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The blue suns of 1831: was the eruption of Ferdinandea, near Sicily, one of the largest volcanic climate forcing events of the nineteenth century?

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Abstract. One of the largest climate forcing eruptions of the nineteenth century was, until recently, believed to have taken place at the Babuyan Claro volcano, in the Philippines, in 1831. However, a recent investigation found no reliable evidence of such an eruption, suggesting that the 1831 eruption must have taken place elsewhere. We here present our newly compiled dataset of reported observations of a blue, purple and green sun in August 1831, which we use to reconstruct the transport of a stratospheric aerosol plume from that eruption. The source of the aerosol plume is identified as the eruption of Ferdinandea, which took place about 50 km off the south-west coast of Sicily (37.1° N, 12.7° E), in July and August 1831. The modest magnitude of this eruption, assigned a volcanic explosivity index (VEI) of 3, has commonly caused it to be discounted or overlooked when identifying the likely source of the stratospheric sulfate aerosol in 1831. It is proposed, however, that convective instability in the troposphere contributed to aerosol reaching the stratosphere and that the aerosol load was enhanced by addition of a sedimentary sulfur component to the volcanic plume. Thus, one of the largest climate forcing volcanic eruptions of the nineteenth century would effectively have been hiding in plain sight, arguably "lowering the bar" for the types of eruptions capable of having a substantial climate forcing impact. Prior estimates of the mass of stratospheric sulfate aerosol responsible for the 1831 Greenland ice core sulfate deposition peaks which have assumed a source eruption at a low-latitude site will, therefore, have been overstated. The example presented in this paper serves as a useful reminder that VEI values were not intended to be reliably correlated with eruption sulfur yields unless supplemented with compositional analyses. It also underlines that eye-witness accounts of historical geophysical events should not be neglected as a source of valuable scientific data.

1 Introduction

Volcanic eruptions that produce sulfate aerosols in the stratosphere are important climate forcing events (Robock, 2000). Ranked in order of the mass of stratospheric sulfate aerosol produced, the most important climate forcing volcanic eruptions of the nineteenth century are as follows: Tambora, in Indonesia, in 1815 (120 Tg); an unidentified eruption in 1809 (59 Tg); Cosegüina, in Nicaragua, in 1835 (40 Tg); Krakatoa, in Indonesia, in 1883 (27 Tg); and another unidentified eruption in 1831 (17 Tg) (Gao et al., 2008). The combination of the 1831 eruption and the 1835 Cosegüina eruption contributed to delaying the end of the Little Ice Age and, hence, the onset of modern anthropogenic warming, until 1850 (Brönnimann et al., 2019). Until recently, the 1831 eruption had commonly been assumed to be an eruption of Babuyan Claro, in the Philippines, which had notionally been assigned a volcanic explosivity index (VEI) of 4 (Zielinski, 1995; Global Volcanism Program, 2013; Arfeuille et al., 2014; Toohey and Sigl, 2017). However, Garrison et al. (2018) found no reliable evidence of such an eruption in 1831, suggesting that the climate forcing eruption must have taken place elsewhere.

Observations of a blue, purple and green sun occurred around the world in August 1831 (Arago, 1832; Kiessling, 1888; Symons et al., 1888). The sun is white when viewed from above Earth's atmosphere. At Earth's surface, however, its observed colour varies due to scattering and absorption by atmospheric gases and aerosols (Bohren and Huffman, 2004). A sufficiently dense aerosol of solid particles or liquid droplets with a radius of about 0.5 µm, and a refractive index of about 1.5 may alter the observed colour of the sun to a pronounced blue, purple or green (La Mer and Kerker, 1953; Penndorf, 1953; Van de Hulst, 1981; Porch, 1989; Horvath et al., 1994; Ehlers et al., 2014; Wullenweber et al., 2021). Such an aerosol is occasionally produced by a volcanic eruption, such as the 1880 eruption of Cotopaxi in Ecuador (Whymper, 1884) or the 1883 eruption of Krakatau in Indonesia (Symons et al., 1888), or by a forest fire, such as the 1950 Chinchaga fire in Canada (Bull, 1951; Wilson, 1951). For as long as an aerosol maintains these parameters whilst being transported in the atmosphere, it will produce a sequence of observations of a blue, purple or green sun at different dates and places. Consequently, a sequence of reported observations of a blue, purple or green sun may be used to reconstruct the atmospheric transport of the aerosol responsible, potentially tracing it back to its source (Symons et al., 1888).

Here, we present our newly compiled dataset of reported observations of a blue, purple and green sun in August 1831, which we use to reconstruct the transport of a stratospheric aerosol plume from the 1831 eruption. We are thus able to constrain the location of the eruption to a mid-latitude site between 30 and 45° N. Using additional reports where a blue, purple or green sun was not seen, despite active observation, we are also able to constrain its longitude and, hence, identify it as the eruption of Ferdinandea, which took place about 50 km off the south-west coast of Sicily (37.1° N, 12.7° E) in July and August 1831. The modest magnitude of this eruption, assigned a VEI of 3 (Global Volcanism Program, 2013), i.e. 10 times smaller in terms of the volume of ejected material than a VEI of 4, has commonly caused it to be discounted or overlooked when identifying the likely source of the stratospheric sulfate aerosol in 1831 (Camuffo and Enzi, 1995; Zielinski, 1995; Robertson et al., 2001, Arfeuille et al., 2014; Toohey and Sigl, 2017). However, we hypothesize that convective instability in the troposphere contributed to aerosol reaching the stratosphere and that the aerosol load was enhanced by addition of a sedimentary sulfur component to the volcanic plume.

2 Methodology

For simplicity, we use the term "blue$^{(+)}$" to include the colours blue, purple and green. A literature search was undertaken to collect as many reported observations of a blue$^{(+)}$ sun in 1831 as possible. The observations compiled by Arago (1832), Kiessling (1888) and Symons et al. (1888) were traced, as far as possible, to their primary sources. Additional primary sources were identified using a combination of "structured" searches (e.g. reviewing obviously relevant national and local newspapers, scientific journals, and collections of published accounts of travel and residence) and "unstructured" searches (e.g. keyword searches of digital archives). A minimum requirement was that a blue$^{(+)}$ sun was observed at least once during the day and that the date and place of the observation was recorded. To determine the boundaries of the region in which a blue$^{(+)}$ sun was observed, the search also extended to reports recording active observation but without a blue$^{(+)}$ sun having been seen ("null" observations). Most of the source materials studied were originally written in western European languages, although at least some were originally written in Arabic, Mandarin and Russian. Online search engines facilitated access to relevant historical materials and translation tools. Supplemental searches of non-digital archives at, for example, the Observatoire de Paris, the Osservatorio Astronomico di Palermo and the British Library were also undertaken. In the course of the search, reported observations of other unusual atmospheric optical phenomena in 1831 were noted and collected and will be referred to in this paper as appropriate.

3 Results

3.1 Reported observations

Thirty one primary sources reporting observations of a blue$^{(+)}$ sun are summarized in Appendix A. The text of three representative reports is reproduced in Table 1. Fifteen of these sources had been identified in Arago (1832), Kiessling (1888) and Symons et al. (1888), but the remaining sixteen are newly identified here. Seventeen primary sources reporting null observations are also summarized in Appendix B. The original language of the sources in Appendices A and B is English (60 %), French (17 %), Italian (8 %), German (6 %), Spanish (4 %), Catalan (2 %) and Arabic (2 %). By type, they comprise newspaper reports (35 %), published accounts of travel and residence (25 %), observational (meteorological) registers published in newspapers or scientific journals (19 %), communications to learned societies published in scientific journals (15 %), letters to newspapers (4 %), and other published records (2 %).

The reported blue$^{(+)}$ sun observations took place between 3 August 1831 (source [A1]) and around 28 August 1831 (source [A31]) in Europe, the Caribbean, the north Atlantic, the USA and China (Fig. 1). The sites were located at latitudes between 19 and 47° N, although about 85 % were restricted to between 30 and 45° N (Figs. 1, 2). The locations of the sites are evidently biased toward regions which had comparatively high population densities in 1831 and, moreover, populations which were likely to report observations in a form which remains accessible today, in particular in Europe and on the eastern coast of the USA. Carpenter (1884) reports that a blue sun was seen "at Washington", in the USA, in "October, especially October 12… [and]… October 13… " 1831. However, this appears to be the result of an erroneous conflation between the date and place of an observation on 12 and 13 August 1831 in Alexandria, Virginia, about 10 km

Table 1. Three representative reported observations of a blue$^{(+)}$ sun in 1831.

Source no.	Date	Place	Text
A5	8/8/1831	Palermo, Sicily, Italy	"Dalle 6 in poi il sole attraversa le dense nebbie presentava un disco con una placida luce bianca turchina; al tramontare lasciò verso ponente una luce rossastra che si prolungò sino a sera avanzata." (Cacciatore, 1831b). Translation (author's own): from 18:00 LT onward, the sun observed through the dense fog appeared as a pale whitish-blue disc; a reddish light to the west after sunset lasted until late in the evening.
A10	10/8/1831	Saint-Sever, Nouvelle-Aquitaine, France	"… vers cinq heures du soir… Le soleil était rond et blanc comme une lune, c'est à dire qu'il était dépourvu de rayons apparens, et qu'on pouvait le regarder en face sans que la vue en fût nullement offensée. Une heure après, cet astre était d'un bleu pâle décidé, toujours dépourvu de rayonnement, et l'horizon de son coucher était d'un rouge vif, comme cela s'observe fréquemment dans les journées chaudes. Une sorte de brume éloignée de la terre, et de densité différente, était uniformément répandue dans les régions supérieures, et voilait l'astre du jour… Dans la journée, on avait remarqué que les objets éclairés par les rayons à nu du soleil avaient une teinte bleuâtre." (Dufour, 1831). Translation: "… about five o'clock in the afternoon… the sun appeared round and white like a moon; that is to say, it emitted no apparent rays, and could be steadfastly regarded without dazzling or in any manner affecting the eyes. An hour afterwards, it appeared of a pale blue colour, but still destitute of rays; and the horizon, at its setting, was of a deep red, such as is frequently observed after a very hot day. A kind of mist, at a considerable distance from the earth, and of trifling density, was uniformly spread in the upper regions of the atmosphere, and veiled the sun… During the day, the objects exposed to the direct rays of the sun had been observed to assume a blueish tint." (London and Paris Observer, 1831).
A22	13/8/1831, 14/8/1831	Norfolk, Virginia, USA	"We have all seen the sun of a dusky red or copper color; but who, until Saturday, the 13th of this month, ever saw it clad in sky blue and pea green? On Saturday, and yesterday morning at its rising, it was of a light but lively green, and as it ascended above the horizon, changed first to cerulean, then to silver white, and finally to pale yellow, when its beams no longer permitted the intrusive gaze of the multitude. And so in its decline, about 5 o'clock in the afternoon it appeared like a globe of silver through the thick haze which overspread the Heavens, shorn of its beams, and gradually assumed the cerulean tint, from which it passed to a light green. A black spot near the centre, was discernible by the naked eye, apparently of the size of a walnut, and with a good spy glass, two others were distinctly visible. In an hour after the sun had set, the horizon in the Northwest exhibited a glare of ruddy light, bearing a strong resemblance to the reflection of a large fire." (Washington National Intelligencer, 1831).

from Washington (source [A18]), and the publication of this observation in the October edition of *Niles' Weekly Register* (1831).

