



After Krakatau: Eurasian Climate and Circulation in Historical Temperature and Pressure Records

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Abstract.

The impact of the Krakatau eruption on Eurasian climate is still not fully understood. Previous studies have provided insight from seasonal averages and gridded datasets, while the month-to-month evolution and the role of atmospheric circulation remain less clearly resolved. Here, we analyse air-temperature and station-pressure observations from the *Annalen des Physikalischen Centralobservatoriums* at monthly and daily resolution. The first complete post-eruption year, 1884, was characterised by marked seasonal variability rather than continuous cooling. Mild conditions in January and February were followed by widespread negative temperature anomalies through much of spring and summer, with particularly coherent cooling in April and August. Network-median anomalies in these months were -1.50°C and -1.91°C , respectively, both ranking as the coldest among the corresponding reference years. Conditions reversed during autumn, culminating in widespread December warmth, with a network-median anomaly of $+2.71^{\circ}\text{C}$, the warmest in the reference-year distribution. Late-summer cooling recurred in August 1885, whereas December warmth was common across much of Eurasia from 1883 to 1886. Simultaneous pressure observations point to a substantial role for atmospheric circulation in the winter anomalies, while the spring and late-summer cooling was not associated with a common pressure pattern. Daily records show that cool conditions could persist for weeks despite changing local pressure differences. The observations therefore indicate strong regional modulation of the post-Krakatau temperature evolution; an additional volcanic influence remains physically plausible but cannot be isolated from the historical station data.

1 Introduction

The climactic eruption of Krakatau in August 1883 was one of the largest tropical volcanic eruptions of the instrumental period. Located in the Sunda Strait between Java and Sumatra, the eruption produced approximately $18\text{--}21\text{ km}^3$ of pyroclastic material and caused extensive regional destruction (Self and Rampino, 1981). Its importance for climate research arises from the substantial perturbation that it produced in the stratospheric aerosol layer and from its occurrence during the late nineteenth-century instrumental era, when direct meteorological observations were already available across parts of Europe and Asia. Krakatau therefore provides an opportunity to investigate the atmospheric and climatic consequences of a major tropical eruption using contemporary observations as well as later reconstructions.



Large explosive eruptions can affect climate when they inject substantial quantities of sulfur-bearing gases into the stratosphere. Their climatic influence does not depend only on the total volume of erupted material, but also on the sulfur yield, injection altitude, eruption latitude, season, atmospheric transport and subsequent aerosol microphysics (Rampino and Self, 1982; Toohey and Sigl, 2017; Robock, 2000). In the stratosphere, sulfur dioxide is oxidised and converted into sulfate aerosols, which scatter incoming solar radiation and reduce the amount of energy reaching the Earth's surface. These aerosols also absorb terrestrial and near-infrared radiation, warming the lower stratosphere and potentially modifying atmospheric circulation (McCormick et al., 1995; Robock, 2000). Model studies further show that the resulting circulation response depends on stratospheric–tropospheric coupling, eddy interactions, aerosol representation, and the background state of the climate system (Stenchikov et al., 2002; Timmreck, 2012; DallaSanta et al., 2019). The resulting surface response is therefore not expected to consist of spatially uniform cooling.

The climatic importance of an eruption also does not scale directly with the volume of erupted material. Rampino and Self (1982) showed that Tambora, Krakatau and Agung differed strongly in their production of fine ash, whereas the differences in estimated long-lived sulfate aerosol loading were much smaller. The three eruptions were followed by hemispheric temperature decreases of broadly comparable order, amounting to a few tenths of a degree. Although these early estimates are uncertain, they illustrate that sulfur loading and stratospheric aerosol formation are more directly relevant to climatic forcing than erupted volume alone.

For Krakatau specifically, several independent lines of evidence indicate the formation of a widespread stratospheric aerosol cloud. Reconstructions suggest that the aerosol was transported into both hemispheres (Toohey and Sigl, 2017), while sulfate anomalies associated with the eruption have been identified in Greenland and Antarctic ice cores (Kohnno and Fujii, 2002; Takahashi et al., 2022). Contemporary observers reported intense twilight glows, atmospheric haze, unusual solar and lunar colours, and Bishop's Ring at widely separated locations (Royal Society of London, Krakatoa Committee, 1888). Historical reconstructions of atmospheric turbidity also identify Krakatau as a major stratospheric aerosol event (Stothers, 1996). In addition, sunshine-duration observations from southern Spain indicate reduced direct surface illumination after the eruption, with particularly low values during 1884 (Obregón et al., 2020).

Early analyses suggested that Northern Hemisphere temperatures decreased by several tenths of a degree for approximately two to three years after Krakatau (Rampino and Self, 1982). Such hemispheric or annual-mean cooling does not imply a spatially uniform regional response. In Northern Hemisphere winter, aerosol-induced lower-stratospheric warming can modify the polar vortex and the North Atlantic circulation, potentially producing relatively mild conditions over parts of Eurasia even while the hemispheric mean cools (Robock and Mao, 1992; Shindell et al., 2004; Stenchikov et al., 2002).

