Clim. Past Discuss., 10, 1901–1932, 2014
www.clim-past-discuss.net/10/1901/2014/
doi:10.5194/cpd-10-1901-2014

Climate of the Past
Discussions
Open Access

This discussion paper is/has been under review for the journal Climate of the Past (CP). Please refer to the corresponding final paper in CP if available.

Observations of a stratospheric aerosol veil from a tropical volcanic eruption in December 1808: is this the "Unknown" ~ 1809 eruption?

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Received: 11 April 2014 – Accepted: 22 April 2014 – Published: 28 April 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The "Unknown" eruption of 1808/1809 was the second most explosive SO_2-rich volcanic eruption in the last two centuries, only eclipsed by the cataclysmic VEI 7 Tambora eruption in April 1815. However, no eyewitness accounts of the event, and therefore its location, or the atmospheric optical effects associated with its aerosols have been documented from historical records. Here we report on two meteorological observations dating from the end of 1808 that describe phenomena we attribute to volcanic-induced atmospheric effects caused by the Unknown eruption. The observations were made by two highly respected Latin American scientists. The first, Francisco José de Caldas, describes a stratospheric aerosol haze, a "transparent cloud that obstructs the sun's brilliance", that was visible over the city of Bogotá, Colombia, from 11 December 1808 to at least mid-February 1809. The second, made by physician José Hipólito Unanue in Lima, Peru, describes sunset after-glows (akin to well-documented examples known to be caused by stratospheric volcanic aerosols) from mid-December 1808 to February 1809. These two accounts provide direct evidence of a persistent stratospheric aerosol veil that spanned at least 2600 km into both Northern and Southern Hemispheres and establish that the source was a tropical volcano. Moreover, these observations confirm that the Unknown eruption, previously identified and tentatively assigned to February 1809 (±4 months) from analysis of ice core sulphate records, occurred in late November or early December 1808 (4 December 1808 ± 7 days). This date has important implications for the associated hemispheric climate impacts and temporal pattern of aerosol dispersal.

1 Introduction

The 1810s were the coldest decade and longest sustained period of below average hemispheric and tropical temperatures in the last 500 years (e.g. Jones et al., 1995; Briffa et al., 1998; D'Arrigo et al., 2009). This decade is also notable for a clustering of climate forcing events that includes a period of low solar activity (the "Dalton minimum"; Eddy, 1976) and the Tambora eruption, Indonesia (climactic phase, 10–11 April 1815), one of the largest magnitude volcanic eruptions of the last millennium (VEI 7; Oppenheimer, 2003). Large explosive volcanic eruptions inject massive amounts of sulphur dioxide directly into the stratosphere where it is rapidly oxidised and concentrated within a stratospheric sulphate aerosol layer (reviewed by Robock, 2000). Cooling of the troposphere and the Earth's surface occurs because the sulphate aerosols reduce surface solar insolation receipt by increasing atmospheric albedo and absorbing shortwave radiation (Robock, 2000). Thus the Tambora eruption has been linked directly to the "year without a summer" (1816), in which crops failed, and there were frosts and famine in Europe and North America (Stothers, 1984).

Global temperatures were cooling prior to the Tambora eruption, however, as illustrated by a 0.53 °C decrease in tropical sea surface temperatures between 1809 and 1810 (D'Arrigo et al., 2009). This temperature perturbation has also been attributed to a large tropical eruption that has been identified from volcanically derived sulphuric acid peaks in Greenland and Antarctica ice cores (Legrand and Delmas, 1987; Dai et al., 1991; Moore, 1991; Cole-Dai et al., 2009). As the source of this eruption has yet to be located, it has been termed either the "AD 1809 eruption" (Dai et al., 1991) or the "Unknown eruption" (Mosley-Thompson et al., 2003). The magnitude of this eruption has been inferred to be at least VEI 6, with an estimated stratospheric sulphuric acid H_2SO_4 loading of 34–68 × 10^{12} g (Zielinkski, 1995) and stratospheric aerosol optical depth of between 0.189 (Crowley and Unterman, 2013) and 0.27–0.28 (Crowley et al., 2008; Arfeuille et al., 2014). This makes the c. 1809 Unknown eruption one of the most SO_2-rich stratospheric tropical eruptions in the last 500 years: it contributed half the sulphate of the Tambora eruption (Dai et al., 1991), two or three times that of the Krakatau eruption (VEI 6, 1883; Dai et al., 1991), and more than three times those of the eruptions of El Chichón (VEI 5, 1982) and Mt Pinatubo (VEI 6, 1991; Bluth et al., 1992), the two strongest events of the second half of the 20th century (Zielinski, 1995). It is remarkable that a recent volcanic eruption of such intensity is absent from

observation-based reconstructions of volcanic climate forcing (e.g. Lamb, 1970), but no eyewitness reports or contemporary observational documentation of the event have been found. For this reason, both the location and the timing of the eruption have been the source of much debate.

The debate about the eruption location has focused primarily on interpretations of a volcanic sulphate signal found in ice cores from both poles (Dai et al., 1991). This bi-polar signal, when combined with analysis of contemporary tephras (Kurbatov et al., 2006; Yalcin et al., 2006), led to the hypothesis that the Unknown eruption actually represented two separate high-latitude events (one volcano in each hemisphere). Further analysis of the ice core record, however, shows a sulphur isotopic anomaly in the ice core record that indicates a stratospheric source, which suggests a single low-latitude eruption (Cole-Dai et al., 2009). The timing of the eruption has also been a source of debate. The earliest date is between March and June 1808. This date was proposed to explain both an abrupt negative anomaly in noon temperatures of two Malaysian records and evidence that the most extreme cooling anomaly in annually averaged tropical marine air temperatures (20° N–20° S) occurred in 1809 (Chenoweth, 2001). The latest suggested date is February 1809 (±4 months), a time bracket that was determined using high-resolution dated ice core records from Antarctica and Greenland and the arrival in 1810 of excess sulphate in both Greenland and Antarctica ice cores, 72–77 months prior to the peak associated with the Tambora eruption in April 1815 (Cole-Dai et al., 2009).