Additional observations of blue$^{(+)}$ sunlight in China in the summer of 1831 are reported in a Mandarin-language compendium of meteorological records (Zhang, 2004). However, this compendium is itself based on an earlier compendium, and the primary sources are not available. These observations have accordingly not been included in the present analysis.

3.2 A sequence of observations of a blue$^{(+)}$ sun

The reported observations of a blue$^{(+)}$ sun in 26 of the 31 sources (Appendix A) form a connected sequence. The earliest observation in the sequence is that reported in Palermo, Sicily, Italy (38.1° N, 13.4° E), at 18:00 LT on 8 August 1831 (source [A5]; Fig. 3a). Over the following 9 d, the locations of the observations move westward, from Europe to the USA, as well as spreading to the north and south, largely across the 30–45° N latitude band, although occasionally further north (to about 50° N; source [A12]) and further south (to about 20° N; source [A19]) (Figs. 3b–j, 4). The observations reported around 28 August 1831 (source [A31]) plausibly extend the connected sequence further westward to China (Fig. 4).

At locations to the east of Sicily from Malta to India, including those across the 30–45° N latitude band, the sources identified reported null observations, i.e. despite observations being actively recorded, no blue$^{(+)}$ sun was seen (Appendix B; Fig. 5). (The apparently exceptional case of the observation reported in Odessa, Ukraine (source [A7]; Fig. 5) is discussed in Sect. 4.1.) The same was true for locations further north and north-west of Sicily from northern Italy,

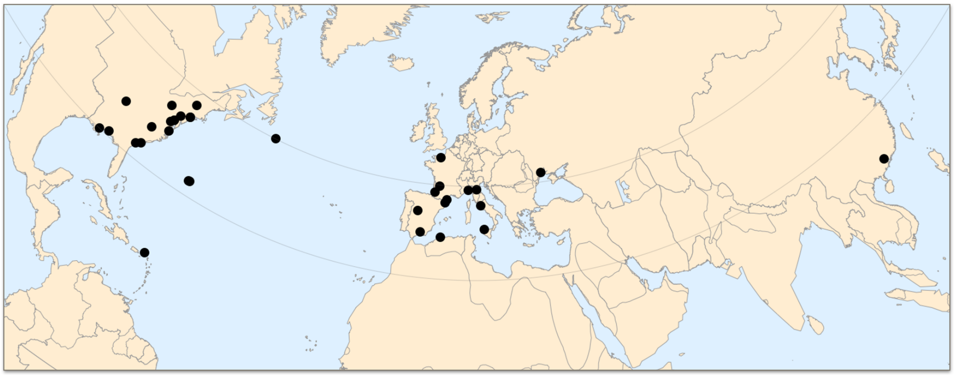


Figure 1. Location of blue$^{(+)}$ sun observations reported in August 1831 (Appendix A). The latitude band shown extends from 30 to 45° N. National borders are shown as correct for 1831 (based on data from Mathematica v. 12.0, Wolfram Research).

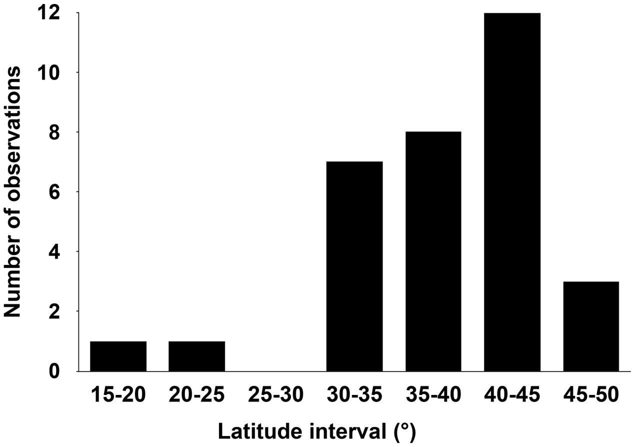


Figure 2. Number of blue$^{(+)}$ sun observations reported in August 1831 in different latitude bands (Appendix A).

Switzerland, Hungary and Germany to the UK (Appendix B; Fig. 5). No reported observations could be found from locations to the south or south-west, across the Sahara Desert. On this basis, the eastern boundary of the region in which the observation of a blue$^{(+)}$ sun was reported in August 1831 can be delineated approximately by the A–A' curve in Fig. 5.

3.3 Reconstruction of aerosol transport

Given the geographical and temporal distribution of these blue$^{(+)}$ sun observations, we propose the following approximate reconstruction of the transport of the aerosol responsible. The aerosol source must have been located in the vicinity of Sicily, near the intersection of the A–A' curve with the centre of the 30–45° N latitude band (Fig. 5). It caused aerosol to be formed between 8 and 13 August 1831 at an altitude with atmospheric circulation from east to west, such that a plume of aerosol lengthened to the west of Sicily (Fig. 6a–f). On 13 August 1831, the aerosol plume extended between about 15° E and 90° W in longitude, over an area of about 14 000 000 km^2 in the latitude band between 30 and 45° N (Fig. 6f; Table 2). Once the source had ceased to cause the formation of aerosol at that altitude, around 14 August 1831, the "detached" aerosol plume continued to be transported westward (Fig. 6g–j) eventually reaching China around 28 August 1831.

3.4 Aerosol transport velocity

Calculating the elapsed time between the earliest and latest progressively further westward blue$^{(+)}$ sun observations from 8 to 17 August 1831 in the latitude band $40 \pm 2°$ N (Appendix A) yields a transport rate of about 0.97° (long.) h^{-1} for the leading edge of the aerosol plume and about 0.73° (long.) h^{-1} for its trailing edge (Fig. 7). Taking the mean transport rate of 0.85° (long.) h^{-1} at 40° N yields a linear velocity of about 20 m s^{-1}.

3.5 Aerosol transport altitude

The prevailing winds in the mid-latitude upper troposphere in the Northern Hemisphere are westerly (Barry and Hall-McKim, 2014). As the aerosol plume transport took place from east to west, it must have been transported at an even higher altitude, above the tropopause. The source event type is most plausibly either a volcanic eruption or a very large forest or bush fire, either of which can inject aerosol into the stratosphere (Robock, 2000; Khaykin et al., 2020); super-eruptions with a VEI of 7 or more may even inject aerosol into the mesosphere (Costa et al., 2018). Given that a super-eruption in the vicinity of Sicily in August 1831 could not have gone un-recorded, however, it is reasonable to assume that the aerosol plume must have been transported in the stratosphere. An easterly stratospheric wind direction at around 40° N in July is also supported by zonal mean wind fields derived from twentieth-century data (Randel, 2003).

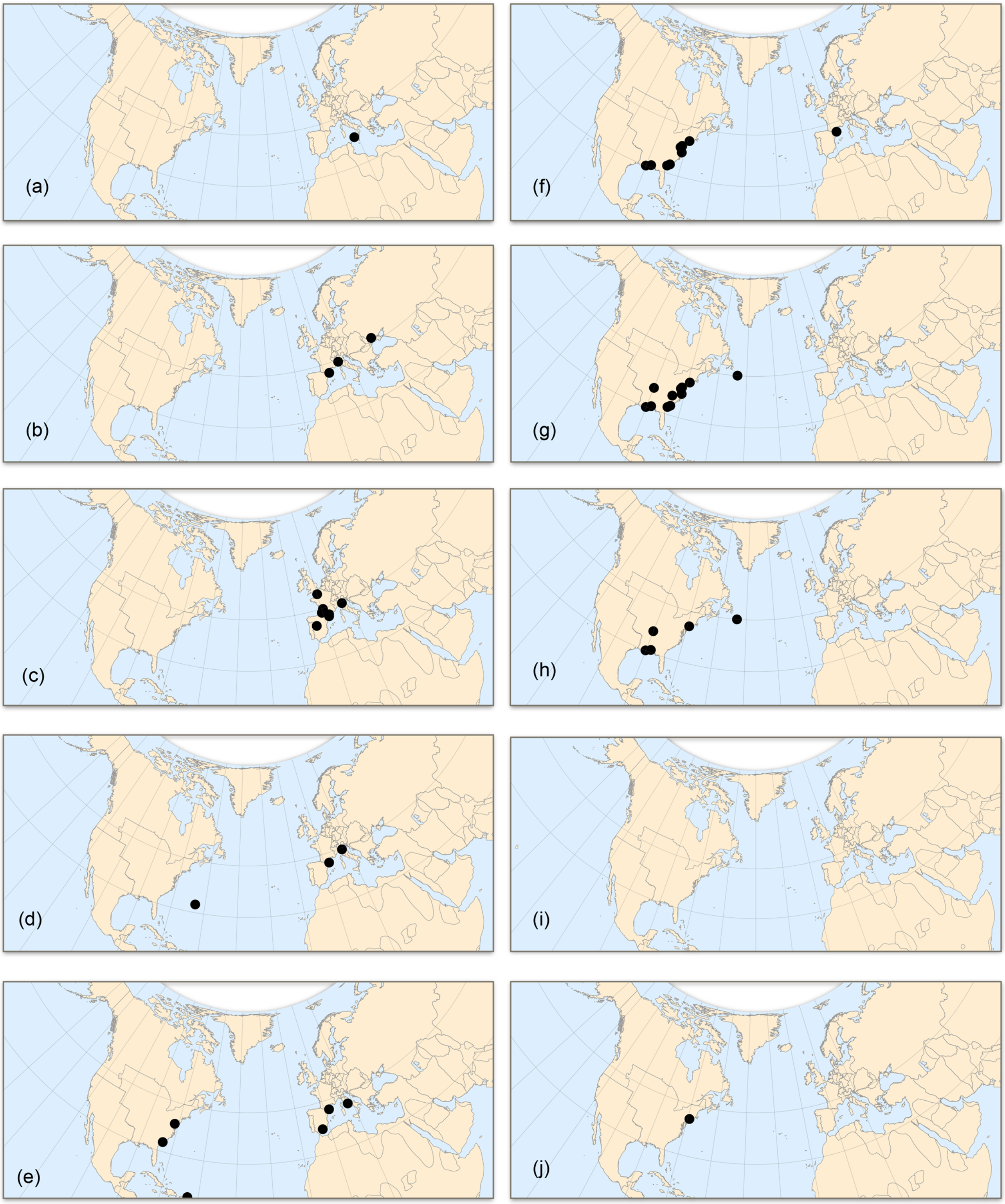


Figure 3. **(a–j)** Progression of observations of a blue$^{(+)}$ sun reported between 8 and 17 August 1831 (Appendix A). The sequence of observations runs day by day from 8 August **(a)** to 12 August **(e)** and from 13 August **(f)** to 17 August **(j)**. No reported observations of a blue$^{(+)}$ sun have been identified on 16 August **(i)**.

Table 2. Parameters for use with Eq. (2) in Sect. 3.6.