Whether this winter dynamical response is robust remains uncertain. Observed Eurasian warming after Krakatau and Pinatubo cannot always be distinguished clearly from internal atmospheric variability (Polvani and Camargo, 2020; Polvani et al., 2019). Polvani and Camargo (2020), for example, found warming during the winter of 1883/84 but concluded that its magnitude was not exceptional relative to other winters, while also identifying cooling over the Urals beginning in February and strengthening in



March. Model results are similarly mixed: some simulations show little forced Eurasian winter response compared with internal variability (Driscoll et al., 2012; DallaSanta and Polvani, 2022), whereas larger ensembles and recent CMIP6 experiments indicate a tendency toward polar-vortex strengthening, a positive NAO-like response, and warming over parts of northern Eurasia (Bittner et al., 2016; Zambri and Robock, 2016; Weber et al., 2026). Last-millennium reconstructions likewise provide no single consistent response (Tejedor et al., 2024; Tao et al., 2025).

Modern eruptions offer a useful comparison, but not a direct analogue. Agung (1963), El Chichón (1982), and Pinatubo (1991) produced substantial stratospheric aerosol perturbations but differed in aerosol distribution and regional climate response, illustrating the importance of eruption characteristics and the contemporaneous atmospheric state (Dhomse et al., 2020; Fujiwara et al., 2020). This variability cautions against expecting one unique Eurasian temperature or circulation pattern after Krakatau.

Previous studies of the post-Krakatau Eurasian response have relied mainly on gridded temperature products and seasonal averages. For example, Polvani and Camargo (2020) analysed the winter of 1883/84 using CRUTEM, GISTEMP and NOAA GlobalTemp, together with the Twentieth Century Reanalysis and climate-model ensembles. These products provide valuable large-scale information, but nineteenth-century station coverage is sparse and spatially uneven across eastern Europe, the Russian Empire and Siberia (Jones et al., 2012; Osborn and Jones, 2014; Hansen et al., 2010; Menne et al., 2018). Moreover, the observational products are based primarily on monthly mean temperatures and do not themselves provide daily pressure information. Although Polvani and Camargo (2020) identified the transition from early-winter warmth towards cooling over the Urals, their analysis was based primarily on overlapping seasonal means. The month-to-month development and its relationship with local pressure variability therefore remain less well resolved.

The original observations published in the *Annalen des Physikalischen Centralobservatoriums* provide an important complementary source of information (Shapiro and Foelsche, 2026). The present study builds on the recovery and digitization work described there, but uses an extended station network tailored to the Krakatau analysis. These observations contain station-level temperature and atmospheric-pressure observations at monthly, daily and, in some cases, subdaily resolution. These records make it possible to investigate the spatial and temporal development of post-eruption anomalies directly from historical measurements rather than relying exclusively on interpolated temperature fields. The simultaneous pressure observations are particularly useful because they provide additional information on atmospheric circulation and allow the temperature evolution to be examined together with changes in local pressure. They cannot by themselves provide a complete circulation diagnosis, but they offer information that is absent from temperature-only analyses.

This study uses monthly and daily temperature and station-pressure observations from the *Annalen des Physikalischen Centralobservatoriums* to examine climatic conditions across Eurasia during the years following the 1883 Krakatau eruption. We first investigate the month-to-month development of temperature and pressure anomalies during 1884, the first complete post-eruption calendar year. Daily observations from a nine-station west–east transect are then used to examine the shorter-term structure underlying the principal monthly temperature patterns, and April, August, and December are compared across 1883–1887 to place the 1884 conditions in a broader temporal context. The aim is to assess the contribution of regional



90 atmospheric variability to the observed temperature anomalies and to identify features that are also physically compatible with a
 broader volcanic influence.

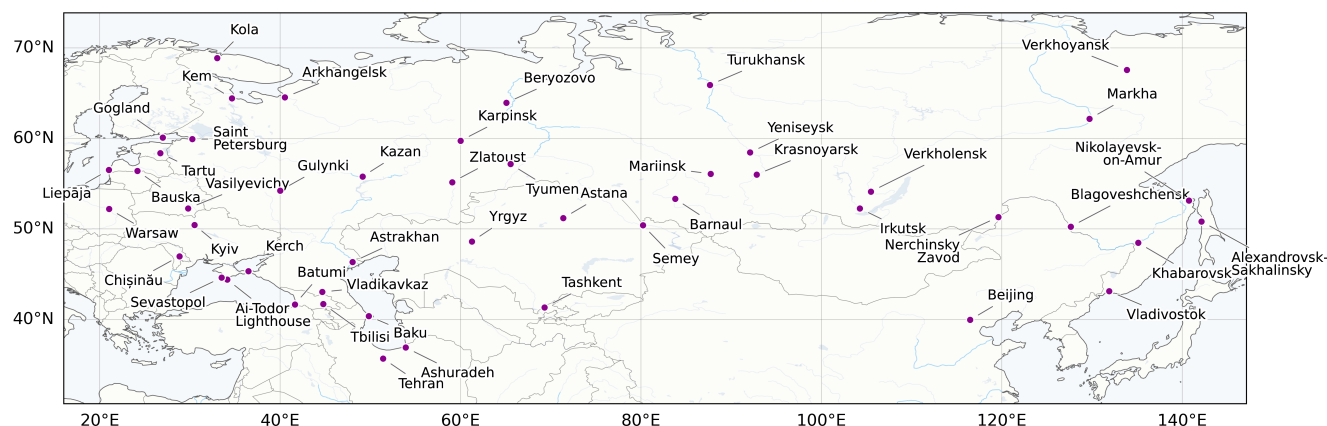


Fig. 1. Network of the selected stations. Purple points represent individual stations; grey shading highlights the present-day countries in which the stations were located.