Both the location and timing of an eruption will affect the eruption impacts. Distinguishing between an extratropical and tropical source is critical because the latitude determines the geographic distribution of both climatic and atmospheric effects. If a strong eruption (VEI 5 or greater) is located in the tropics, the stratospheric aerosol layer rapidly spreads zonally ($> 20\,m\,s^{-1}$; Bluth et al., 1992) within the "tropical pipe" region around the Equator (Plumb, 1996). Aerosol transport toward the poles follows with preference towards the winter hemisphere (Trepte et al., 1993), as a strengthened meridional temperature gradient leads to increased planetary wave propagation into the stratosphere (Holton et al., 1995). Sulphate aerosols from tropical volcanic eruptions have been observed to form a stratospheric layer across the entire globe (e.g. following Mt Pinatubo, 1991) with an *e*-folding residence time of 1 year (Robock, 2000). In contrast, it is rare for stratospheric aerosols to reach the tropics following similarly strong high-latitude volcanic eruptions (Graf, 1992; Oman et al., 2005), due to rapid removal through both strong subsidence in the polar vortex and mid-latitude tropospheric folding (Hamill et al., 1997). Hence, the climatic effects of high-latitude stratospheric eruptions are restricted primarily to the extratropics, and to the hemisphere in which the eruption occurred (e.g. Oman et al., 2005; Schneider et al., 2009). The timing is critical because seasonality controls the hemispheric distribution of radiative impacts, dynamic responses and therefore climatic perturbations (Robock, 2000). Associated temperature anomalies are predominantly determined by the amount of shortwave radiation that arrives at the Earth's surface and, therefore, impacts are greatest for the tropics and the summer hemisphere (Robock, 2000).

Large eruptions produce global impacts that extend beyond cooling; atmospheric effects are commonly observed, such as a haze that filters and refracts light (e.g. Symons, 1888; Stothers and Rampino, 1983; Stothers, 1999) and vivid sunset "glows" (Symons, 1888; Lamb, 1970; Deirmendjian, 1973). The haze is caused by concentrated layers of volcanic aerosols, within the troposphere or stratosphere depending on the altitude where the sulphate aerosols are injected, and can become widely dispersed (Stothers, 1999). The best-known example of a tropospheric "dry fog" is the one that Europe experienced after the Laki Eruption (Iceland, 1783), which affected large parts of the continent, damaged crops and caused widespread health problems (Stothers, 1996). Historical documents also detail the visual effects of stratospheric volcanic haze. For example, global dispersal and optical impact of an upper atmosphere aerosol layer following the Krakatau eruption (Indonesia, 1883) was documented thoroughly in the report on the event edited by Symons (1888). The atmospheric effects from the Krakatau 27 August eruption were observed in the Atlantic Ocean within a week, for example: "On September 1st, the *Queen of Cambria* in 9° S., 28° W., at 8 a.m., notices 'a peculiar

thin haze in the air through which the sun is seen with a clearly defined circumference, and almost white in colour; at 8 p.m., stars dimly visible through haze'." (Archibald in Symons, 1888, p. 220). Various ships reported the phenomena as it spread to circumnavigate the Equator over a 2 week period: "On September 6th, Eastern time, the same ship [the *Papa*], in 8°1′ N., 161°4′ W., remarks: 'the entire sky is covered by an even yellowish-red, high layer of cirro-stratus. The sun pierces through, but looks pale, as when seen through a blue glass, with sharply marked edge, nice for observations, well tolerable to the eye, without nimbus or halo. At night the stars were dimly visible'. Thenceforward we have with little intermission, accounts worded in very similar language, of the sky being 'covered with a light haze'; 'the sun, when green, stands out from a smoky sky', ... Together with the accompanying phenomena of the blue and green suns, it appeared after the first revolution of these round the globe, at higher latitudes than on its first journey." (Archibald in Symons, 1888, p. 221).

Perhaps the most common atmospheric disturbances described following large explosive eruptions are vivid sunsets, and in particular a prolonged twilight after-glow due to the enhanced forward scattering caused by the volcanic aerosols in the stratosphere (Symons, 1888; Deirmendjian, 1973). This phenomenon has been observed worldwide after recent major volcanic eruptions and reported in contemporary documents following historic events such as Awu (Indonesia, 1641), Katla (Iceland, 1660), Laki (Iceland, 1783), Tambora (Indonesia, 1815), Krakatau (Indonesia, 1883) (e.g. Symons, 1888; Lamb, 1970). The colours of these sunsets are so distinctive that contemporary paintings have been used to estimate aerosol optical depths after major volcanic eruptions (e.g. Zerefos et al., 2007).

Here we present evidence of atmospheric disturbances that are drawn from the work of two of the most prominent Latin American scientists of the early 19th century, and published within a few years of the ∼ 1809 Unknown eruption. We argue that these records of unusual meteorological events in Colombia and Peru can be used to constrain both the location and timing of the Unknown eruption. Importantly, the authors describe, in scientific terms, phenomena such as a stratospheric aerosol veil and sunset after-glows occurring from 11 December 1808 until February 1809. Together, the accounts suggest that these phenomena were produced by a single low-latitude stratospheric volcanic eruption that occurred in late November or early December 1808.

2 Materials, methods and description of sources

The first observation (reproduced in full in Appendix A) appeared in February 1809 in the *Semanario del Nuevo Reyno de Granada*, a periodical edited by Francisco José de Caldas, Director of the Astronomical Observatory of Santa Fe de Bogotá (Colombia). Published weekly from 1808 to 1810, the *Semanario's* principal purpose was the diffusion of practical and scientific knowledge relating to the geography, demography, natural history, and climate of what was one of Spain's principal colonial territories in the Americas. The second appeared as a footnote in the second edition of Peruvian physician José Hipólito Unanue's *Observaciones sobre el clima de Lima y sus influencias en los seres organizados, en especial el hombre*, published in Madrid in 1815. Bogotá and Lima, both capitals of Spanish viceroyalties, were important centres of intellectual activity and rigorous scientific research in the late eighteenth and early nineteenth centuries, and as Glick (1991) and others have shown, Caldas and Unanue were leading figures in their respective circles and disciplines (Appel, 1994; Nieto et al., 2005; Nieto Olarte, 2007; Zimmerer, 2006; Cushman, 2011). They shared a profound interest in the varied climates of the territories of their birth, in Unanue's case particularly due to his concern for understanding the impact of climate phenomena on human health (Cushman, 2011). As American-born Spaniards, they also became deeply engaged in long-standing debates, which gained renewed impetus under the influence of the European Enlightenment, regarding the alleged inferiority of the New World climate and its supposedly deleterious effects on its people, fauna, and flora. This engagement with the science of the day required extensive investigations, for which they drew not only on their own work – as director of the Bogotá Observatory, for instance, Caldas established a regular programme of astronomical and meteorological observations (Caldas,

1912) – but also on that of a wide network of correspondents in towns and cities across modern-day Colombia and Peru. Their significance as scientists (and, in Caldas' case, as collaborator) were acknowledged by Alexander von Humboldt, whose own writings, many based on the results of his travels in Latin America between 1799 and 1804, are widely recognised as contributing to the development of modern geography, ecology, and environmental sciences (Glick, 1991; Zimmerer, 2006; Cushman, 2011).