Parameter	Approximate value	Rationale
Extinction efficiency (Q)	2	As an approximation to Mie's (1908) rigorous description, Van de Hulst (1981) describes the extinction of light of wavelength λ by idealized spherically symmetric particles with radius r and (real) refractive index m, in terms of an extinction efficiency function: $Q = 2 - \frac{4}{P}\sin P + \frac{4}{P^2}(1-\cos P)$, where $P = \left({}^{4\pi r}/\lambda\right)(m-1)$. The conditions required for the observation of a purple sun occur at the first maximum of Q, around $P = 4.1$, where longer (redder) and shorter (bluer) wavelengths of visible light are extinguished less strongly than intermediate (green) ones; those for a blue sun occur around $P = 5.5$, where longer (redder) wavelengths of visible light are extinguished more strongly than shorter (bluer) ones; and those for a green sun occur at the first minimum of Q, around $P = 7.7$, where both longer (redder) and shorter (bluer) wavelengths of visible light are extinguished more strongly than intermediate (green) ones (La Mer and Kerker, 1953; Ehlers et al., 2014). Assuming a particle refractive index $m = 1.5$ and that $\lambda = 0.55\,\mu$m is the centre of the visual light spectrum, extinction efficiency Q varies between 1.5 and 3.2 over this range of parameter P.
Refractive index (m)	1.5	The aerosol particle refractive index (m) typically varies within a range from 1 to 2, including $m = 1.33$ (water droplets), $m =$1.43–1.46 (volcanogenic sulfate droplets), $m = 1.46$ (organic oil droplets produced by forest fires) and $m = 1.55$ (desert sand particles) (Penndorf, 1953; Yue et al., 1994).
Radius (r)	0.5 µm	Assuming a particle refractive index $m = 1.5$, the above range of parameter P from 4.1 to 7.7 corresponds to a range of aerosol particle radius from $r = 0.36\,\mu$m (a purple sun) to $r = 0.48\,\mu$m (a blue sun) and $r = 0.67\,\mu$m (a green sun). Non-ideal aerosols produced by natural sources likewise produce the observation of a purple, blue or green sun if their size distribution is dominated by particles in this narrow range (Penndorf, 1953; Horvath et al., 1994), although somewhat broader particle distributions may do so too (Horvath et al., 1994; Wullenweber et al., 2021).
Density (ρ)	$1500\,\mathrm{kg\,m^{-3}}$	Stothers (1984b) assumes a typical aerosol particle density of approximately $\rho = 1500\,\mathrm{kg\,m^{-3}}$.
Optical depth (τ)	4.8 ± 1.2	Sect. 3.6 of this paper.
Area (A)	$14\,000\,000\,\mathrm{km^2}$	Sect. 3.3 of this paper.
Homogeneity fraction (f)	0.3	Sect. 3.6 of this paper.

3.6 Aerosol optical depth and mass

In addition to altering the colour of the sun, the scattering and absorption of sunlight by atmospheric gases and aerosols dims its observed brightness (Bohren and Huffman, 2004). The sun has a visual magnitude $M = -26.74$ (Schaefer, 1993). Adapting Stothers (1984a, b), the optical depth (τ) of an atmospheric aerosol (at zenith angle $z = 0°$, i.e. overhead) is related to the reduction in solar magnitude (ΔM) that it produces at an elevation angle (α) as follows:

$$\tau = \frac{\ln 10}{2.5}(\Delta M \sin\alpha - 0.2)(\alpha > 15°), \tag{1}$$

where elevation angle (α) and zenith angle (z) are related as $\alpha = 90 - z$. Atmospheric refraction can be neglected for $\alpha > 15°$ (Stothers, 1984b; Schaefer, 1993).

Horvath et al. (1994) report that, due to the physiology of human colour perception, the colour of a blue$^{(+)}$ sun remains too bright to be perceived unless its light has been attenuated by a factor of at least 10^{-4} and that it is most readily perceived when its light is attenuated by a factor of between 10^{-5} and $10^{-6.6}$, equivalent to a reduction in magnitude of between $\Delta M = 12.5$ and 16.5. Even if too bright to be perceived as such, a blue$^{(+)}$ sun will still be sufficiently reduced in magnitude to be able to be viewed with the naked eye without damage or discomfort at a reduction in magnitude of between, at the very least, about $\Delta M = 3.4$ (Stothers, 1984a,

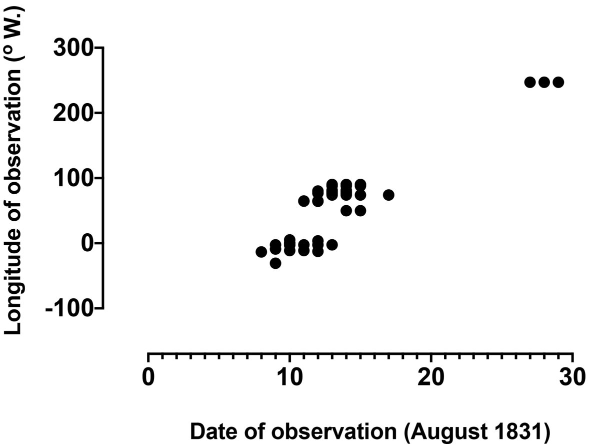


Figure 4. Longitude of blue$^{(+)}$ sun observations reported in August 1831 (Appendix A).

b) and, more likely, about $\Delta M = 12$ (Schaefer, 1993). At lower reductions in magnitude still, $\Delta M < 3.4$, the sun will be more normal in appearance and too bright to observe with the naked eye.

Thus, for suitable aerosol optical depth values (τ), three observational phases may be distinguished: at higher solar elevations, a sun of normal or near-normal appearance (for $\Delta M < 3.4$ and likely for some part of the range from $\Delta M =$ 3.4 to $\Delta M = 12$); at lower solar elevations, a pale sun able to be viewed with the naked eye (for the remaining part of the range from $\Delta M = 3.4$ to $\Delta M = 12$); and at lower solar elevations still, a blue$^{(+)}$ sun able to be viewed with the naked eye (between $\Delta M = 12.5$ and $\Delta M = 16.5$).

These three observational phases are illustrated, for example, in two of the reports reproduced in Table 1 (sources [A10] and [A22]). It is noteworthy that the ratio between the brightness of the typical zenithal sun and a white object diffusely reflecting its light is about 80 000 : 1 (Minnaert, 1954). This presumably explains the otherwise paradoxical observation of blue$^{(+)}$ sunlight illuminating surfaces and objects when the sun is too bright to be observably blue$^{(+)}$ (source [A22]), as the associated attenuation factor of $10^{-4.9}$ is sufficiently close to meet the threshold requirement reported by Horvath et al. (1994).

Nine of the sources (Appendix A) report the local time at which a blue$^{(+)}$ sun was observed. The corresponding solar elevation angle (α) can be recovered from this local time, for example, using the National Oceanic and Atmospheric Administration (NOAA) Solar Calculator (available at https://gml.noaa.gov/grad/solcalc/, last access: 30 May 2021) (Appendix A). Therefore, using this solar elevation angle (α) and the range of reduction in solar magnitude associated with a blue$^{(+)}$ sun observation ($\Delta M = 12.5$ to $\Delta M = 16.5$), Eq. (1) yields a corresponding range of instantaneous aerosol optical depth values (τ) in each case (Fig. 8).

Five of the sources (Appendix A) report the local time at which the sun was observed with the naked eye after having been observably blue$^{(+)}$ in the morning or before becoming observably blue$^{(+)}$ in the afternoon. The qualitative descriptions of the appearance of the sun in these latter reports, for example, as a "crystal globe" (source [A8]) or as "moonlike" (source [A10]), suggest the upper end of the $3.4 < \Delta M < 12$ range in magnitude reduction, i.e. $8 < \Delta M < 12$. Likewise, recovering solar elevation angle (α) from local time and using this solar elevation angle (α) with the range of reduction in solar magnitude associated with such a naked-eye sun observation ($\Delta M = 8$ to $\Delta M = 12$), Eq. (1) yields a corresponding range of instantaneous aerosol optical depth values (α) in each case (Fig. 8).

Based on the observations reported in sources [A8]–[A30] between 8 and 17 August 1831, the mean instantaneous optical depth of the aerosol plume is estimated to be $\tau = 4.8 \pm 1.2$ (Fig. 8).

Had the aerosol plume produced between 8 and 13 August 1831 been homogenous, however, it would have taken 6 d to pass over each site and reports of 6 consecutive days of identical blue$^{(+)}$ sun observations would have been expected. In fact, the number of consecutive days of blue$^{(+)}$ sun observations varied between 1 and 5 with a mean of about 1.8. Therefore, the aerosol plume cannot have been homogenous. We instead assume that it was sufficiently dense to produce observations of a blue$^{(+)}$ sun, with a mean optical depth $\tau = 4.8 \pm 1.2$, over only a fraction (approximately $f = 1.8/6 = 0.3$) of its area. Although the remainder of the aerosol plume was evidently occasionally dense enough to produce ancillary observations of a pale sun (e.g. sources [A9], [A13], [A17] and [A18]), it will be neglected in comparison; taking into account background atmospheric Rayleigh scattering, Wullenweber et al. (2021) determined that in order for an aerosol which is capable of producing observations of a blue$^{(+)}$ sun to do so, it must have an optical depth $\tau > 0.5$.

Adapting Stothers (1984b, 1996), the mass M of a homogenous atmospheric aerosol over an area A is related to its optical depth (τ) (at $z = 0°$) as follows:

$$M = \frac{4r\rho}{3Q}\tau A, \qquad (2)$$

where the aerosol particles all have radius r, density ρ and extinction efficiency Q. To account for the inhomogeneity in this case, we treat the area of the aerosol plume over which it was sufficiently dense to produce observations of a blue$^{(+)}$ sun. Using appropriate values for parameters r, ρ, Q, τ, A and f (Table 2), Eq. (2) yields an aerosol plume mass $M = 10.1 \pm 2.5 \times 10^9$ kg $= 10.1 \pm 2.5$ Tg.

This is a minimum value for the total mass of stratospheric aerosol produced by the source. It does not include the portion of the aerosol plume outside the 30–45° N latitude band, which might be approximately estimated to be 15 % (Fig. 2). Further, assuming that the four earlier observa-

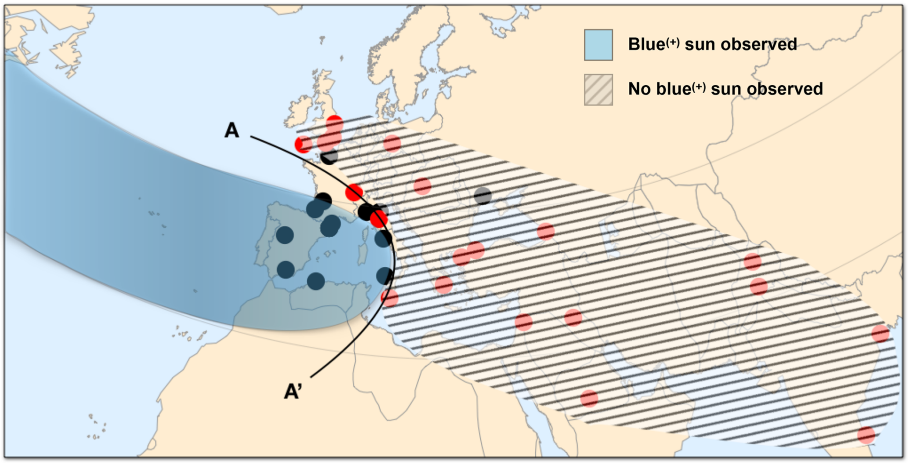


Figure 5. Locations of observations of a blue$^{(+)}$ sun (black points) and of null observations (red points) reported in August 1831 (see Appendices A and B). The boundary between the region where a blue$^{(+)}$ sun was observed and the region where it was not is delineated approximately by the A–A' curve.

tions of a blue$^{(+)}$ sun in the 30–45° N latitude band reported from North Africa on 3 August 1831 (source [A1]) and the north-eastern USA on 4 August 1831 (sources [A2]–[A4]) were caused by aerosol produced by the same source, they would be consistent with two smaller bodies of stratospheric aerosol having been produced between 31 July 1831 and 2 August 1831 (sources [A1]–[A3] in Fig. 8).