2 Data and methods

2.1 Historical observations and station network

The meteorological observations analysed in this study originate from the annual publications of the Central Physical Observatory
 95 in St. Petersburg. The *Annalen* consist of centrally compiled and typographically printed annual tables rather than original
 station journals. During 1870–1894, the volumes were published in parallel German and Russian versions; from 1878 onward,
 the meteorological observations from the wider station network were published in Teil 2. The present study draws on these
 historical observations to investigate temperature and pressure variability across Eurasia following the August 1883 eruption of
 Krakatau.

100 Our analysis is based primarily on monthly air-temperature and pressure observations from 1874–1894. In addition, subdaily
 temperature and pressure observations are examined for selected stations during November 1883–December 1884. At most
 stations, observations were made at 07:00, 13:00, and 21:00. For temperature and barometric pressure, published daily means
 were generally calculated as simple arithmetic means of the three fixed-time observations, and monthly means were then derived
 from the available daily values. Days for which one of the three observations was missing were not assigned an interpolated daily
 105 mean. The pressure values published in the *Annalen des Physikalischen Centralobservatoriums* represent barometric pressure
 at instrument height. The published barometer readings were corrected for documented instrumental effects and reduced to
 a standard mercury temperature of 0 °C; the height of the barometer above sea level was reported separately for each station.



Table 1. Stations

Historical name	Present-day name	Latitude (°N)	Longitude (°E)	Covered years
Aitodor Leichttuttm	Ai-Todor Lighthouse	44.42	34.13	1884, 1886–1893
Akmoilinsk	Astana	51.20	71.38	1874–1877, 1879–1885, 1890–1894
Alexandrowka	Alexandrovsk-Sakhalinsky	50.83	142.12	1884, 1886–1893
Archangelsk	Arkhangelsk	64.55	40.53	1874–1877, 1879–1894
Aschur_Ade	Ashuradeh	36.90	53.92	1884, 1886
Astrahan	Astrakhan	46.35	48.03	1874–1877, 1879–1894
Baku	Baku	40.37	49.83	1874–1877, 1879–1894
Barnaul	Barnaul	53.33	83.78	1874–1877, 1879–1894
Batum	Batumi	41.67	41.63	1884, 1886–1893
Bauske	Bauska	56.42	24.18	1884, 1886–1888
Berezov	Beryozovo	63.93	65.07	1879–1894
Blagoveschensk	Blagoveshchensk	50.25	127.63	1877, 1879–1890, 1892–1894
Bogoslovsk	Krasnoturyinsk	59.75	60.02	1874–1877, 1879–1894
Chabarovka	Khabarovsk	48.47	135.12	1879–1881, 1890–1894
Derpt	Tartu	58.38	26.72	1874–1877, 1879–1891
Eniseisk	Yeniseysk	58.45	92.10	1874–1877, 1879–1894
Gulinki	Gulyнки	54.23	40.00	1874–1877, 1879–1893
Hogland	Gogland (Suursaari)	60.10	26.98	1874–1877, 1879–1894
Irgis	Irgiz	48.62	61.27	1874–1877, 1879–1893
Irkutsk	Irkutsk	52.27	104.27	1874–1877, 1879–1894
Kazan	Kazan	55.78	49.13	1874–1877, 1879–1894
Kem	Kem	64.45	34.65	1874–1877, 1879–1893
Kertsch	Kerch	45.35	36.48	1874–1877, 1879–1893
Kiew	Kyiv	50.45	30.50	1874–1877, 1879–1893
Kischinew	Chişinău	46.98	28.85	1874–1877, 1879–1880, 1886–1893
Kola	Kola	68.88	33.02	1879–1894
Krasnojarsk	Krasnoyarsk	56.02	92.82	1884, 1886–1892
Libava	Liepāja	56.52	21.02	1876–1877, 1879–1894
Marchinsk	Markha	62.17	129.72	1884, 1886–1893
Mariinsk	Mariinsk	56.10	87.72	1884
Nerchinskii zavod	Nerchinsky Zavod	51.32	119.62	1874–1877, 1879–1880, 1882–1894
Nikolaevsk-on-Amur	Nikolaevsk-on-Amur	53.13	140.75	1874–1877, 1879–1881, 1883–1894
Peking	Beijing	39.95	116.48	1874–1877, 1879–1884, 1886, 1889–1894
Semipalatinsk	Semey	50.40	80.22	1884, 1886–1888, 1892–1893
Sevastopol	Sevastopol	44.62	33.52	1874–1877, 1879, 1882–1893
St.-Petersburg	Saint Petersburg	59.93	30.27	1874–1877, 1879–1893
Taschkent	Tashkent	41.33	69.30	1874–1877, 1879–1887, 1892–1893
Tegeran	Tehran	35.68	51.42	1884, 1886–1888, 1890, 1892
Tifliss	Tbilisi	41.72	44.78	1874–1877, 1879–1893
Tjumen	Tyumen	57.17	65.53	1884, 1886–1893
Turuhansk	Turukhansk	65.92	87.63	1877, 1879–1894
Warsaw	Warsaw	52.22	21.03	1874–1877, 1879–1881, 1883–1894
Wasilevichi	Vasil'yevichy	52.27	29.80	1879–1894
Werchojansk	Verkhoyansk	67.57	133.85	1884, 1886–1893
Wercholensk	Verkholensk	54.13	105.50	1884
Wladikawkas	Vladikavkaz	43.03	44.68	1874–1877, 1879–1893
Wladivostok	Vladivostok	43.12	131.90	1874–1877, 1879, 1881–1894
Zlatoust	Zlatoust	55.17	59.07	1874–1877, 1879–1894



Because the present study considers pressure anomalies independently for each station, no additional reduction of the historical pressure measurements to mean sea level was applied.

