in its wider region. This suggests that post-volcanic cholera outbreaks will occur with high probability. This high probability may serve as a powerful predictor in mechanistic modelling of cholera outbreaks, and could also be used as a basic alarm signal for public health agencies in the concerned regions in the event of future large tropical or NH volcanic eruptions.

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Appendix. Additional data

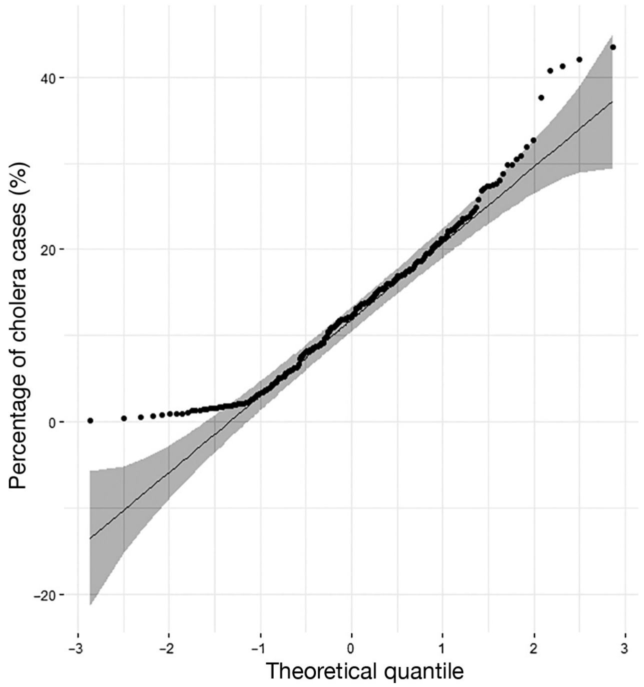

Fig. A1. Distribution of the percentage of cholera cases in Dhaka between 1980–1997 (Pascual et al. 2000)

Table A1. Number of cholera deaths in Calcutta between 1871–1885 (Simpson 1887)

Year	Number
1871	796
1872	1102
1873	1105
1874	1245
1875	1674
1876	1851
1877	1418
1878	1338
1879	1186
1880	805
1881	1693
1882	2240
1883	2037
1884	2272
1885	1603

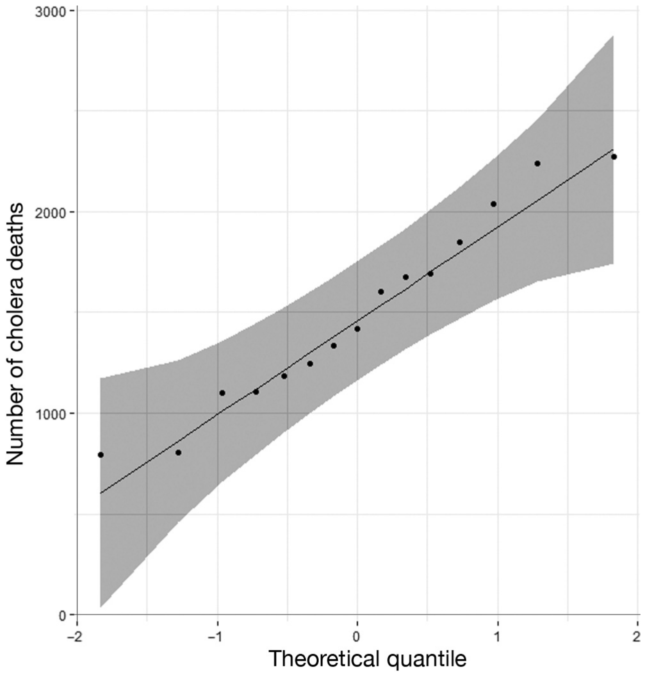

Fig. A2. Distribution of the number of cholera deaths in Calcutta between 1871–1885 (Simpson 1887)

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