3.7 Aerosol source

The 1831 eruption of Ferdinandea (also known as "Campi Flegrei Mar Sicilia" and "Graham Island") occurred about 50 km off the south-west coast of Sicily (Gemmellaro, 1831; Washington, 1909; Dean, 1980; Global Volcanism Program, 2013). Starting from a submarine base approximately 150 m b.s.l. (below sea level), it produced a volcanic island that first rose above sea level around 16 July 1831 and subsequently grew to about 60 m high and 2 km in circumference by the time the eruption ceased around 16 August 1831 (Dean, 1980; Spatola et al., 2018). Based on the close coincidence in place ("in the vicinity of Sicily") and date ("between 31 July 1831 and 13 August 1831"), we identify the Ferdinandea eruption as the source of the stratospheric aerosol that was responsible for the blue$^{(+)}$ sun observations in August 1831. It is noteworthy that Riccò (1886) made a similar suggestion in the late nineteenth century.

The compositional dynamics of volcanic aerosol plumes can be complex (Mather et al., 2004). However, volcanogenic aerosol in the stratosphere is typically treated as being composed of sulfate droplets containing three-quarters sulfuric acid (H_2SO_4) and one-quarter water (H_2O) (Zielinski, 1995; Toohey and Sigl, 2017). Therefore, in order to produce a minimum 10.1 ± 2.5 Tg of stratospheric sulfate aerosol, the sulfur yield of the Ferdinandea eruption could not have been less than about 2.5 ± 0.6 Tg.

4 Discussion

4.1 The plausibility of the Ferdinandea eruption as the aerosol source

The Ferdinandea eruption is described as a small phreatomagmatic ("surtseyan") eruption (Self et al., 1989). The remnant cone today lies underwater and has a volume of about 0.06 km^3 (Spatola et al., 2018). The eruption has been assigned a VEI of 3, which is associated with a total volume of erupted tephra of the order of 0.1 km^3 (Global Volcanism Program, 2013). Tephra typically has a density of about $10^{12}\ \mathrm{kg\,km}^{-3}$ (Crosweller et al., 2012). In order to estimate a sulfur yield for this eruption from these parameters, the typical ocean island basalt affinity for the Sicily Straits Rift Zone (White et al., 2020) is assumed, as is the pre-eruptive melt sulfur content of 3000 ppm reported from Etna by Spilliaert et al. (2006), which marks the very upper end of the concentration range for this volcanic environment (Oppenheimer et al., 2011). These values yield a maximum sulfur yield of 0.3 Tg, which is about an order of magnitude smaller than our estimated minimum sulfur yield.

We hypothesize (hypothesis "H1") that the release of the additional sulfur was the result of magma interacting with layers of sulfur-rich sedimentary deposits recently identified at the site of the Ferdinandea eruption (Spatola et al., 2018). These include Messinian evaporites (Spatola et al., 2018). Evaporitic sequences are typically associated with gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$) and halite (NaCl). The 1982 eruption of El Chichón, in Mexico, injected about 3.8 Tg of sulfur into the stratosphere (Krueger et al., 2008), as much as 2 orders of magnitude more than would have been expected on the basis of the volume and type of magma erupted alone (Luhr, 1984; Devine et al., 1984; Oppenheimer et al., 2011). The two possible sources for the additional sul-

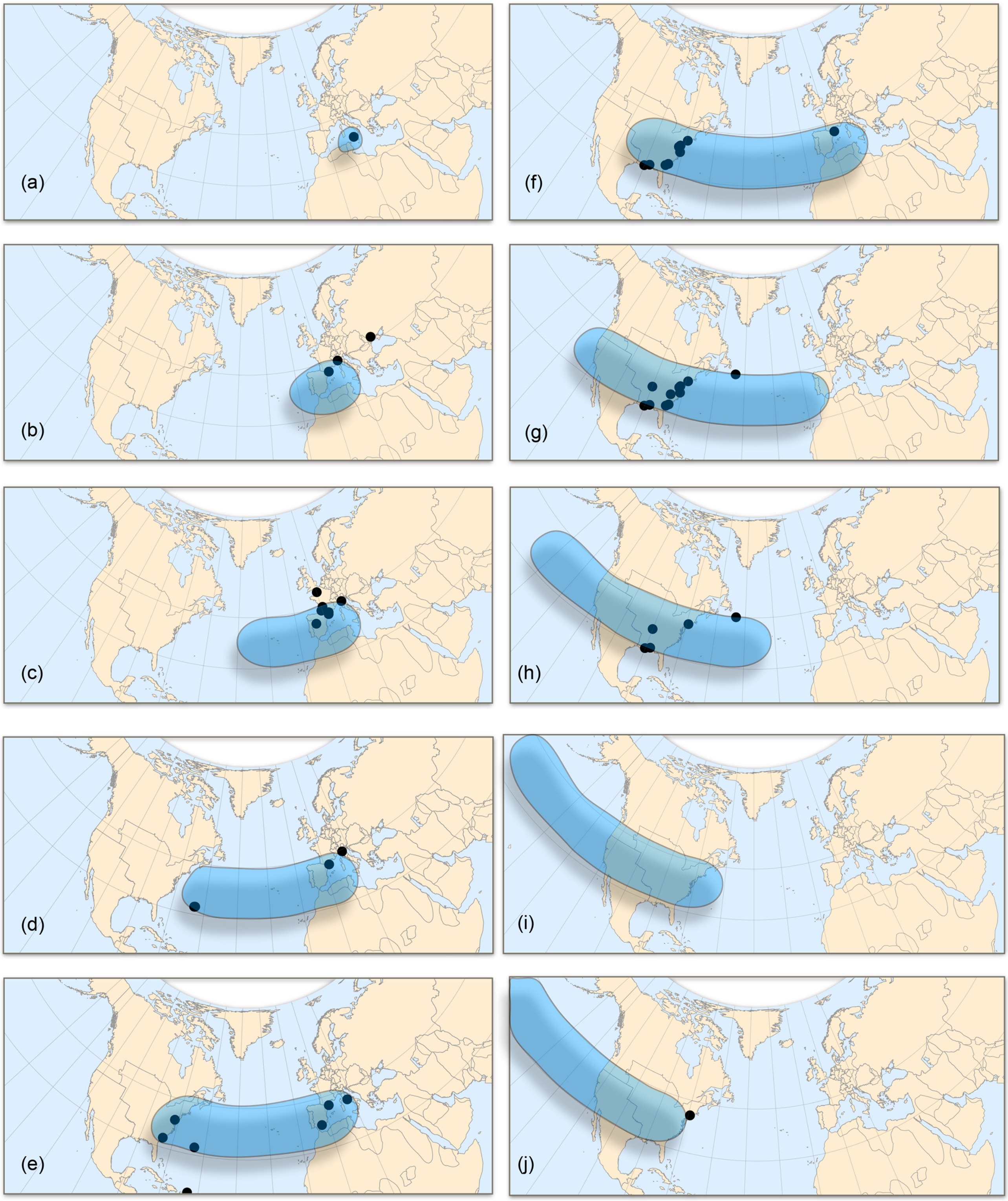


Figure 6. **(a–j)** Approximate reconstruction of the generation and transport of the aerosol plume responsible for the blue$^{(+)}$ sun observations in August 1831. The sequence of observations runs day by day from 8 August **(a)** to 12 August **(e)** and from 13 August **(f)** to 17 August **(j)**. The more minor portion of the aerosol plume which lies outside the 30–45° N latitude band is not shown.

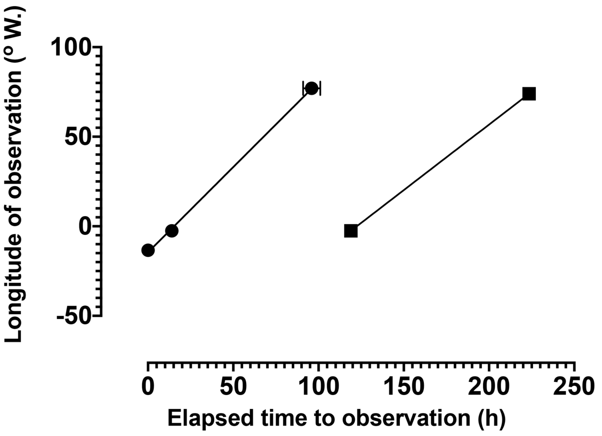


Figure 7. Rate of westward transport of the leading (left) and trailing (right) edges of the aerosol plume, based on sources [A5], [A6], [A17] and [A18] (left) and sources [A6] and [A30] (right). Elapsed time is measured in hours from 18:00 LT (local time, UTC +1) in Sicily on 8 August 1831 (source [A5]).

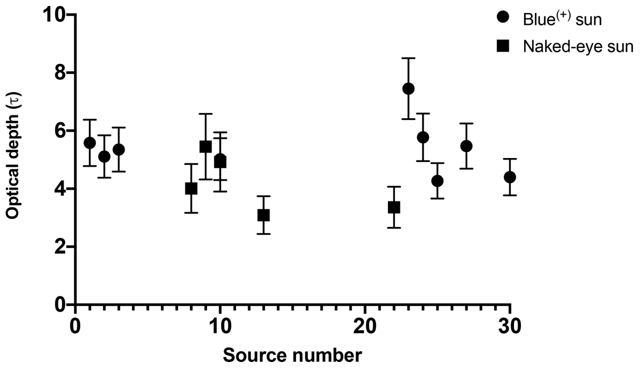


Figure 8. Estimated instantaneous aerosol optical depth ranges. Those marked with a circle represent ranges derived from observations of a blue$^{(+)}$ sun, whereas those marked with a square represent ranges derived from observations of a naked-eye sun (either after having been observably blue$^{(+)}$ in the morning or before becoming observably blue$^{(+)}$ in the afternoon) (see Sect. 3.6).

fur have been identified as an evaporitic anhydrite-bearing sedimentary layer at the site of the El Chichón eruption and deeper subducted sulfide deposits (Rampino and Self, 1984; Duffield et al., 1984; Luhr, 2008). In the case of the Ferdinandea eruption, however, other sulfur-rich components may be relevant too. In some Sicilian Messinian evaporite contexts where hydrocarbons are present, sulfate-reducing microbial activity has resulted in conversion of the gypsum or anhydrite to more easily mobilizable hydrogen sulfide and native sulfur (Ziegenbalg et al., 2010). A hydrocarbon signature has been detected in gas emissions from an active fumarole field about 1 km from the submerged Ferdinandea cone, although concentrations of sulfur species were not determined (Coltelli et al., 2016).

This hypothesis (H1) is supported by eye-witness observations. During the eruption in July and August 1831, a very strong and unpleasant smell described as a "stink" of sulfur ("una puzza di zolfo") or of sulfur and bitumen ("una puzza di zolfo e di bitume") was reported in towns along or near the south-west coast of Sicily (Gemmellaro, 1831; Russo Ferrugia, 1831). The distance at which it was reported peaked at 100 km on 11 August 1831 (Russo Ferrugia, 1831), i.e. during the generation of the reconstructed stratospheric aerosol plume between 8 and 13 August 1831. Silver objects became tarnished at the same time (Gemmellaro, 1831; Russo Ferrugia, 1831), suggesting that sufficiently high atmospheric concentrations of hydrogen sulfide (and water vapour) reacted with the silver to form a blackened ("tarnished") surface layer of silver sulfide (Inaba, 1996).