110 The historical observing network expanded substantially during the late nineteenth century and covered a large part of northern Eurasia, with particularly dense station coverage in European Russia. For the present analysis, stations were selected to provide broad spatial coverage from eastern and central Europe across European Russia, the Urals and Siberia to the Russian Far East (Fig. 1). Selection was guided primarily by the availability and continuity of observations over the study period and by the aim of maintaining broad longitudinal coverage while avoiding excessive representation of the more densely sampled western part of
 115 the network. The historical and present-day station names, geographical coordinates, and temporal coverage of the digitized monthly observations are summarised in Table 1.

The resulting station distribution remains spatially heterogeneous, with considerably higher station density in European Russia than in Siberia and the Far East. We analyse the observations at their original station locations and do not interpolate the anomaly fields onto a regular grid. Station availability also varies between years, months, and variables because not all stations reported
 120 continuously throughout 1874–1894. For the higher-temporal-resolution analysis, we selected nine stations spanning the network from Libava (present-day Liepāja, Latvia) in the west to Nerchinsk (Russia) in the east. The stations were chosen to provide a broad west–east transect for examining the temporal evolution of temperature and pressure across Eurasia.

2.2 Digitization and quality control

The scanned volumes of the *Annalen* were accessed through the digital collections of the Bayerische Staatsbibliothek in Munich.
 125 The printed meteorological tables have a relatively regular structure, but OCR quality varies between volumes; later volumes, particularly those from 1888–1894, required more extensive manual checking because of typographic differences. The tables were converted into machine-readable form using optical character recognition with ABBYY FineReader and were subsequently checked manually against the original scanned pages. For the present study, this procedure was also supplemented by AI-assisted transcription using ChatGPT (OpenAI). ChatGPT was used to assist with the recognition, extraction, and restructuring of
 130 numerical entries from selected scanned tables, particularly in cases where conventional OCR did not preserve the historical tabular structure reliably. Values obtained through AI-assisted transcription were checked against the corresponding scanned source pages before being included in the dataset. Conventional OCR and direct manual transcription were retained where these approaches provided clearer or more reliable results. Particular attention was given to station identifiers, column alignment, decimal signs, missing entries, and values that appeared inconsistent with neighbouring observations. The resulting dataset
 135 therefore combines conventional OCR, manual transcription, and AI-assisted transcription while retaining direct documentary traceability to the published *Annalen*. A detailed description of the recovery, digitization, and quality-control workflow is provided by Shapiro and Foelsche (2026); the same workflow was applied here to the additional station records included in the extended network.



2.3 Calculation of monthly anomalies

140 Temperature and pressure anomalies were calculated separately for each station and calendar month for the period 1883–1887. The reference climatologies were constructed from the available observations within 1874–1894 while excluding the potentially affected interval from August 1883 through December 1887. For the 1883 anomaly calculation, observations from 1883 were excluded from the reference climatology. When calculating anomalies for 1884–1887, January–July 1883 were retained because these months preceded the climactic eruption of Krakatau in August 1883. The calculation was performed independently for
 145 each station. Each symbol in the anomaly maps therefore represents a value calculated directly from the historical observations at an individual station. As a compact robustness check for the three focus months, the network-median temperature anomaly in April, August, and December 1884 was also ranked against the corresponding network-median values from the available reference years listed in Table 2. For each month, the 1884 network median was calculated using all stations with an available temperature anomaly. The same station set was then used for the reference-year comparison; a reference year was included
 150 when observations were available for at least 75 % of these stations. The reference years therefore differ slightly among April, August, and December because of variations in station data availability.

2.4 Subdaily observations and daily differences

To complement the monthly anomaly fields, subdaily air-temperature and pressure observations were examined at nine stations between November 1883 and December 1884. The original series contain observations reported at 07:00, 13:00, and 21:00.
 155 These subdaily values are retained as a record of short-term variability in the *Annalen* and are shown separately in the Supplement (Fig. S1).

For the daily analysis, the observations at 07:00, 13:00, and 21:00 were averaged to obtain one daily temperature and pressure value for each station, provided that all three observations were available. For each station and calendar month, a climatological mean was calculated from the available observations during 1874–1894. As in the monthly analysis, observations from August
 160 1883 through December 1887 were excluded from the reference period, while January–July 1883 were retained because they preceded the Krakatau eruption. This provided twelve monthly climatological reference values for each station. These values were treated as a repeating annual cycle and assigned to the midpoint of their respective calendar months. A shape-preserving piecewise cubic Hermite interpolation (PCHIP) was then used to obtain a daily climatological reference for each date in the analysed period, November 1883–December 1884. The annual cycle was repeated across year boundaries to maintain continuity
 165 between December and January. For each day, the interpolated reference value was subtracted from the observed daily mean. No temporal smoothing was applied to the daily differences.

The resulting daily values therefore represent differences from an interpolated monthly climatology rather than anomalies relative to a true daily climatology. This distinction is important because the reference for each day is estimated from the surrounding monthly climatological means rather than from a multi-year set of observations for that specific calendar day.