3 Results

The report published by Caldas in February 1809 describes an anomalous thin upper atmospheric cloud in Bogotá (Colombia) that had been uniform and persistent since 11 December 1808, and affected the visibility of the sky, the stars and the sun: "As of 11 December of last year, the disk of the sun has appeared devoid of irradiance, its light lacking that strength which makes it impossible to observe it easily and without pain. Its natural fiery colour has changed to that of silver, so much so that many have mistaken it for the moon. This phenomenon is very noticeable at sunrise, and particularly when the sun sets. When [the sun] is at its zenith, it shines more brightly and cannot be looked at with the naked eye. Near the horizon, it has been seen to take on a light rosy hue, [or] a very pale green, or a blue-grey close to that of steel. [. . .] The whole vault of the sky has been covered by a light cloud as widespread as it is transparent. [. . .] [Also] missing have been the emphatic coronas which are so frequently seen around the sun and the moon when those clouds that meteorologists know by the name of Veil are present. The stars of the first, second and even the third magnitude have appeared somewhat dimmed, and those of the fourth and fifth have completely disappeared, to the observer's naked eye. This veil has been constant both by the day and by night . . . ".

This account resembles descriptions of volcanic-induced stratospheric haze, particularly in the shared emphasis on the effect of the aerosol cloud on the visibility of the sun, which changes its colour to silver, green or grey (reviewed in Symons, 1888). Caldas also records the anomalous colour of the sky, which we take to be particularly significant because of his familiarity with the use of the cyanometer (invented by Horace-Bénédict de Saussure; Lilienfeld, 2004), and the related discovery that the blueness of the sky is more intense at higher altitudes. Indeed, in a report on the instruments held by the Astronomical Observatory, published in the *Semanario* in February 1808, Caldas specifically made reference to the clarity and intense blueness of the sky over Bogotá. From the Observatory, he said, the “stars could be seen to shine with such clarity upon a sky so blue” as to be the envy of European astronomers (*Obras de Caldas*, 274–275). Therefore his observation that in Bogotá in late 1808 and early 1809 the sky had become so pale that it “corresponded to the lowest degrees of the cyanometer, and on some days appeared to be truly white” is of crucial importance. Of equal significance is that the upper atmospheric veil Caldas observed in Bogotá between December 1808 and February 1809 was also reported from other parts of Colombia (Fig. 1), which led Caldas to suspect that it was even more widespread: “This phenomenon has been observed in Pasto, in Popayán, in Neiva, in Santa Marta, in Tunja and no doubt throughout the entire Viceroyalty. To a physicist it would not be at all surprising were it to be seen in all countries located within the tropics.”

As Director of the Astronomical Observatory, Caldas was engaged in a range of activities, including meteorological readings of pressure, temperature, rainfall and cloudiness, which were also published in the *Semanario*. We reproduce some of the available data he published from January 1807 to July 1808 (Fig. 2) to demonstrate Caldas’ experience and knowledge in relation to the climate anomalies he later describes; unfortunately the original records and measurements after July 1808 appear lost. The 1807 observations include the warmest day mean temperature and the coldest day mean temperature taken in the interior of the Observatory for each month, the annual mean average taken in the exterior of the Observatory, in addition to pressure, rainfall and number of rainy days. The 1808 observations (January to July) are compiled differently, and include the daily mean temperature for each month in the interior and the exterior of the Observatory, pressure, rainfall, number of rainy days and cloudiness (Caldas, 1912). Air temperature measurements are subject to a number

of biases, including thermometer exposure, and it is clear Caldas is aware of this as he records both internal and external measurements. The external monthly average temperatures (obviously without the modern Stevenson-type screen) are warmer and more variable than the internal data by 3.3 °C (Fig. 2). It is also apparent that all Caldas’ measurements are too high, with the reported temperatures comparable or warmer than modern climatology (monthly average El Dorado Observatory of Bogotá, IDEAM and Fondo de Prevención y Atención de Emergencias, 2007). However, these measurements demonstrate that Caldas knew of the stability of seasonal and interannual air temperatures in Bogotá. Similarly his reports of the number of rainy days per month (Fig. 2) demonstrate that January and February are consistently the driest months of the year in Bogotá, in agreement with modern rainfall seasonality (monthly average 1971–2004, El Dorado Observatory of Bogotá, IDEAM and Fondo de Prevención y Atención de Emergencias, 2007). So, although no meterological measurements for December 1808 to February 1809 were published in the *Semanario*, Caldas was evidently continuing these measurement time series and could report with high confidence that these months were uncharacteristically cold for Bogotá: “We have experienced very cold mornings, far colder than should be the case in this city, given its altitude and geographic location. Many mornings the fields have been covered in ice, and we have all seen trees and other particularly sensitive crops damaged by frost. [. . .] the weather has been dry, and, intermittently, the southerly winds have been dominant, followed by periods of considerable calm.”

The observation of regular frosts is also significant in comparison to modern climatology (Fig. 2). Although there is an increased likelihood for a frost event to occur in December, January, and February, only 2–3 frost days are typically recorded in total for these 3 months at the El Dorado Observatory in Bogotá, and on average only 3 events per year (averaged over the period 1987–2007; Fig. 2 data reproduced from Márquez et al., 2008). Additionally, the southerly wind regime Caldas describes does not correspond to modern wind climatology for these three months, or for any season, instead the dominant winds are persistently and anomalously W/N/NE (Fig. 3; El Dorado

Observatory in Bogotá; IDEAM and Fondo de Prevención y Atención de Emergencias, 2007).

No additional published or archival information describing the upper atmospheric veil observed in Colombia between December 1808 and February 1809 has been recovered to date. However, we note that at the same time as Bogotá was experiencing the climatic anomalies described by Caldas, unusual optical effects at sunset were observed in the Chorrillos district of Lima, as recorded by the Peruvian physician Hipólito Unanue in the 1815 edition of his *Observaciones sobre el clima de Lima y sus influencias en los seres organizados, en especial el hombre*: "At sundown in the middle of the month of December, there began to appear towards the S.W, between cerro de los Chorrillos and the sea, an evening twilight that lit up the atmosphere. From a N. S. direction on the horizon, it rose towards its zenith in the form of a cone, [and] shone with a clear light until eight [o'clock] at night, when it faded. This scene was repeated every night until the middle of February, when it vanished."