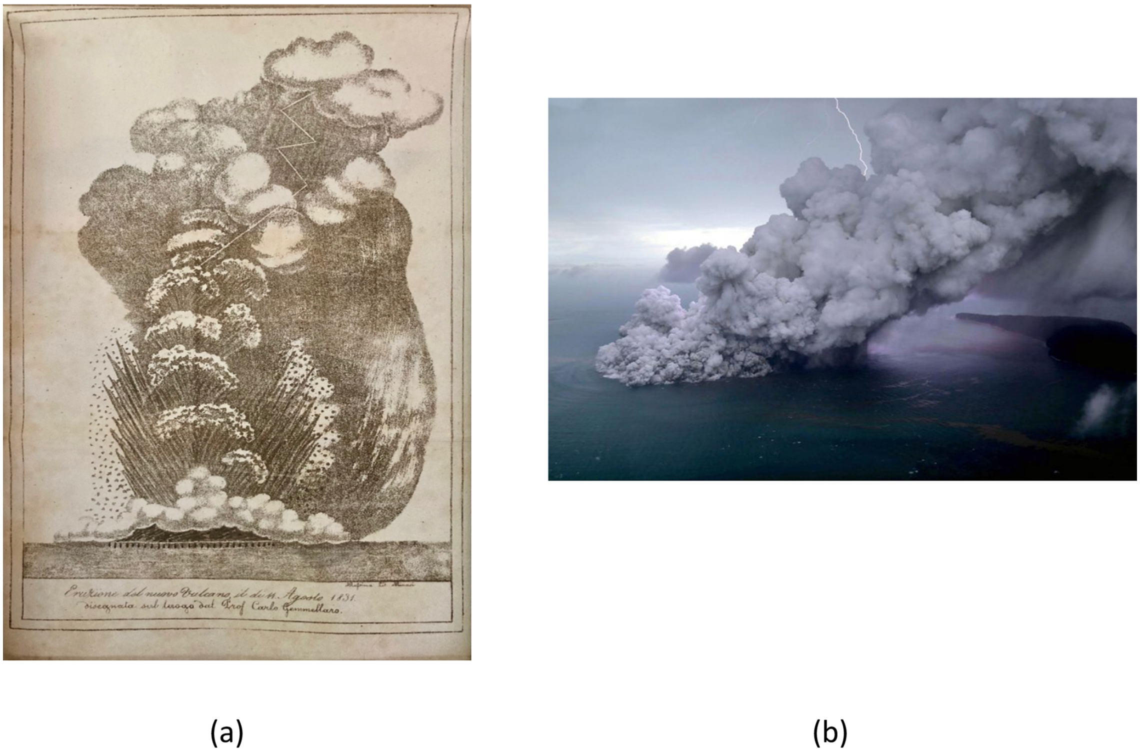
A VEI of 3 is associated with "possible" stratospheric injection rather than the "definite" stratospheric injection associated with a VEI of 4 (Newhall and Self, 1982; Global Volcanism Program, 2013). We hypothesize (hypothesis "H2") that injection of the volcanic aerosol into the stratosphere by the Ferdinandea eruption was supported by favourable meteorological conditions. The 2018 eruption of Anak Krakatau, an island volcano on the rim of the Krakatau volcano, in Indonesia, was similar in style and magnitude to that of Ferdinandea (Table 3; Fig. 9a, b). It is likewise assigned a VEI of 3 (Global Volcanism Program, 2013). Crucially, sustained phreatomagmatic activity during the eruption produced a column with an updraught in which the vertical velocity was enhanced by convective instability (Prata et al., 2020). Thus, for 6 continuous days, a plume of positively buoyant aerosol was able to reach an altitude which varied between 16 and 18 km a.s.l. (above sea level), at times above the local tropopause at 16.8 ± 0.8 km (Prata et al., 2020).

Anticyclones with subsiding air typically inhibit deep convection in high summer in the central Mediterranean region, even though large amounts of convective instability may be present in the mid-troposphere above an inversion (Taszarek et al., 2018). The mean height of the tropopause over the south-eastern Mediterranean in the summer is approximately 14 km (Retalis and Cartalis, 1997). We hypothesize (H2) that phreatomagmatic activity during the Ferdinandea eruption was sufficiently sustained, at times, to produce a column with updraughts enhanced by environmental convective instability above any inversion, such that positively buoyant aerosol was able to breach the tropopause, similar to the Anak Krakatau eruption.

This hypothesis (H2) is also supported by eye-witness observations. Approaching the site of the eruption on 5 August 1831, i.e. just prior to the generation of the reconstructed stratospheric aerosol plume between 8 and 13 August 1831, Smythe (1831) reported from a distance of 55 km that: "… a stupendous column of white steam was observed, rising majestically far above the western horizon, splendidly illumined (sic) by the setting sun…". At that time, on 6 August 1831, continuous episodes of violent "cypress-tree-like"

Table 3. Comparison of the eruptions of Ferdinandea and Anak Krakatau. References: Dean (1980), Retalis and Cartalis (1997), Global Volcanism Project (2013), Spatola et al. (2018), Gouthier and Paris (2019), and Prata et al. (2020).

Eruption	Ferdinandea ("Campi Flegrei Mar Sicilia" and "Graham Island")	Anak Krakatau
Location	In the Straits of Sicily, 50 km off the south-west coast of Sicily, Italy (37.1° N, 12.7° E)	At sea level in the caldera of the Krakatau volcano, in Indonesia (6.1° S, 105.4° E)
Date	Around 16 July to 16 August 1831 (with a prior submarine phase from around June to 16 July 1831)	22 December 2018 to 6 January 2019
Predominant eruption style	Surtseyan (phreatomagmatic)	Surtseyan (phreatomagmatic)
Erupted volume	0.06–0.1 km^3	0.045 km^3
VEI	3	3
Altitude of local tropopause	Approximately 14 km a.s.l.	16.8 ± 0.8 km a.s.l
Max. column height	Above the local tropopause (see Sect. 3.5 of this paper)	18 km



(a) (b)

Figure 9. **(a)**. Sea-level sketch of the Ferdinandea eruption on 11 August 1831 drawn by Gemmellaro (1831). Characteristic features of phreatomagmatic activity are portrayed: pyroclastic material is being explosively ejected in successive cypress-tree- or cock's-tail-like forms at the base of a rising column of steam and ash (Francis and Oppenheimer, 2004); a "base surge" is visible. The column appears to be sheared downwind from the observer. A volcanic lightning discharge in the upper part of the eruption column is visible. **(b)** Photograph of the Anak Krakatau eruption taken from a light aircraft on 23 December 2018. (Image reproduced with permission: Nurul Hidayat/Antara Foto Agency/Reuters.) Characteristic features of phreatomagmatic activity are again visible (Francis and Oppenheimer, 2004) including a "base surge". The column is inclined up and to the right of the observer. A volcanic lightning discharge is again visible.

phreatomagmatic explosions were separated by quiescent periods of 2–3 h (Smythe, 1831). By 11 August 1831, however, phreatomagmatic activity had significantly intensified: Gemmellaro (1831) reported that the continuous episodes lasted between 30 and 45 min (Fig. 9) and were separated by quiescent periods of only 2–3 min. Stratospheric injection may also have been achieved earlier in the eruption, even if it did not lead to the formation of an aerosol with the parameters necessary to produce observations of a blue$^{(+)}$ sun. On 22 July 1831, the eruption column reportedly subtended an angle of at least 20° at a distance of 50 km from the site of the eruption, suggesting that the (visible) column was at least 18 km high (Hoffmann, 1831; Symons et al., 1888).

Profiles of temperature, humidity and winds in the atmospheric column in the central Mediterranean in late July and early August 1831 will be required to test the hypothesis (H2) that environmental convective instability increased the height of the eruption column, permitting aerosol injection above the tropopause. Although no observations comparable to modern radiosonde ascents exist for this period, a proxy is provided by the recent extension of global atmospheric reanalysis datasets to the early nineteenth century, for example, the Twentieth Century Reanalysis (20CR) versions 2 and 3 (Compo et al., 2011; Slivinski et al., 2019).

Zonal mean wind fields derived from twentieth century data suggest that easterly wind velocity (40° N, July) would not be expected to exceed about 10 $\mathrm{ms^{-1}}$ below an altitude of approximately 20 km (30 hPa) in the low stratosphere and that a velocity of about 20 $\mathrm{ms^{-1}}$ would only be expected to be reached at an altitude of approximately 35 km (8 hPa) in the mid-stratosphere (Randel, 2003). A particular focus for this hypothesis testing will therefore examine whether the aerosol is likely to have reached only the low stratosphere, in which case the easterly aerosol transport velocity estimated in Sect. 3.4 (20 $\mathrm{ms^{-1}}$) would be inconsistent with the easterly wind velocity suggested for the lower stratosphere by the zonal mean wind field data (10 $\mathrm{ms^{-1}}$) by a factor of 2, or whether it could have reached the mid-stratosphere.

A reanalysis-based reconstruction of atmospheric circulation will also permit investigation of whether aerosol transport in different wind directions from the eruption site at different altitudes was responsible for the only blue$^{(+)}$ sun observation otherwise unaccounted for, which reportedly occurred on 9 August 1831 in Odessa, Ukraine (source [A7]; Fig. 5), as well as ancillary reports of unusual haze or fog elsewhere in the Mediterranean or Europe (e.g. sources [A1], [A5], [B8], [B13] and [B15]).

4.2 Comparison with independent datasets

Assuming that the sulfate aerosol plume was transported in the stratosphere, it could have been expected to produce occasional observations of a fiery twilight glow from 8 August 1831 onward. Such twilight glows are often referred to as “volcanic sunsets” and are characteristic of volcanogenic sulfate aerosols in the stratosphere (Meinel and Meinel, 1991). The stratospheric altitude is sufficiently high for the sulfate aerosol to continue to scatter (“reflect”) sunlight, so long as it is not blocked by tropospheric clouds, even when the sun is well below the horizon (Symons et al., 1888; Meinel and Meinel, 1991). Thus, stratospheric aerosol to the east of an observer may produce the observation of a twilight glow before dawn, whereas stratospheric aerosol to the west may produce the observation of a twilight glow after sunset.

Consistent with this expectation, nine of the sources that report observations of a blue$^{(+)}$ sun between 8 and 17 August 1831 also report observations of a fiery twilight glow whose locations move from east to west in conjunction with the sites of the blue$^{(+)}$ sun observations (Appendix A). In addition, a longer sequence of twilight glow observations was reported at Palermo between August and October 1831 (source [A5]). The sequence appears to have a periodicity of about 18 d. This suggests that, although the stratospheric aerosol plume only maintained the parameters necessary to produce observations of a blue$^{(+)}$ sun over about three-quarters of one circuit of Earth (path A–B–C–D in Fig. 10), it nevertheless remained dense enough thereafter to continue to produce observations of a twilight glow over two further circuits of Earth (path A–B–C–D–A in Fig. 10 and Fig. 11). A periodicity of 18 d is equivalent to a transport rate of 20° (long.) $\mathrm{d^{-1}}$ or about 0.84° (long.) $\mathrm{h^{-1}}$, very close to the aerosol plume transport rate (0.85° (long.) $\mathrm{h^{-1}}$) estimated in Sect. 3.4 on the basis of the blue$^{(+)}$ sun observations.