170 3 Results

Here, we examine the monthly evolution during 1884, the first full calendar year following the eruption. We then use daily temperature and pressure differences from a nine-station west–east transect to examine the temporal structure underlying the monthly fields. Finally, we examine April, August, and December anomalies during 1883–1887. April and August represent the pronounced spring and late-summer cooling identified in 1884, whereas December provides a contrasting case of recurrent winter warmth. April and August 1883 are retained for context but are not interpreted as representative of post-eruption conditions. The Supplement contains the original subdaily series (Fig. S1), the complete daily-difference record (Fig. S2), and the full monthly temperature and pressure anomaly fields for 1883–1887 (Figs. S3 and S4).

3.1 Monthly evolution during 1884

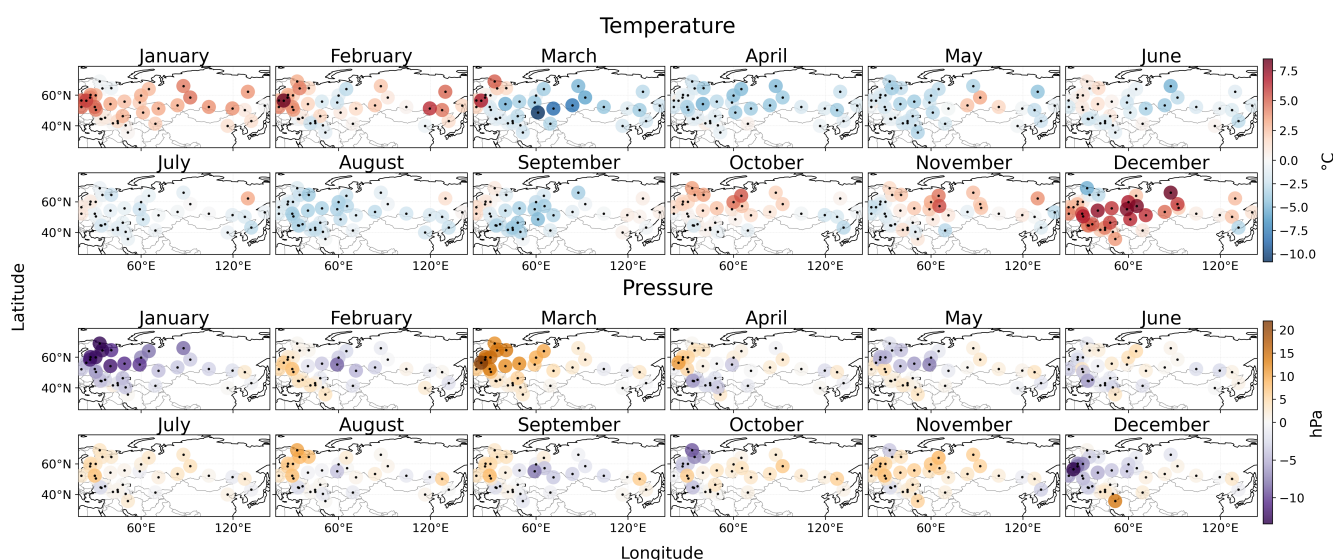


Fig. 2. Monthly air-temperature (top) and station-pressure (bottom) anomalies across the Eurasian station network in 1884. Each panel shows the anomalies at individual stations for the indicated month. The black dots mark the station locations, while the colour of the surrounding circles indicates the value of the corresponding anomaly according to the colour scale. The circle size is fixed for visual clarity and does not represent the magnitude of the anomaly.

The temperature anomalies during 1884 show a pronounced seasonal evolution rather than a persistent, spatially uniform response (Fig. 2). January and February were predominantly mild across western and central Eurasia. By March, negative anomalies occupied much of the central observing network, and in April the cooling became widespread from eastern Europe through western Russia and the Urals into substantial parts of Siberia. Cool conditions remained evident through much of spring and early summer. A second coherent cooling episode occurred in August, extending across a broad longitudinal sector, and negative anomalies remained common over western and central Eurasia in September. Conditions then reversed during autumn,



Table 2. Network-median temperature anomalies for April, August, and December 1884 and their position within the corresponding reference-year distributions.

Month	Network-median anomaly (°C)	Rank	Reference years used
April	−1.50	coldest	1879, 1881, 1882, 1883, 1888, 1889, 1890, 1891, 1892, 1893
August	−1.91	coldest	1877, 1879, 1881, 1882, 1888, 1889, 1890, 1891, 1892, 1893
December	+2.71	warmest	1879, 1882, 1888, 1889, 1890, 1891, 1892, 1893

185 culminating in strong December warmth across European Russia and western Siberia, with local anomalies approaching 10 °C. The network-median ranking supports this seasonal contrast: April and August 1884 are the coldest, and December 1884 the warmest, within their corresponding reference-year distributions (Table 2).

The pressure anomalies varied alongside these temperature changes. January warmth coincided with strongly negative pressure anomalies over a substantial part of western and northern Eurasia. In March, as temperatures shifted toward widespread cooling,
 190 positive pressure anomalies developed over western Russia and adjacent regions. The spring and summer pressure fields subsequently became more heterogeneous, with positive and negative anomalies occurring simultaneously across different parts of the domain.

The widespread negative temperature anomalies of April and August were not accompanied by a pressure anomaly of one sign across the observing network. In contrast, the pronounced December warmth occurred together with predominantly negative
 195 pressure anomalies over much of northern and western Eurasia. This correspondence suggests that atmospheric circulation contributed substantially to the large winter temperature anomalies. Circulation probably also influenced temperatures in spring and summer, but the pressure anomalies varied across the region and do not point to one common circulation pattern behind the widespread cooling.