This phenomenon, known as a "twilight glow", typically follows in the aftermath of strong volcanic eruptions (e.g. observations reported in Symons, 1888) with the prolonged afterglow caused by light scattering from stratospheric aerosols (Deirmendjian, 1973). These dates coincide with those mentioned by Francisco José de Caldas for the upper atmospheric veil in Colombia, suggesting that the same aerosol cloud was responsible for the sunset after-glow described by Hipólito Unanue in Peru. This cloud, therefore, spanned at least 2600 km (from Santa Marta, Colombia to Lima, Peru; Fig. 1) across both the Northern and Southern Hemispheres.

4 Discussion

We have presented two published sources from Colombia and Peru that describe anomalous atmospheric and meteorological conditions that started in mid-December (11 December in Bogotá) and lasted for more than two months. Taking into account the description of the upper atmospheric veil, the vivid sunset "glow", the unexpectedly low

temperatures and high frost frequency, as well as the consistent timing and duration of the observations, we propose that a stratospheric aerosol veil spread across equatorial Latin America from 11 December 1808. Here, we analyse the descriptions contained within the two accounts to provide supplementary insights regarding the nature and source of the upper atmospheric haze. We argue that the atmospheric phenomena described by Caldas and Unanue provide evidence for a stratospheric aerosol cloud caused by the Unknown eruption of 1808–1809.

There is good evidence from the careful and scientific description written by Caldas that the haze was stratospheric: "… this whole mystery derives from a cloud equally extended in the upper part of the atmosphere, from some vapours above the horizon, and from the refraction that the light undergoes when it enters the air mass. It is this that explains the weak silvery sun; the red, the blue and the green; and it is this that explains the cold, the ice and all other features of this phenomenon that has so alarmed those of a timid disposition." Note that the term "stratospheric" was only introduced to meteorology at the start of the 20th century, however Caldas demonstrated his awareness that the atmosphere consisted of layered zones, and that the haze was concentrated "in the upper part of the atmosphere". Caldas also makes no reference to either a fog or an unpleasant smell, which are common descriptions for tropospheric dry fogs caused by volcanic eruptions (usually the acidic fumes are concentrated near the ground surface and are commonly associated with distinctive odours; Grattan and Pyatt, 1999). Troposphere dry fogs are also typically unstable, being dispersed by rain or wind, and found close to the volcanic source (Camuffo and Enzi, 1994; Grattan and Pyatt, 1999; Longo et al., 2010). The upper atmospheric cloud described by Caldas, in contrast, was observed for more than two months across Colombia, without noticeable alteration or dispersal ("This veil has been constant both by the day and by night …"). Such stability is consistent with the interpretation of a stratospheric aerosol layer caused by an explosive volcanic eruption, and the effects match those famously documented following the tropical stratospheric eruptions of both Tambora (Oppenheimer, 2003) and Krakatau (Symons, 1888). Similarly the astronomical consequences of the upper level haze described by Caldas ("The stars of the first, second and even the third magnitude have appeared somewhat dimmed, and those of the fourth and fifth have completely disappeared, to the observer's naked eye.") are identical to descriptions by astronomers impacted following the Krakatau eruption: "Dr. Krone noticed that at midnight the haze obscured all stars below the 4th and 5th magnitude, and Mr. Winlock reports [in *Science* (1884), vol. 4: 94–95] – 'Stars of the 3rd or 4th magnitude, which have frequently been seen on a good observing day, it is almost useless to try for now. The phenomenon is evidently not local'." (Archibald in Symons, 1888, p. 225).

Coincident with the persistent upper atmospheric cloud, Caldas documented anomalously cold overnight land surface temperatures, evidenced by frequent early morning frost and frost-damaged vegetation. Frosts are more likely between December and February in Bogotá (Fig. 2), however they are rare, with modern meteorological observations showing, on average, only 3 frost events per year (Márquez et al., 2008). Thus, it can be inferred from Caldas' document that the cold episode of December 1808 to February 1809 was unusual, and the number of frost days was atypically high. Moreover, radiative frosts typically occur during clear nights. Frosts are not associated with high non-volcanic clouds, cirrostratus nebulosus, because these clouds trap outgoing longwave radiation emitted from the Earth's surface at night (Schneider, 1972; Liou, 1986). A volcanic aerosol veil, on the other hand, causes a negative temperature anomaly by reducing incoming shortwave radiation (Robock, 2000). Further evidence that the veil observed in Bogotá was not an ordinary water vapour cloud comes from Caldas' observation that no coronas or halos were visible. Coronas are caused by refraction of sunlight by ice crystals, and are commonly reported when there is a water vapour veil (Liou, 1986). Following the Krakatau eruption, Archibald (in Symons 1888, p. 238) also notes "the remarkable absence of notice of the corona all over the northern parts of South America" and summarises that this absence was typical of observations across the tropics where the volcanic aerosol layer was most concentrated.

The equatorial location of the 1808 stratospheric aerosol veil, and its extension into both the Northern (Bogotá and northern areas of Colombia) and Southern Hemispheres

(Lima, Peru; Fig. 1), is consistent with a tropical source for the Unknown eruption, and the single event interpretation of the bi-polar ice core sulphate records (e.g. Dai et al., 1991; Mosley-Thompson et al., 2003; Cole-Dai et al., 2009). If the erupting volcano were located in either hemisphere outside of the tropics, then the stratospheric aerosols would have been confined in that hemisphere, without reaching the tropics and crossing the equator (Graf, 1992). The "twilight glows" described by Unanue in Peru, but significantly not discussed by Caldas in Bogotá, also support a tropical volcanic origin. Six days after the 27 August 1883 Krakatau eruption "a long belt of vaporous sky" was observed at Medellin (6.24° N, 75.58° W), Colombia, "in connection with coloured suns and glows in that part of South America" (Archibald, in Symons, 1888, p. 220). Apart from this initial report, presumed to accompany the leading edge of the aerosol cloud, reports of "glows" are noted instead for their absence within equatorial regions where the aerosol layer was thickest (Archibald, in Symons, 1888). However, within six weeks of the Krakatau eruption sunset "glows" identical to Unanue's description from mid-December 1808 were observed across all longitudes (outside the equatorial band) between 30° N and 45° S, as the aerosol layer dispersed (Archibald, in Symons, 1888). For example, "Very strong glows, as never before seen" were reported from Arequipa (16.4° S), Peru ("Met. Zeitschrift" cited by Russell in Symons, 1888, p. 289) starting a month after the Krakatau 27 August 1883 event. The exact location of the volcano responsible for the $\sim$1809 Unknown eruption remains unresolved. However, it is unlikely that it occurred in Latin America. We base this conclusion on two observations. First, we expect that such a large volcanic eruption would have been recorded in the Spanish colonial archive, given both the number and quality of scientific observations in many parts of the continent. Second, there is no apparent anomaly in the rate of particle deposition in the Quelccaya ice core record (Peru; 13.93° S, 70.83° W), in contrast to the obvious ash layer deposited from the 1600 Huaynaputina (Peru) eruption (Thompson et al., 1985).