Six of the null observation sources also report observations of a twilight glow in August 1831 (Appendix B), appearing to reflect the initial transport of the stratospheric aerosol plume or the two smaller precursory bodies of stratospheric aerosol (e.g. sources [B12], [B13] and [B14]) and/or the return of the aerosol plume after a first (e.g. sources [B5] and [B14]) or second circuit (e.g. source [B16]) of Earth.

As the stratospheric sulfate aerosol plume continued to be transported, it would have dispersed to form a more homogenous stratospheric sulfate aerosol. Assuming that sulfate aerosol typically has a stratospheric residence time with an e-folding timescale (i.e. the time taken to decline by a value $e^{-1} = 0.37$) of about 1 year (Robock, 2000), approximately 63 % of it would have returned to the troposphere after 1 year and 86 % after 2 years. Under the premise that the earliest possible sulfate deposition on the Greenland ice sheet from the Ferdinandea eruption could have taken place via a direct tropospheric route from July or August 1831 and that significant deposition via the stratospheric route could continue for no more than 2 years (Robock, 2000), it would be expected that an increase in sulfate deposition would be detected in Greenland ice cores between July or August 1831 and around August 1833. The magnitude of the expected increase should correspond to our estimated minimum sulfur yield for the Ferdinandea eruption of about 2.5 ± 0.6 Tg.

Consistent with this expectation, Sigl et al. (2013) report a peak in sulfate deposition in a Greenland ice core between

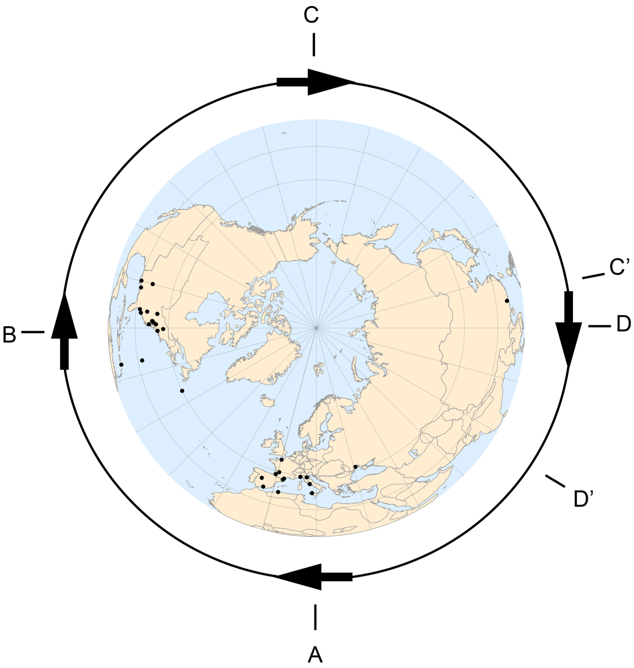


Figure 10. Aerosol transport path A–B–C–D–A around Earth in 1831. The locations of the blue$^{(+)}$ sun observations reported in August 1831 (Appendix A) are shown. The last reported observation of a blue$^{(+)}$ sun occurred around 28 August 1831 in China (source [A31]) near point C', whereas the first observations where no blue$^{(+)}$ sun was reported occurred in India and Pakistan (sources [B1]–[B4]) near point D'.

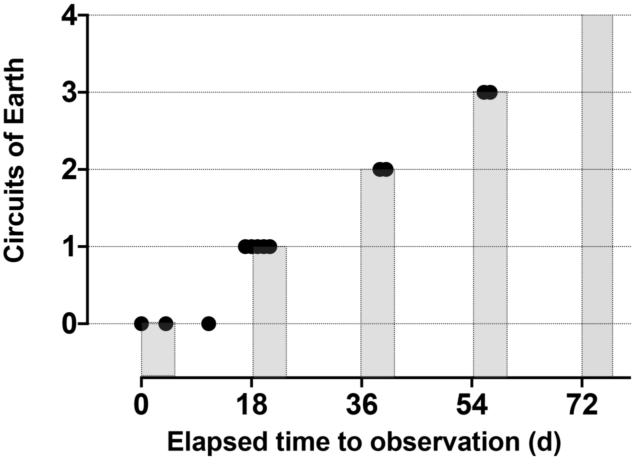


Figure 11. Twilight glow observations reported in Palermo, Sicily, Italy, between August and October 1831 (source [A5]). Elapsed time is calculated in days from the twilight glow observation on 8 August 1831 (source [A5]). The periodicity of the observations is consistent with the aerosol responsible completing one circuit of Earth around transport path A–B–C–D–A (Fig. 10) in approximately 18 d.

1831.4±0.25 and 1833.7±0.25. Assuming a source eruption of Babuyan Claro, in the Philippines, Toohey and Sigl (2017) estimate that the sulfur yield of the eruption responsible for the peak was 12.98±3.41 Tg. However, if the source eruption had been located at a mid- or high-latitude site, instead of a low-latitude site, this estimate could be reduced by as much as 60 % (Toohey and Sigl, 2017). Presuming a source eruption at an unidentified site in the Northern Hemisphere (and using a different set of Greenland ice cores), Gao et al. (2008) estimate the sulfur yield of the eruption responsible for the peak to have been lower at about 4.2 Tg. Thus, our estimated minimum sulfur yield for the Ferdinandea eruption already represents about 60 % of the total eruption sulfur yield estimated by Gao et al. (2008).

Based on this close coincidence in the expected and actual sulfate deposition profile (and although more minor contributions from other sources cannot be ruled out), we identify the Ferdinandea eruption as the source of the climate forcing stratospheric sulfate aerosol in 1831.

5 Conclusions

One of the largest climate forcing volcanic eruptions of the nineteenth century took place in 1831 (Zielinski, 1995; Gao et al., 2008; Arfeuille et al., 2014; Toohey and Sigl, 2017). Here, we have used a newly compiled dataset of reported observations of a blue, purple and green sun in August 1831 to reconstruct the transport of a stratospheric aerosol plume from that eruption. Thus, we are able to constrain the location of the eruption to a mid-latitude site between 30 and 45° N. Those prior estimates of the mass of stratospheric sulfate aerosol responsible for the 1831 Greenland ice core sulfate deposition peaks which assumed a source eruption at a low-latitude site will, therefore, have been overstated (Zielinski, 1995; Arfeuille et al., 2014; Toohey and Sigl, 2017). For a given mass of stratospheric sulfate aerosol, Toohey et al. (2019) recently demonstrated that eruptions at mid- or high-latitudes can produce stronger hemispheric climate forcing than low-latitude eruptions.

Using additional reports where a blue, purple or green sun was not recorded, despite active observation, we are also able to constrain the longitude of the eruption and, hence, are able to identify it as the eruption of Ferdinandea, which took place about 50 km off the south-west coast of Sicily (37.1° N, 12.7° E) in July and August 1831. The eruption is assigned a VEI of 3 (Global Volcanism Program, 2013). Its modest magnitude has commonly caused it to be discounted or overlooked when identifying the likely source of the stratospheric sulfate aerosol in 1831 (Camuffo and Enzi, 1995; Zielinski, 1995; Robinson et al., 2001, Arfeuille et al., 2014; Toohey and Sigl, 2017). However, we argue here that the Ferdinandea eruption must be considered in the context of its geological and meteorological environment, rather than in isolation. We hypothesize (H1) that despite its modest magnitude, its magmatic system was nevertheless sufficient to trigger the release of sulfur from sedimentary deposits at the site of the eruption and (H2) that convective instability in the troposphere contributed to aerosol reaching the stratosphere, such that the Ferdinandea eruption did indeed result in the production of the stratospheric sulfate aerosol in 1831.

Our reconstruction of the transport of the stratospheric aerosol plume can be tested and improved upon with a search for further sources reporting the observation of a blue, purple or green sun in 1831. Our two hypotheses (H1, H2) as to the Ferdinandea eruption can be tested through further study of its magmatic system and geological context as well as with a reanalysis-based reconstruction of atmospheric circulation in July and August 1831. If we are correct, one of the largest climate forcing volcanic eruptions of the nineteenth century would effectively have been hiding in plain sight. This would arguably "lower the bar" for the types of eruptions capable of having a substantial climate forcing impact. This example serves as a useful reminder that VEI values were not intended to be reliably correlated with eruption sulfur yields unless supplemented with compositional analyses (Newhall and Self, 1982).

Analysis of reported observations of unusual atmospheric optical phenomena both in 1831 and in 1883 may support further investigation in a number of additional directions.

For example, the first observation of a blue$^{(+)}$ sun in the equivalent connected sequence following the onset of the most explosive phase of the 1883 Krakatau eruption occurred of the order of 1 d later (Symons et al., 1888). This suggests the rapid formation of a stratospheric aerosol whose size distribution is dominated by particles with a radius of the order of 0.5 µm (Table 2). The close coincidence between the substantial increase in the intensity of phreatomagmatic activity during the Ferdinandea eruption between 6 and 11 August 1831 and the first observation of a blue$^{(+)}$ sun in the connected sequence on 8 August 1831 (Sect. 4.1) suggests that a similarly rapid stratospheric aerosol formation occurred in that case too. Given that, for example, the stratospheric aerosol produced by the 1991 Pinatubo eruption took several months to grow to a typical size between 0.3 and 0.5 µm (Self et al., 1993), it would be interesting to consider the nature of the atypical microphysical processes that could be involved in these two rare cases.

Further, the durations of reported twilight glow observations in 1883 were used to constrain the altitude of the aerosol responsible (Symons et al., 1888; Meinel and Meinel, 1991). In the context of testing hypothesis H2, an analysis of the duration of the reported twilight glow observations mentioned in Sect. 4.2 as well as an analysis of a supplementary collected body of contemporary observations of twilight glows (and other unusual twilight phenomena) should provide independent evidence as to the altitude reached by the aerosol responsible in 1831.

Thus, the examples of 1831 and 1883 again underline that eye-witness accounts of historical geophysical events should not be neglected as a source of valuable scientific data (Guidoboni, 2010; Pyle and Barclay, 2020). The further before the nineteenth century an event took place, the more difficult it is likely to be to be able to collect primary sources reporting any associated observations of a blue, purple or green sun, or of other unusual atmospheric optical phenomena such as twilight glows. Nevertheless, where an adequate collection of primary sources can be collated, it can likewise be expected to be helpful in terms of, for example, reconstructing the circulatory state of the stratosphere (Hamilton and Sakazaki, 2018) or constraining the latitude, longitude and date of the source event which produced the aerosol responsible and the altitude at which it was present (Symons et al., 1888).

Appendix A

Table A1. Observations of a blue, green or purple sun in August 1831.