The magnitude of the local monthly temperature anomalies also requires careful interpretation. Rampino and Self (1982)
 200 estimated that the large-scale surface cooling following Krakatau was of the order of a few tenths of a degree, whereas monthly anomalies at individual stations in our dataset often reach several degrees. The large local anomalies therefore cannot be interpreted as a direct measure of volcanic cooling and are likely dominated by regional weather and atmospheric circulation, with any volcanically forced temperature response being considerably smaller.

3.2 Daily differences along the west–east station transect

205 To examine the temporal structure underlying the spring cooling, late-summer cooling, and December warmth seen in the monthly 1884 fields (Fig. 2), Fig. 3 shows the corresponding daily temperature and pressure differences. During March–April, below-reference temperatures recur for several weeks at a number of central and eastern stations, interrupted by shorter warm intervals. Pressure differences change sign and vary among stations, arguing against a single short-lived circulation event as the explanation for the spring cooling.

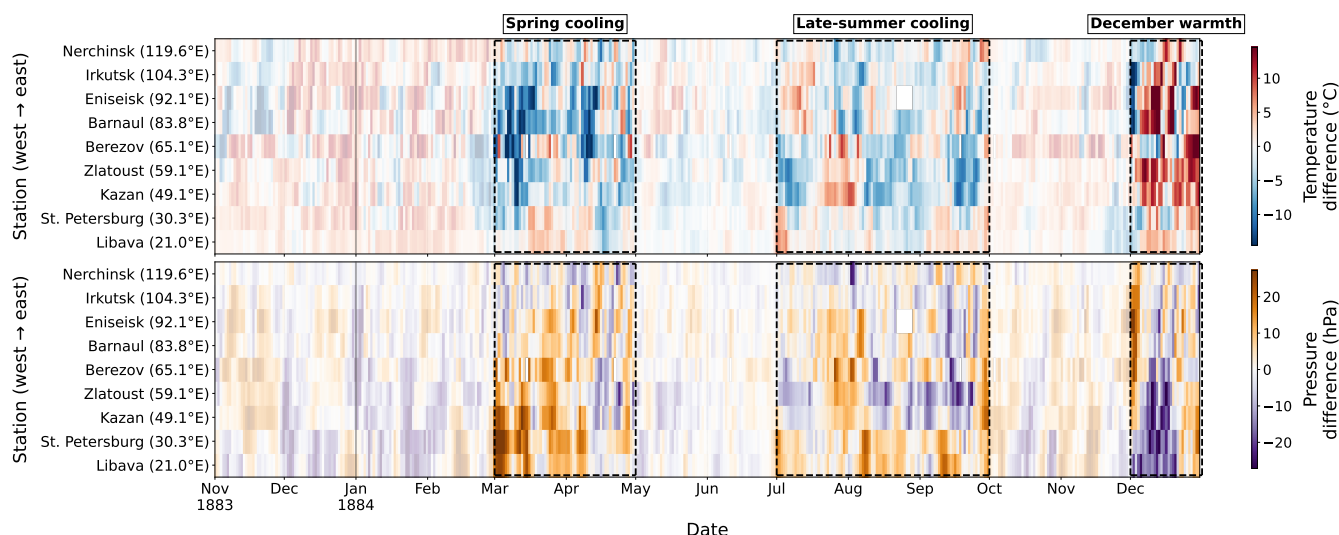


Fig. 3. Daily air-temperature (top) and station-pressure (bottom) differences from the interpolated monthly climatology at nine stations ordered from west to east, from Libava (present-day Liepāja, Latvia) to Nerchinsk (Russia), for November 1883–December 1884. Daily means were calculated from the 07:00, 13:00, and 21:00 observations, and the monthly climatological reference was interpolated to daily resolution. The three intervals —March–April 1884 (spring cooling), July–September 1884 (late-summer cooling), and December 1884 (December warmth)—are outlined by dashed boxes and shown at full opacity. All other dates are displayed at 50 % opacity for context. The opacity adjustment is purely graphical and does not alter the underlying values. Each column represents one day; white cells indicate missing observations.

210 A similar persistence is evident during July–September. Negative temperature differences recur through much of the interval, particularly across the central and eastern transect, while the pressure field remains variable on shorter time scales. The late-summer cooling therefore cannot be reduced to one common pressure regime.

December 1884 is different. Positive temperature differences occur frequently at several central stations, but are interrupted by short-lived cold episodes. Pressure variations are also large, and their relationship with temperature differs among stations. The daily observations therefore support an important role for atmospheric circulation during the December warming while leaving open the possibility of an additional volcanic contribution. The daily record distinguishes persistent multi-day temperature departures from shorter weather fluctuations, but it does not by itself separate circulation effects from volcanic forcing. The full-opacity version of the daily differences is shown in the Supplement (Fig. S2).

3.3 April and August anomalies during 1883–1887

220 To place the spring and late-summer features in a broader post-eruption context, we first examine April and August anomalies during 1883–1887. Figure 4 shows these three months for 1883–1887. April 1883 is pre-eruption, while August 1883 is dominated by pre-eruption observations because the climactic Krakatau eruption occurred only at the end of the month (Self and

Rampino, 1981). These two months are therefore retained for context but are not representative of post-eruption conditions. December 1883, by contrast, represents a fully post-eruption month.