Taking into account the dates given by Caldas and Unanue, the eruption clearly occurred before 11 December 1808. We can further constrain the eruption date as unlikely to have been any earlier than late November 1808. We therefore conclude that the Unknown eruption occurred on 4 December 1808 ± 7 days based on the precise timing given by Caldas and consistent stratospheric aerosol dispersal rates from other well-monitored tropical eruptions. Modern observations show that stratospheric aerosols are dispersed rapidly around the Equator, forming a continuous layer between 10° N to 20° S within two weeks of an eruption, as measured by global SO_2 mapping from the satellite-based Total Ozone Mapping Spectrometer following the El Chichón (1982) and Pinatubo (1991) eruptions (Bluth et al., 1992). A similar rapid rate of dispersal was documented after the 1883 Krakatau eruption (Symons, 1888), with a "blue sun" first reported in Bogotá just 7 days after Krakatau erupted; the volcanic aerosol layer was recorded across Latin America from Maracaibo, Venezuela (11° N) to Guayaquil, Ecuador (3° S) on the same day (Russell, in Symons, 1888, p. 276). An eruption date for the Unknown of early December 1808 also agrees with the tentative estimate of February 1809 ± 4 months calculated by Cole-Dai et al., (2009) from the timing of elevated sulphate concentrations in well dated ice core layers from late 1809 followed by an ∼ 19 month period of deposition at both poles (Cole-Dai et al., 2009).

The season of an eruption is a critical factor in determining when stratospheric aerosols are initially transported into the extratropics and the hemispheric partitioning of the sulphate from a low-latitude eruption (Trepte et al., 1993). For example, greater aerosol mass from the April Tambora eruption was transported into the Southern Hemisphere (Arfeuille et al., 2014). By comparison, ice core sulphate flux measurements indicate that the Unknown eruption deposited relatively more aerosols to the Northern Hemisphere high latitudes than the Tambora eruption: the sulphate flux signal for the Unknown eruption is 61 % of that for the Tambora eruption in Greenland ice cores, compared to 45 % in Antarctic ice cores (Cole-Dai et al., 2009). The asymmetry in the sulphate flux between the Unknown eruption and Tambora 6 years later provides further support for the two eruptions being almost 6 months out of phase in terms of the annual cycle. Importantly, this pattern of hemispheric bias is not reproduced by models that assume a February 1809 date of the Unknown eruption (Arfeuille et al., 2014). It is

also noteworthy that Lamb (1970) identified possible evidence for volcanic haze from changes in sunset colouration seen over London in early April 1809, but did not calculate a Dust Veil Index value for 1809 due to the lack of a known associated volcanic eruption. This historical report occurs too early for volcanic aerosols to reach ∼ 52° N if the eruption was in February of the same year (i.e. within ∼ 2 months), especially considering seasonal and hemispheric differences in global aerosol dispersal, but it is well within a realistic timescale if it is associated with a tropical eruption from early December 1808.

The tropical ocean–atmosphere system is highly sensitive to changes in radiative forcing caused by stratospheric aerosols (D'Arrigo et al., 2009). The immediate climate anomalies reported by Caldas included uncharacteristically cold temperatures leading to increased incidence and severity of frosts, which is consistent with the strong negative tropical sea surface temperature anomalies observed during 1809 from proxy sources (D'Arrigo et al., 2009) and marine and land temperature observations (e.g. Chenoweth, 2001, found a pronounced cooling of −0.84 °C in annually averaged data from 20° N–20° S in 1809). Caldas would also have been aware of the normal seasonality experienced in Colombia in terms of both wind and precipitation, supported by his time series of meteorological observations. Typically the region of intense tropical rainfall, the Inter Tropical Convergence Zone (ITCZ) is located south of the Bogotá region during the Southern Hemisphere summer months causing dry conditions locally (Fig. 2) with a predominance of N/NE winds (Fig. 3). Caldas' report of dry weather between December 1808 and February 1809 therefore follows rainfall seasonality, although it is also consistent with a post-volcanic reduction in precipitation as observed in this region in the year following the Pinatubo eruption (negative anomaly of −2 to −0.4 mm day^{-1}; Trenberth and Dai, 2007). In contrast, the dominant southerly wind regime in Bogotá described by Caldas during December 1808 to February 1809 is extremely unusual according to modern climatology for this area (Fig. 3). One possibility is that the ITCZ remained in a more northerly position at the end of 1808, which would be a likely result of radiative forcing from the stratospheric aerosol layer initially strengthening the meridional temperature gradients in the Southern Hemisphere (as seen in modelling studies of e.g. Yoshimori and Broccoli, 2008, 2009; Schneider et al., 2009). However, the description by Caldas of calm conditions in Bogotá, in addition to the southerly winds, may also be explained by more stable local conditions due to surface cooling reducing the vertical thermal gradient and decreased evaporation. Further regional-scale proxy or historical evidence is needed to confirm whether a northward displacement of the ITCZ occurred following the 1808 Unknown eruption as is suggested from the observations of Caldas.