Source no.	Lat. (° N)	Long. (° E)	Time zone (UTC)	Brief description of source	Solar elevation (°)	Elapsed time (h)
A1	36.7 (est.)	1.8 (est.)	+1	Whilst sailing off the coast of Algeria from Oran to Algiers the French military engineer Antoine Rozet observed a "clear blue" naked-eye sun (with a sunspot) through a "very remarkable" fog between 07:00 and 07:15 LT on 3 August (Rozet, 1833). He also reported that this fog had appeared at intervals all along the North African coast between 15 July and 15 August and that, at Oran, he had seen a naked-eye sun through the fog on several occasions for several minutes at a time (Rozet, 1833). Note that the *Dordogne* left Oran on 1 August and arrived at Algiers on 4 August (Rozet, 1832).	25.6 (07:15 LT)	
A2	42.9	−74.6	−5	A meteorological register taken at Canajoharie (New York State, USA) relates the observation of a "pale violet" naked-eye sun at 17:00 LT on 4 August (Hough, 1855).	23.3	
A3	40.0 (est.)	−76.3 (est.)	−5	A traveller on the Susquehanna River (Pennsylvania, USA) related the observation of a "violet" naked-eye sun through a thin cloud "overspreading the sky" at 17:00 LT on 4 August to the editors of the *Lancaster Miscellany* (Hazard's Register, 1831).	24.5	
A4	40.4	−80.0	−5	A report from Pittsburgh (Pennsylvania, USA), reproduced in the *New York Evening Post* (1831a), relates the observation of sunlight whose colour "resembled that of the lilach (sic) flowers" on 4 August. The article also relates the observation of unusual twilight phenomena from the first week of August (New York Evening Post, 1831a).		
A5	38.1	13.4	+1	Niccolò Cacciatore, the Italian astronomer and director of the Palermo Observatory (Sicily, Italy), observed a "pale whitish-blue" sun through a "dense" fog at 18:00 LT on 8 August (Cacciatore, 1831b). The full text of this report is reproduced in Table 1. He also reported the observation of dense fogs between 23 and 26 July and 5 and 8 August as well as twilight glows on 4, 6, 8, 12 and 19 August and between 25 and 29 August, 17 and 18 September, and 4 and 5 October (Cacciatore, 1831a, b, c, d).		0
A6	42.2	2.5	+1	The Catalan naturalist Francesc Bolòs recorded 5 or 6 d of observations of unusually coloured and dimmed suns at Olot (Garrotxa, Catalonia, Spain): on 9 and 10 August, the sun appeared "white", "silvery", "shimmering" and "moon-like" from its rise until 08:00 LT, when it began to produce weak sunlight with a "purplish" colour, remaining in this state for the remainder of the day; the appearance of the sun on 11 and 12 August was much the same, although it appeared to be briefly "red" before it became "white" and began to shine earlier at 07:00 LT and a little less weakly than the previous 2 d; on 13 August, the sun rose with a "blue" colour (and a sunspot) beginning to shine with a "blueish" colour at 07:00 LT and remaining like this until 17:00 LT when it dimmed again such that at 18:30 LT it looked "white" and "moon-like"; the sun was brighter on 14 August and was restored to its normal appearance on 15 August (Bolòs, 1831). Bolòs (1831) also reported the observation of a twilight glow between 9 and 10 August 1831.		14 (08:00 LT) 119 (17:00 LT)

"est." denotes estimated.

Table A1. Continued.

Source no.	Lat. (° N)	Long. (° E)	Time zone (UTC)	Brief description of source	Solar elevation (°)	Elapsed time (h)
A7	46.5	30.7	+2	A report from Odessa (Ukraine), reproduced in the German newspaper *Augsburger Ordinari Postzeitung* (1831), relates the observation of an "almost violet" naked-eye sun (with a sunspot) through an "almost invisible" fog through the whole afternoon on 9 August. The article also relates the observation of unusual twilight phenomena in the first week of August (Augsburger Ordinari Postzeitung, 1831).		
A8	44.4	8.9	+1	A report in the Italian newspaper *Gazzetta di Genova* (1831) relates that the sun appeared at Genoa (Liguria, Italy) through a "thin layer of vapour" as a naked-eye "crystal globe" (with a sunspot) at 17:00 LT on 9 August, before turning "pale red" and then "violet" in colour.	27.1	
A9	40.6 (est.)	−5.0 (est.)	+1	A meteorological report from Ávila Province (Castile and Léon, Spain) in the Spanish newspaper *El Correo* (1831) relates that at about 17:00 LT on 9 August, the sun was observed to become as "pale and white as the moon" and that on 10 August, the sun continued to be pale but with a "bluish" and subsequently "whitish" colour. Note that a report from Madrid (Castile and Léon, Spain) dated 18 August, reproduced in the German newspaper *Allgemeine Zeitung München* (1831a), also relates that an unusual appearance of the sun had recently been observed for several days, with a colour varying between "blue", "red" and "white".	37.7	
A10	43.8	−0.6	+1	A letter from the French naturalist Léon Dufour was read out on 22 August at the meeting of the Académie des Sciences relating the observation of a "white moon-like" naked-eye sun at Saint-Sever (Nouvelle-Aquitaine, France) at 17:00 LT which turned "pale blue" at 18:00 LT (Dufour, 1831). The full text of this report is reproduced in Table 1.	33.7 (17:00 LT) 22.9 (18:00 LT)	
A11	44.8(B) 42.7(P)	0.6(B) 2.9(P)	+1	The French scientist François Arago informed the 22 August meeting of the Académie des Sciences that, on the basis of letters he had received from Bordeaux (B) and Perpignan (P), the same phenomenon observed at Saint-Sever (source [A10]) was observed throughout southern France (Arago, 1831).		
A12	49.5	0.1	+1	The French scientist François Arago informed the 29 August meeting of the Académie des Sciences that the same phenomenon observed at Saint-Sever (source [A10]) had also been seen at Le Havre (Seine-Maritime, France) by M. Mathieu on 10 August (Mathieu, 1831). Note that, at the same meeting of the Académie des Sciences, the French naturalist François Désiré Roulin related that it had also been seen to the east as far as Bologna (Emilia-Romagna, Italy), where it lasted for several days (Roulin, 1831).		

"est." denotes estimated.

Table A1. Continued.

Source no.	Lat. (° N)	Long. (° E)	Time zone (UTC)	Brief description of source	Solar elevation (°)	Elapsed time (h)
A13	41.9	12.5	+1	The future Roman Catholic archbishop Vicenzo Tizzani recorded several days of observations of unusually coloured and dimmed suns at Rome (Lazio, Italy) between 9 and 16 August: a thick fog covering the sky about 17:20 LT ("ore 22" – a locally defined time of 22 h after sunset the previous day) on the 9 August caused a "veiled moon-like" naked-eye sun to be seen; the appearance of the sun was the same on 10 August; on 12 August, from about 17:16 LT ("ore 22") onwards, a naked-eye sun was variously seen through a dense fog to be "turquoise", "ashy","yellowish" and "rosy" in colour; and a "rosy" naked-eye sun was seen at sunset on 16 August (Tizzani and Croce, 2015). He also reported the observation of a twilight glow on 3, 9, 10 and 12 August (Tizzani and Croce, 2015). Note that a system of time-keeping in widespread use in (especially southern) Italy at the time reckoned the 24 h period to start at sunset, requiring the resetting of clocks and watches according to almanacs of changing sunset times (Laurent, 1821). Sunset on 9 August took place at 19:20 LT and on 12 August at 19:16 LT (National Oceanic and Atmospheric Administration (NOAA) Solar Calculator: https://gml.noaa.gov/grad/solcalc/, last access: 30 May 2021).	20.8 (17:20 LT) 20.9 (17:16 LT)	
A14	37.2	−3.6	+1	A letter from Sr. Estrella (1831) to the Spanish newspaper *El Correo* relates the observation, at Granada (Andalucia, Spain), of a "blue" sun through a "thin cloud along the horizon" by the "tarce" (sic) on 12 August. He also relates the observation of twilight glows there on 10, 11, 12 and 13 August (Estrella 1831).		
A15	32.3	−64.8	−4	Sir David Brewster read a letter from Augustus Harvey, a doctor in Bermuda, before the 10th meeting of the British Association for the Advancement of Science, relating his memory of observation of "blue" or "bluish" sunlight there on 11 and 12 August (Harvey, 1839).		
A16	32.3	−64.5	−4	Sir David Brewster read a letter from lieutenant colonel William Reid, governor of Bermuda, before the 10th meeting of the British Association for the Advancement of Science, relating that the present collector of customs in Bermuda had been on board a boat 15 miles (approx. 24 km) east of the island on 11 August and had noticed that the sun was of a "light green" or "bluish green" colour (Reid, 1839).		
A17	32.7	−80.0	−5	An article in the *Charleston Courier* (South Carolina, USA), reproduced in the *Savannah Republican* (1831, p.2), relates the observation of 5 d of unusually coloured and dimmed suns: on 11 August, the sun was "pale" and "feeble" throughout the day; on 12 August, the sun was the same but with the addition of a "slight bluish tinge"; on 13 August, the sun was the same, if less pronounced; on 14 August, the sunlight at noon was a "very sensible blue" colour and as dim as during the recent eclipse (12 February), whereas the sun was a "pale green-blue" and could be observed with the naked eye at a few minutes before 18:00 LT; and on the evening of 15 August, the sun had still not recovered "his usual splendour". The article also relates the observation of a twilight glow on 12 August 1831 (Savannah Republican, 1831).		96 ± 5 (12 Aug)

Table A1. Continued.

Source no.	Lat. (° N)	Long. (° E)	Time zone (UTC)	Brief description of source	Solar elevation (°)	Elapsed time (h)
A18	38.8	−77.0	−5	A meteorological register taken at the Alexandria Museum (Alexandria, Virginia, USA), reproduced in the *Alexandria Gazette* (1831a) which relates the observation of 5 d of unusually coloured and dimmed suns: on 11 August, the sun had a pale and “silver-like” appearance; between 12 August and 14 August, the sun was alternately “white”, “brassy”, “green” and “blue” (with a naked-eye sunspot); and it began resuming its normal appearance on 15 August. The notes also relate the observation of a twilight glow as the sun set “each day” at the same time that resembled the “light of a great fire” (Alexandria Gazette 1831a).		96 ± 5 (12 Aug)
A19	18.7	−64.3	−4	Whilst surveying around the island of Anegada (British Virgin Islands), the British explorer Sir Robert Schomburgk observed the overcast sky to be a “threatening” dark bluish colour on 12 August (Schomburgk, 1848).		
A20	30.0	−90.1	−6	A report from New Orleans (Louisiana, USA) in the local French language newspaper *L’Abeille* (1831, p.1) relates that, between 12 or 13 and 15 August, the sun was observed to set in a “suspended sea” which dimmed its light and made it a “blue”, “indigo-blue” or “greenish” colour.		
A21	38.3	−77.5	−5	An article in the *Fredericksburg Arena* (Virginia, USA), reproduced in the *Alexandria Gazette* (1831b), relates the observation of a pale blue sun (with a naked-eye sunspot) on the evening of 13 and the morning of 14 August.		
A22	36.9	−76.3	−5	A report from Norfolk (Virginia, USA), reproduced in the *Washington National Intelligencer* (1831), relates the observation of a variously “lively green”, “cerulean”, “silver white” and “pale yellow” sun (with a naked-eye sunspot) on 13 and 14 August. At 17:00 LT on 13 August, it appeared like a “a globe of silver through the thick haze which overspread the Heavens, shorn of its beams”. The full text of this report is reproduced in Table 1. The report also relates a twilight glow on 13 August (Washington National Intelligencer 1831).	22.7	
A23	38.8	−77.0	−5	A letter from the American amateur scientist Benjamin Hallowell (1831) to the *Washington National Intelligencer* relates that, at about midday on 13 August in Alexandria (Virginia, USA), he observed that the sun shining through a “body of vapor suspended in the heavens” had a “silvery” appearance, changing between 15:00 LT and 16:00 LT to a “greenish-blue” and that it descended “below the body of vapor” about 15–20 min before sunset; he noted the presence of a naked-eye sunspot. He also reported a twilight glow on 12 August (Hallowell, 1831). Note that Breen (2005) reproduces a similar account from a letter written by Emma Mordecai who relates the observation of a blue sun at about 16:00 LT on 13 August nearby in Richmond (Virginia, USA).	34.9 (16:00 LT)	

Table A1. Continued.