225 April 1884 shows the clearest spring cooling in the sequence, with negative temperature anomalies extending across a broad part of the station network. The April fields in the following years are less spatially coherent and contain a mixture of positive and negative anomalies. A similar but more persistent signal is evident in August. August 1884 stands out as one of the clearest large-scale cool patterns in the analysis, with negative anomalies extending from western Russia through the Urals and across much of Siberia. Widespread cooling is also evident in August 1885, although its spatial distribution differs from that in 1884. By
 230 1886 and 1887, the August fields become more heterogeneous, with substantial regional differences in both sign and magnitude.

The corresponding pressure fields vary substantially between years in both April and August and do not reproduce a common spatial configuration alongside the cool temperature anomalies. The spring and late-summer cooling therefore cannot be attributed straightforwardly to one recurring pressure pattern across the post-eruption years.

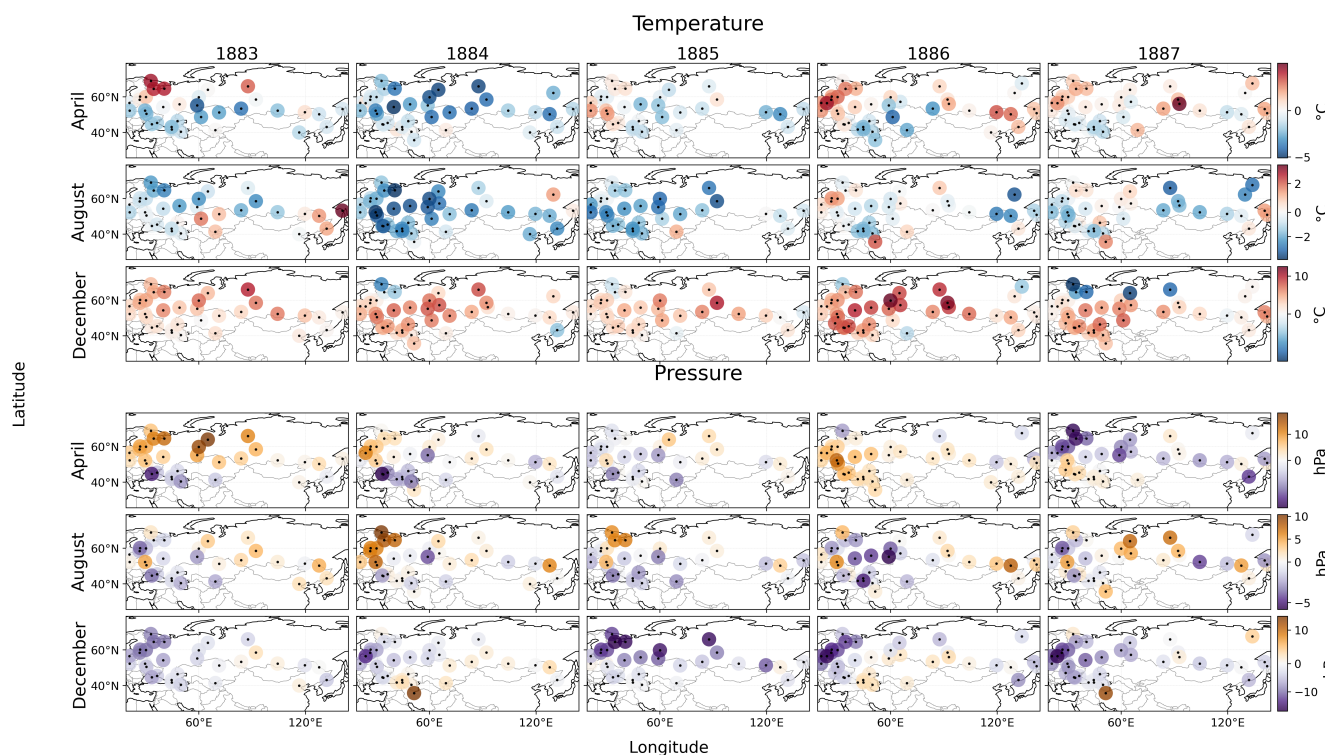


Fig. 4. April, August, and December air-temperature (top three rows) and station-pressure (bottom three rows) anomalies across the Eurasian station network for 1883–1887. April 1883 is pre-eruption, while August 1883 is dominated by pre-eruption observations; these two panels are retained for context. Each panel shows the anomalies at individual stations for the indicated month. The black dots mark the station locations, while the colour of the surrounding circles indicates the value of the corresponding anomaly according to the colour scale. The circle size is fixed for visual clarity and does not represent the magnitude of the anomaly.



3.4 December anomalies during 1883–1887

235 The December sequence contrasts sharply with the predominantly cool April and August patterns (Fig. 4). Positive temperature anomalies dominate much of the network in December 1883–1886, although their magnitude and spatial distribution vary among years; December 1887 is more heterogeneous. Several of the warm Decembers coincide with negative pressure anomalies over western or northern Eurasia, providing a plausible dynamical context for at least part of the warmth. Station pressure alone, however, does not identify the underlying circulation pattern, so the winter anomalies cannot be interpreted as a direct thermal
240 consequence of volcanic aerosol forcing. Together with the April and August fields, the December sequence shows that the post-eruption years were characterised by alternating regional regimes rather than a monotonic response.

4 Discussion

4.1 Seasonal evolution and the role of circulation

The historical observations show that the Eurasian response after Krakatau was strongly season dependent. In 1884, mild
245 conditions in January–February were followed by broad spring and late-summer cooling and then by pronounced late-year warmth. The network-median rankings emphasise this contrast, with April and August 1884 at the cold end of their reference distributions and December 1884 at the warm end (Table 2).