5 Conclusions

We have presented evidence that a stratospheric aerosol cloud was present over Colombia from 11 December 1808 and extended into the Southern Hemisphere at least as far south as Lima, Peru, within the same week. The evidence comes from a commentary published in the *Semanario del Nuevo Reyno de Granada* in 1809 by the scientist Francisco José de Caldas in response to the unusual atmospheric, weather and optical phenomena being observed at the time, and a contemporaneous observation of "twilight glow" events recorded by the scientist Hipólito Unanue in the 1815 edition of his study on the climate of Lima (*Observaciones sobre el clima de Lima*). We suggest that this stratospheric aerosol layer was generated by the VEI 6 Unknown volcanic eruption previously identified and dated from bi-polar ice core sulphate anomalies and tentatively estimated as having erupted in February (±4 months) 1809 (Cole-Dai et al., 2009). Caldas and Unanue made their observations in Bogotá (4° N) and Lima (12° S), which means the stratospheric aerosol cloud could only have originated from a large explosive tropical eruption, as proposed by Cole-Dai et al. (1997), and not the two separate high-latitude volcanic eruptions from both hemispheres identified by Yalcin et al. (2006) and Kurbatov et al. (2006). The dates given in the two documents restrict the actual eruption date of the Unknown eruption to between late November and early December 1808 (4 December 1808 ± 7 days). This estimate is based on observed

rates of stratospheric aerosol dispersal from satellite monitoring (e.g. the El Chichón 1982 and Pinatubo 1991 eruptions; Bluth et al., 1992) and identical descriptions of the phenomena observed by Caldas and Unanue by observers of the after effects from the 1883 Krakatau eruption (as summarised in Symons, 1888 and Simkin and Fiske, 1984). This new eruption date means the hemispheric partitioning of aerosol loading (e.g. Arfeuille et al., 2014) and consequently the climatic and dynamic response of the volcanic forcing will need to be reconsidered.

It is remarkable that the location of the December 1808 Unknown volcanic eruption is still a mystery given that it is a relatively recent and a very large explosive event with associated global climatic impacts. It is even more extraordinary that the Caldas and Unanue observations are the first eyewitness accounts of its indirect atmospheric effects to have been identified. The political environment on both sides of the Atlantic at the beginning of the 19th century may explain the absence of documentation in the historical record for this recent eruption despite its intensity. The eruption coincided with the Napoleonic Wars in Europe, the Peninsular War in Spain, and with political developments in Latin America that would lead, between 1810 and 1825, to the independence of almost all of Spain's American colonies. It is possible that these circumstances meant that, in Europe and Latin America at least, the attention of individuals who might otherwise have provided us with a record of unusual meteorological or atmospheric effects simply turned to military and political matters, as suggested by the content of both official correspondence and the periodical press in Spain and its colonies during these critical years. Thus Caldas and Unanue's reports may be exceptional in their description of the atmospheric and meteorological effects of the Unknown eruption of 1808.

Appendix A

Translation in English of the article written by Francisco José de Caldas

"Meteorological News" (published in *Semanario del Nuevo Reyno de Granada*), in Eduardo Posada (Ed.), *Obras de Caldas* (Bogotá: Imprenta Nacional, 1912), 347–350.

"As of 11 December of last year, the disk of the sun has appeared devoid of irradiance, its light lacking that strength which makes it impossible to observe it easily and without pain. Its natural fiery colour has changed to that of silver, so much so that many have mistaken it for the moon. This phenomenon is very noticeable at sunrise, and particularly when the sun sets. When [the sun] is at its zenith, it shines more brightly and cannot be looked at with the naked eye. Near the horizon, it has been seen to take on a light rosy hue, [or] a very pale green, or a bluey-grey close to that of steel. We have experienced very cold mornings, far colder than should be the case in this city, given its altitude and geographic location. Many mornings the fields have been covered in ice, and we have all seen trees and other particularly sensitive crops damaged by frost. The whole vault of the sky has been covered by a light cloud as widespread as it is transparent. The blue of the sky has corresponded to the lowest degrees of the cyanometer, and some days it has appeared to be truly white. [Also] missing have been the emphatic coronas which are so frequently seen around the sun and the moon when those clouds that meteorologists know by the name of Veil are present. The stars of the first, second and even the third magnitude have appeared somewhat dimmed, and those of the fourth and fifth have completely disappeared, to the observer's naked eye. This veil has been constant both by the day and by night, the weather has been dry, and, intermittently, the southerly winds have been dominant, followed by periods of considerable calm.

This phenomenon has been observed in Pasto, in Popayán, in Neiva, in Santa Marta, in Tunja and no doubt throughout the entire Viceroyalty. To a physicist it would not be at all surprising were it to be seen in all countries located within the tropics.

Some have thought this phenomenon to be unique, extraordinary, and almost beyond the laws of nature, and the common people have taken it as a sure portent of great calamities [to come]. So many have consulted me, and so many have I had to reassure! The need to allay everyone's [anxiety] regarding a phenomenon that is not in the least extraordinary, and that conforms in all senses to the soundest principles of physics, has obliged me to fill [these] two pages in our *Semanario*, to explain that this whole mystery derives from a cloud that extends across the upper part of our atmosphere, from some vapours above the horizon, and from the refraction that the light undergoes when it enters the air mass. It is this that explains the weak silvery sun; the red, the blue and the green; and it is this that explains the cold, the ice, and all other features of this phenomenon that has so alarmed those of a timid disposition. I have seen the same sky a thousand times, and a thousand times I have had to remove the lenses from the quadrants, and from the telescope itself, the opaque or coloured glasses that temper the brightness of the sun's light in order to see its disk with clarity. History, moreover, records similar phenomena occurring in the past. Throughout the year 1673, during the reign of Philip IV, the sun appeared darkened and with an ashy hue in Cologne, Ulm and Heidelberg, and in all of Europe. Astrologers of the time, that is to say the prophets of doom, announced great things [to come], the common people and the ignorant feared [the worst]; the years passed; in the natural and the political worlds, things went on as normal; time itself disabused the concerned, and showed that the darkness of the sun was down to nothing more than an atmospheric phenomenon, extraordinary only in the sense that it was unusual. Why, then, should we be afraid? Why should we be alarmed by the effects of some vapours, by illusions created by our own senses, by inflexions of light, and by a thousand different circumstances that come together, appear and disappear like smoke, without there ever having been disastrous consequences?