Source no.	Lat. (° N)	Long. (° E)	Time zone (UTC)	Brief description of source	Solar elevation (°)	Elapsed time (h)
A24	32.1	−81.1	−5	A report in the *Savannah Georgian* (Georgia, USA), reproduced in the *Georgia Messenger* (1831), relates that on 13 August a "blue" naked-eye sun was seen from 17:00 LT until sunset and that, although less dim, a "blue" sun (with a sunspot) continued to be seen on 14 August.	26.5	
A25	30.7	−88.0	−6	A report reproduced from the *Mobile Register* (Alabama, USA) (1831) relates that a variously "pale blue", "violet" or "sea-green" naked-eye sun (with a sunspot) was seen from 17:00 LT until 18:00 LT on 13 August, a "bluish" sun was seen on the morning of 14 August and a "pale green" sun was seen at 06:00 LT on the morning of 15 August (Mobile Register, 1831).	19.5 (17:00 LT)	126 (18:00 LT)
A26	40.7	−74.0	−5	A report published in the *New York Evening Post* (New York State, USA) on 16 August relates the observation of a sun for "several days past" (i.e. likely between 13 and 15 August) which on rising was "dull white, slightly tinged with green" and which, between 30 and 45 min later, was brighter but with sunlight of a "faint silvery hue, somewhat greenish, not unlike the color of the silk of green corn" (New York Evening Post, 1831b, p. 2). The report also relates the observation of a twilight glow (New York Evening Post, 1831b).		
A27	45.0 (est.)	−50.0 (est.)	−3 or −4	Whilst sailing across the north Atlantic from New York to Liverpool, the American clergyman Calvin Colton observed 2 or 3 d of an unusually coloured and dimmed sun: on 14 August, a "dark purple" naked-eye sun (with a sunspot) was seen at around 17:00 LT (although a member of the ship's crew indicated that the phenomenon had begun around 15:00 LT with the "unusual symptoms" gradually increasing); on 15 August, the appearance of the sun was the same, although even darker in the afternoon; and it was "not till the third or fourth day that the heavens began to wear their natural appearances" (Colton, 1835). Note that the *Silas Richards* left New York on 9 August and arrived at Liverpool on 28 August; Colton believed that the ship was "on the Banks of Newfoundland, or in the neighbourhood" when the observations took place (Colton, 1835).	25.1 (17:00 LT)	
A28	35.7	−80.5	−5	A report in the *Western Carolinian* (Salisbury, North Carolina, USA) relates the observation of a "blue" naked-eye sun (with a sunspot) on 14 August; the report further relates that "some of the old inhabitants of this place say that it presented the same appearance in 1816 or 1817" (Western Carolinian, 1831).		
A29	36.0	−90.0	−6	A handwritten note inscribed in a family Bible by Margaret Hess relates that she observed the sun to have a "clear blue culler (sic)" in Trenton (Tennessee, USA) on the afternoon of 14 and the morning of 15 August (Hess, 1831).		
A30	40.7	−74.0	−5	A report in the *New York Commercial Advertiser* (New York State, USA), reproduced in the *London Morning Post* (1831), relates that a naked-eye sun which was "green, as the sea water or Brazilian emerald" was observed between 17:00 LT and 19:30 LT on 17 August.	20.1 (17:00 LT)	223.5 (19:30 LT)
A31	23.1	113.3	+8	A report in the English language *Canton Register* newspaper (Guangzhou, China) relates the observation of two parhelia "here" on 4 September as well as the observation, "about a week previously" and "for several days" (i.e. likely between 27 and 29 August), of a pale green sun on both rising and setting (Canton Register, 1831).		

"est." denotes estimated.

Appendix B

Table B1. Null Observations.

Source no.	Lat. (° N)	Long. (° E)	Brief description of source
B1	22.0 (est.)	88.0 (est.)	The *Repulse*, an Honourable East India Company vessel, was at anchor at the entrance to the Hooghly River (now Bhāgirathi-Hooghly River), West Bengal, India, from 5 June until 8 August 1831, before sailing to Penang, Malaysia, and reaching Singapore by 28 August (Bayliffe and Rawes, 2016). Whilst recording daily weather conditions, no observations of unusual atmospheric optical phenomena (UAOP) were reported in the logbook in July or August.
B2	13.1	80.3	Astronomical observations were recorded at the Honourable East India Company Observatory at Madras (now Chennai), India, in 1831 (Taylor, 1832). No episodes of unusual stellar dimming were reported. No equivalent meteorological observation book can be found.
B3	34.0 (est.)	75.0 (est.)	The French naturalist Victor Jacquemont was travelling in "Cashmere" (now Jammu and Kashmir, India) between 8 May and 19 September 1831 (Jacquemont, 1834). He reported no UAOP in July nor August.
B4	31.5	74.3	The British explorer Sir Alexander Burnes was resident in Lahore, Pakistan, between 18 June and 16 August before travelling onward to reach Simla (now Shimla), India, in September 1831 (Burnes, 1834). He reported no UAOP in July nor August.
B5	25.0 (est.)	45.0 (est.)	A record of historical events (*Enwan Al-Majed fi Tarekh Najd*) in Najd Province, Saudi Arabia, reports unusual twilight phenomena during the first and second week of August 1831 and a twilight glow in the evening of 23 August (Basurah, 2010). Two less precisely dated observations of a twilight glow are also related, one lasting 3 d (between 1831 and 1832) and another which lasted some months (between 1832 and 1833) (Basurah, 2010).
B6	33.3	44.4	An English Protestant missionary, Anthony Groves, kept a day-to-day journal of his residency in Baghdad, Iraq, in 1830 and 1831 (Groves, 1832). He reported no UAOP in July nor August.
B7	42.3	41.7	The Swiss naturalist and antiquarian Frédéric Du Bois de Montpéreux, travelled in the Caucasus between 1831 and 1834. Despite, for example, recording weather observations in Redoute-Kalé (now Kulevi, Georgia) on 2, 3 and 4 August 1831, he reported no UAOP in July nor August (Du Bois de Montpéreux, 1839).
B8	33.5	36.3	The head of the Lazaristes mission in Damascus (Syria), M. Poussou, reported in a letter to M. Etienne, procureur général of the Lazaristes congregation, dated 12 September 1831, that for "about the last two months" (i.e. likely since about mid-July) the atmosphere there had been "laden [with vapours]" and the sun had been pale, including appearing as if seen through "crêpe" [fabric] for at least fifteen minutes after sunrise' (Poussou, 1831). He also reported the observation of a twilight glow "during this period", both before sunrise and after sunset, although he does not say whether continuously or occasionally and, if the latter, on which dates (Poussou, 1831).
B9	41.0	29.0	Gustavus Richard Brown Horner, surgeon aboard the American vessel, the *John Adams*, arrived at Constantinople (now Istanbul, Turkey) on 10 August 1831 (Horner, 1831). The *John Adams* had arrived off the Dardanelles (now Çanakkale Boğazı, in Turkey) on 4 August (see source [B10]). He kept a day-to-day record of the weather. With the exception of an "atmosphere loaded with vapours impenetrable to the sun" on 22 August, he mentioned no UAOP in July nor August (Horner, 1831).

"est." denotes estimated.

Table B2. Continued.

Source no.	Lat. (° N)	Long. (° E)	Brief description of source
B10	40.3	26.4	The American naval officer David Porter arrived off the Dardanelles (now Çanakkale Boğazı, in Turkey) on 4 August 1831 aboard the American vessel the *John Adams* and reached Constantinople (now Istanbul, Turkey) by 10 August (Porter, 1835). The purpose of his visit to Constantinople was to ratify the first treaty agreed between the USA and the Ottoman Empire. He reported no UAOP in July nor August, although he did describe a remarkable hail storm which took place in Istanbul on the same day as the ratification ceremony.
B11	37.5	23.4	The American zoologist, James DeKay, sailed through the Mediterranean to Turkey in 1831. He gave a close description of an early phase of the eruption of Ferdinandea, off the coast of Sicily, Italy, as he passed it on the morning of the 16 July (DeKay, 1833). The vessel reached the island of Crete, Greece, around 27 July, and then made its way via Milos, Hydra (around 30 July), Poros (a few days before 13 August), Tinos, Andros, Chios, Lemnos, Tenedos and the Dardanelles (now Çanakkale Boğazı, in Turkey) to reach Constantinople (now Istanbul, Turkey) later in August (DeKay, 1833). He reported no UAOP in July nor August, although he did describe a remarkable hail storm which took place in Istanbul (see source [B10]).
B12	35.9	14.4	The British doctor (and assistant inspector of army hospitals) John Davy reported the observation in Malta of a twilight glow for many evenings successively in August 1831 (Davy, 1832).
B13	43.8	11.3	An article in the Italian newspaper, the *Gazzetta di Firenze* (Florence, Tuscany, Italy) (1831) reports the observation of a dense haze and a twilight glow in the evenings for several days prior to 13 August.
B14	46.2	6.1	Referring to the observations of a blue sun made by Léon Dufour in France on 10 August 1831 (source [A10]), an article in the Swiss newspaper, the *Journal de Genève* (Geneva, Switzerland) (1831) reports the observation of a twilight glow there in the evenings of 10 and 30 August.
B15	47.5	19.0	An article in the German newspaper *Allgemeine Zeitung München* (1831b, p. 936) relates that the air in Budapest, Hungary, was filled with a thin fog on 11 August 1831 which dimmed the distant mountains and “almost made it difficult for anyone to breathe”.
B16	51.8	12.3	The German astronomer Samuel Heinrich Schwabe, whose dedicated solar observations between 1826 and 1843 led to his discovery of the 11-year sunspot cycle, lived in Dessau, Germany. Whilst reporting all of the most notable astronomical and meteorological phenomena he observed in 1831, he mentioned a twilight glow that had occurred on 25, 26 and 27 September (Schwabe, 1831).
B17	50.8 (G) 51.5 (C) 50.1 (P) 53.0 (B)	1.1 (G) 0.3 (C) 5.5 (P) 0.0 (B)	Meteorological observations across the UK for August 1831 were reported by “Dr. BURNEY” in Gosport (G), “Mr. THOMPSON” in Chiswick, London (C), “Mr. GIDDY” in Penzance (P) and “Mr. VEALL” in Boston (B), all in England, UK (Philosophical Magazine 1831). No UAOP were reported in the accompanying day-to-day comments.

Data availability. All of the data necessary to repeat our analyses are found in the tables in this paper.

Author contributions. CG carried out the analysis presented in this study and drafted the paper. CK and SE provided guidance and expertise on the volcanological and geological contexts and critically reviewed the paper. DS provided guidance and expertise on the meteorological context (including proposing the pertinence of the convective instability mechanism) and critically reviewed the paper.

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