The pressure observations support an important contribution from circulation to this regional structure. The largest winter warm anomalies coincided with substantial pressure departures, whereas the coherent spring and late-summer cooling was not
250 associated with a common pressure configuration across the network or from year to year (Figs. 2 and 4). The daily records lead to the same conclusion: cool periods can persist for weeks while local pressure differences change sign and vary among stations (Fig. 3). Because the several-degree local temperature anomalies are much larger than estimates of the large-scale post-Krakatau surface cooling, regional weather and circulation must account for a major fraction of the observed station-level variability (Self et al., 1981; Rampino and Self, 1982).

255 4.2 Relation to previous studies

The monthly station observations are broadly consistent with the transition described by Polvani and Camargo (2020), who found relatively warm conditions during the first post-eruption winter followed by cooling over the Urals from February into March. The *Annalen* records add month-to-month and daily detail to that picture, showing that the transition developed into widespread March–April cooling and that recurrent negative anomalies continued through parts of spring and summer.

260 The winter interpretation remains uncertain. Large-ensemble and stratosphere-resolving studies indicate that a forced Eurasian winter response can be small relative to internal variability (Polvani et al., 2019; DallaSanta and Polvani, 2022), whereas recent CMIP6 simulations show a multi-model tendency toward polar-vortex strengthening, a positive NAO-like response, and warming over parts of northern Eurasia following Krakatau and Pinatubo (Weber et al., 2026). The historical pressure fields are consistent



with a strong contribution from circulation to the regional winter anomalies, but they do not permit a unique attribution of that
 265 circulation to volcanic forcing.

The response to modern eruptions illustrates the same ambiguity. Following Pinatubo, global surface cooling was only a few
 tenths of a degree, while substantially larger regional anomalies arose as circulation and weather variability modified the
 response (McCormick et al., 1995; Robock, 2000). Models reproduced both continental winter warming and summer cooling
 after Pinatubo (Kirchner et al., 1999; Stenchikov et al., 2002), but later large-ensemble studies showed that much of the observed
 270 winter warming could also arise from internal variability (Polvani et al., 2019). Comparisons among Agung, El Chichón, and
 Pinatubo further demonstrate that major tropical eruptions can differ substantially in aerosol distribution and regional surface
 response (Dhomse et al., 2020; Fujiwara et al., 2020). These modern events are therefore most useful as mechanistic rather than
 exact analogues of Krakatau.

The widespread August 1884 cooling stands out in this comparison. It occurred during a period of substantial Krakatau aerosol
 275 loading (Stothers, 1996; Toohey and Sigl, 2017; Obregón et al., 2020), recurred in August 1885, and was not accompanied by
 a network-wide pressure anomaly of one sign. The daily observations likewise show recurrent below-reference temperatures
 through parts of July–September amid changing pressure differences. This combination is compatible with a broad background
 cooling influence superimposed on regional weather variability, but it does not uniquely identify a volcanic signal.

5 Conclusions

280 Original meteorological observations from a broad Eurasian station network reveal a strongly season-dependent post-Krakatau
 evolution. In 1884, mild January–February conditions were followed by widespread spring and late-summer cooling, with
 particularly coherent negative anomalies in April and August, and then by a pronounced reversal toward December warmth.
 August cooling recurred in 1885, while December warmth was common across much of the network from 1883 to 1886.

The accompanying station-pressure observations support the conclusion that circulation variability was an important component
 285 of these regional temperature changes. Winter warmth was more clearly associated with large pressure departures, whereas the
 spring and late-summer cooling occurred without a common pressure pattern across the network. Daily observations further
 show that cool periods could persist for weeks while pressure differences varied, indicating that these episodes were not simply
 isolated weather events. At the same time, the historical station data do not provide a unique attribution of the cooling to
 Krakatau.

290 The main contribution of the *Annalen* observations is therefore to resolve the spatial and temporal development of the
 post-eruption anomalies directly from contemporaneous measurements. They complement gridded products and seasonal
 averages by combining month-to-month fields with co-located daily temperature and pressure records. The results are consistent
 with a picture in which a relatively small large-scale volcanic forcing is strongly modulated by regional circulation and internal
 variability, and they identify the coherent spring and late-summer cooling episodes as useful targets for further dynamical and
 295 attribution studies.



Code availability. The scripts used for data processing, analysis, and visualization are available from the corresponding author upon reasonable request.

300 *Data availability.* The digitized monthly air-temperature and station-pressure observations used to calculate the anomaly fields in this study, together with the daily and subdaily temperature and pressure observations used for the higher-temporal-resolution analyses, as well as the station coordinates and essential metadata required to interpret the records, are publicly available at <https://zenodo.org/records/22954773>. The archived dataset includes the extended station network analysed in this study, rather than only the station subset presented by Shapiro and Foelsche (2026). The original scanned volumes of the *Annalen des Physikalischen Centralobservatoriums* are publicly available through the digital collections and catalogue of the Bayerische Staatsbibliothek, Munich: <https://opacplus.bsb-muenchen.de/>. The relevant volumes can be found by searching for *Annalen des Physikalischen Centralobservatoriums*.

305 *Author contributions.* AVS conceived and led the study, designed the research, digitized and processed the data, performed the analysis, and wrote the manuscript. UF supervised the work, provided scientific guidance and advice throughout the study, and contributed to the interpretation of the results.

Competing interests. The authors declare that they have no conflict of interest.

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