NOTE: The history of physics is full of extraordinary phenomena, which seem astonishing and almost supernatural at first sight, but which turn out when subjected to critical examination by a real physicist to be ordinary phenomena, their causes well-known. The aurora borealis, that ocean of fire swimming above our heads: bars,

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plumes, ziezaes, fountains, armies of men, and all the phantoms that the most vivid imagination can conjure up – are these not down to nothing greater nor more unusual than a transparent cloud that obstructs the sun's brilliance? Spectacular cloud [formations], blood rain, rocks falling from the sky, parhelions, paraselenae which look like newly created celestial bodies, coronas, the ox eye which fill the Hottentots with horror and fright, the tremendous ebb and flow of the [bore] tides at the mouth of the Amazon River, whirlpools and waterspouts, etc.: are these not more terrible, more extraordinary, and more fascinating than the phenomenon which we have been observing these last two months? As our knowledge increases, as physics and the other sciences break new ground, and as people become enlightened, what once seemed marvellous, and manifestations [of natural phenomena] that formerly filled them with terror and fear, become familiar and common. Let us open the annals of history: on each page we will read how some peoples devised extraordinary and cruel [forms of] penitence; how others submerged themselves in water, how others cried, and how others feared that the sun would be destroyed when its disk was eclipsed by the opaque body of the moon. Not even the Greeks, that wise and inventive civilization, were exempt from this [kind of] puerile fear. We know that the great Pericles would have lost a naval battle had he not explained to the pilot of his vessel the natural and simple cause behind the sun becoming obscured. Thanks to astronomers, mankind has shaken off this preoccupation and this fear. When we are as enlightened about other phenomena as we are about eclipses, then we will look on the opacity of the sun and the loss of its rays as calmly as we do a rainbow after a storm."

Appendix B

Original text in Spanish of the article written by Francisco José de Caldas

"Noticias Meteorológicas" (published in *Semanario del Nuevo Reyno de Granada*), in Eduardo Posada (Ed.), *Obras de Caldas* (Bogotá: Imprenta Nacional, 1912), 347–350.

"Desde el día 11 de diciembre del año último, se comenzó a observar el disco del sol desnudo de irradiación, y de aquella fuerza de luz que impide mirarlo con tranquilidad y sin dolor. El color de fuego que le es natural se ha cambiado en el de plata, hasta el punto de equivocarlo muchos con la luna. Este fenómeno es muy notable al nacer, y principalmente al ponerse este astro. Cuando corre la mitad del cielo, su luz es más viva y no permite mirársele a ojo desnudo. En las cercanías del horizonte, se le ha visto teñido de un color de rosa muy ligero, de un verde muy claro o de un azulado gris que se acerca al del acero. Se ha sentido generalmente por las mañanas un frío pungente y muy superior al que exigen la altura y la posición geográfica de esta capital. Muchos días ha amanecido el campo cubierto de hielo, y todos hemos visto quemados los árboles y demás vegetales que por su organización son demasiado sensibles a este meteoro. Toda la bóveda del cielo se ha visto cubierta de una nube muy ligera igualmente extendida y transparente. El azul del cielo ha tocado en los primeros grados del cianómetro, y algunos días se ha visto de un verdadero blanco. Han faltado las coronas enfáticas que se observan con tanta frecuencia alrededor del sol y de la luna cuando existen aquellas nubes que los meteorologistas conocen con el nombre de Velo. Las estrellas de primera, de segunda y aun de tercera magnitud se han visto algo obscurecidas, y absolutamente han desaparecido las de cuarta y quinta, a la simple vista del observador. Este velo ha sido constante tanto de día como de noche, el tiempo ha sido seco, y han reinado los vientos del Sur por intervalos, sucediéndoles calmas muy considerables.

Este fenómeno se ha observado en Pasto, en Popayán, en Neiva, en Santa Marta, en Tunja y seguramente en toda la extensión del Virreinato. Nada tendría de extraño a los ojos del físico que se observase igualmente en todos los países situados dentro de los trópicos.

Algunos han creídos que este fenómeno es único, extraordinario y casi fuera de las leyes comunes de la naturaleza, y el vulgo sencillo lo ha tomado como indicio seguro de grandes calamidades. !Cuántos me han consultado, y a cuántos he tenido que serenar! La tranquilidad de todos sobre un objeto que nada tiene de extraordinario, y que en todas sus partes está conforme con los principios más sanos de la verdadera física, me han obligado a llenar dos páginas de nuestro *Semanario*, diciendo que todo el misterio consiste en una nube extendida igualmente en la región superior de nuestra atmósfera, en algunos vapores del horizonte y en las refracciones que sufre la luz al entrar en la masa de aire. De aquí el sol lánguido y de color de plata; de aquí el rojo, el azul, el verde; de aquí el frío, los hielos y todo lo que constituye el fenómeno que ha alarmado a los espíritus débiles. Mil veces he observado la misma disposición en el cielo, y mil veces he tenido que desnudar los anteojos de los cuartos de círculo y el telescopio mismo de los vidrios opacos o de color que templan la vivacidad de la luz, para poder observar el disco del sol con claridad. Por otra parte, la historia nos conserva la memoria de semejantes meteoros. En el reinado de Felipe IV, en todo el año de 1673, el sol se vio en Colonia, en Ulma, en Heidelberg y en toda la Europa, obscurecido y de color de ceniza. Los astrólogos de aquella edad, es decir, los profetas fanáticos de la suerte del género humano, anunciaron grandes cosas; el vulgo y los ignorantes temieron; los años pasaron; las cosas naturales y políticas se mantuvieron en el estado en el que exigían las circunstancias; el tiempo desengañó a los preocupados y manifestó que la obscuridad del sol no era otra cosa que un meteoro que no tenía más de extraordinario que el ser raro. ¿Porqué pues hemos de temer? porqué nos hemos de afligir por unas apariencias producidas por vapores, por ilusiones de nuestros sentidos, por inflexiones de la luz y por otras mil circunstancias que se combinan, que varían, que suceden y desaparecen como el humo, sin que jamás hayan tenido funestas consecuencias?

NOTA: La historia de la física está llena de fenómenos extraordinarios y que al primer aspecto llevan consigo todos los caracteres de asombrosos y casi sobrenaturales; pero sujetos al examen detenido y profundo del verdadero físico, no son otra cosa que fenómenos regulares y de causas conocidas. La aurora boreal, ese océano de fuego nadando sobre nuestras cabezas, barras, plumas, ziezaes, fuentes, ejércitos y todas las fantasmas que puede suministrar la imaginación más viva, ¿no tienen más de grande y de raro que una nube transparente que le quita sus resplandores al

sol? ¿Las nubes espectaculares, las lluvias de sangre, de piedra, los parhelios y las paraselenas en quienes parece se ha obrado una nueva creación de los cuerpos más brillantes del universo, las coronas enfáticas, el ojo del buey que llena de espanto y de terror a los Hotentotes, el flujo y reflujo terrible de las embocaduras del Amazonas, la bomba marina, los vórtices, etc., no son más terribles, más extraordinarios, más seductores que el fenómeno que ha dos meses observamos? A proporción que hacen progresos nuestros conocimientos, al paso que la física y las otras ciencias dilatan sus límites, y a proporción que los pueblos se ilustran, desaparece lo maravilloso, y las apariencias que antes los llenaban de terror y de miedo, vienen a serles familiares y comunes. Abramos los anales de la historia: en cada página leeremos que unos pueblos hacían penitencias extraordinarias y crueles, que otros se sumergían en el agua, que aquellos lloraban, que estos temían la ruina del astro del día, cuando su disco se ocultaba por el cuerpo opaco de la luna. Los Griegos mismos, este pueblo sabio y original, no estuvo exento de este temor pueril. Sabemos que el gran Pericles habría perdido una batalla naval, si no hubiera explicado al piloto de su nave, la causa natural y sencilla de la oscuridad del sol. Gracias a los astrónomos, el género humano ha sacudido esta preocupación y este temor. Cuando estemos tan ilustrados sobre los demás fenómenos como lo estamos sobre los eclipses, entonces miraremos las opacidades del sol y la pérdida de sus rayos con la misma tranquilidad que vemos el iris después de una tormenta.”

Appendix C

Translation in English of the extract from Hipólito Unanue’s *Observaciones sobre el clima de Lima* (Madrid, 1815)

“At sundown in the middle of the month of December, there began to appear towards the S. W., between cerro de los Chorrillos and the sea, an evening twilight that lit up the atmosphere. From a N. S. direction on the horizon, it rose towards its zenith in the form of a cone, [and] shone with a clear light until eight [o'clock] at night, when it faded. This scene was repeated every night until the middle of February, when it vanished."

Appendix D

Extract from Hipólito Unanue's *Observaciones sobre el clima de Lima*

"A mediados del mes de Diciembre, comenzó a aparecer al S. O., entre el cerro de los Chorrillos y el mar al ponerse el Sol, un crepúsculo vespertino que iluminaba la atmósfera: lanzábase del horizonte N. S. hasta el cenit en forma de cono, brillaba con luz clara hasta las ocho de la noche en que se extinguía; y esta escena se renovaba todas las noches hasta mediados de Febrero en que desapareció."

Acknowledgements. This work was supported by a joint U. Bristol postgraduate scholarship and La Caixa Scholarship to A. Guevara-Murua, a Royal Society Fellowship to A. C. Rust, a RCUK Academic Fellowship to E. J. Hendy, and the AXA Research Fund (to K. V. Cashman). Simon Powell kindly produced Fig. 1. The authors also acknowledge support from the Cabot Institute, University of Bristol.

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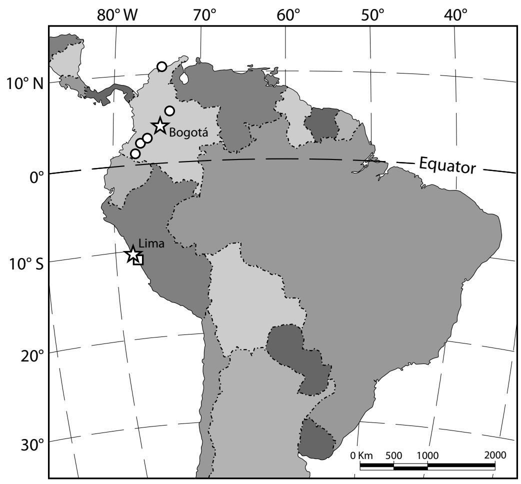

Fig. 1. Map of South America indicating the six locations in Colombia reported by Caldas (1809) where the stratospheric aerosol veil had been observed from 11 December 1808 (circles: Pasto, Popayán, Neiva, Santa Marta, Tunja). The square shows the location of the district of Chorrillos, Lima, Peru, where after-glows were observed following sunsets from mid-December 1808 to February 1809 as reported by Unanue (1815).

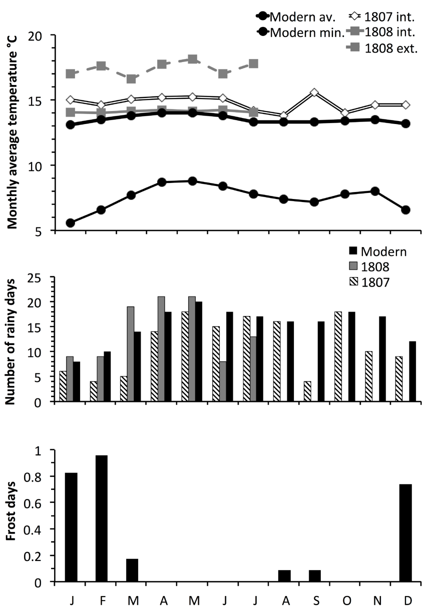

Fig. 2. Meteorological data for the city of Bogotá, Colombia. Modern data (black) are from the El Dorado Observatory (IDEAM and Fondo de Prevención y Atención de Emergencias 2007; Márquez et al., 2008); 1807 and 1808 data as recorded by Francisco José de Caldas and published in the *Semanario* (Caldas, 1912; 331–337 pp. and p. 500). Top panel: monthly mean and minimum temperatures (black circles, climatological average for 1970–1980; white diamonds, interior average temperature for 1807; dark grey diamonds, interior and exterior temperatures for 1808). The 1807 and 1808 data were reported by Caldas in ˚R and have been converted to ˚C. Middle panel shows the number of rainy days per month for January–December 1807, January–July 1808 and modern rainfall climatology for 1971–2004. Lower panel: average number of frost days per month over the period 1985–2007 (from Márquez et al., 2008).

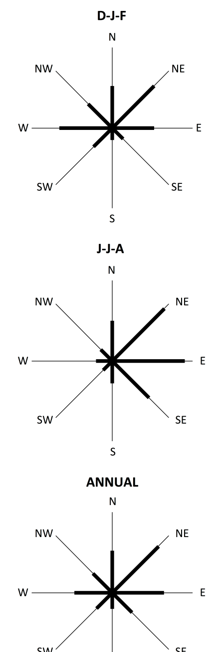

Fig. 3. Wind direction at El Dorado Observatory in Bogotá, 1977–2001 (IDEAM and Fondo de Prevención y Atención de Emergencias, 2007). Top wind rose shows average wind direction for December to February (i.e. the months when the veil and southerly winds were reported by Caldas in Bogotá). Middle wind rose shows average wind direction for June to August, when the Inter Tropical Convergence Zone (ITCZ) is located to the north of Colombia, and lower wind rose is the annual average.

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