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Climate effects of the 1883 Krakatoa eruption: Historical and present perspectives

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Abstract

The climatic impact of the Krakatoa eruption in 1883 was intensively studied by scientists at that time and had lasting effects both in volcanology and atmospheric sciences. The theoretical concept of enhanced volcanic aerosol concentration, blocking short-wave radiation and possibly cooling the Earth's surface was first formulated after the eruption. Later studies addressed the relation between volcanic eruptions and zonal circulation in the midlatitudes. A century later, the Pinatubo eruption (in 1991) played a similar role for climate science, demonstrating the importance of stratospheric processes and their coupling with climate near the ground. Here we revisit the Krakatoa eruption from a present-day perspective. Using reconstructed upper-level circulation fields we find that the Krakatoa effects in the first winter after the eruption fit well with the currently accepted mechanism. The data suggest a strengthened polar vortex in the Arctic stratosphere, while Europe experienced a warm winter at the Earth's surface. The second winter does not show this signal anymore, calling for a «life cycle» view of volcanic effects. Results are important also in the context of the current debate on «geoengineering» of the global climate system.

Klimatische Auswirkungen des Krakatau-Ausbruchs von 1883: Historische Sicht und heutige Ergebnisse

Der Krakatau-Ausbruch von 1883 und seine Auswirkung auf Atmosphäre und Klima beeinflussten entscheidend sowohl die Vulkanologie als auch die Atmosphärenwissenschaften. Die Strahlungseigenschaften vulkanischer Aerosole, insbesondere die Streuung der kurzwelligen Strahlung und dadurch ermöglichte Abkühlungseffekte auf das globale Klima, wurden untersucht. Spätere Arbeiten behandelten auch den Einfluss auf die zonale Zirkulation in den mittleren Breiten. Ein Jahrhundert später spielte der Ausbruch des Pinatubo (1991) eine ähnliche Rolle für die Atmosphärenwissenschaften. Dieser Ausbruch demonstrierte die Wichtigkeit stratosphärischer Prozesse und deren Kopplung mit dem bodennahen Klima. In diesem Artikel betrachten wir die Klimaeffekte des Krakatau-Ausbruchs aus einer heutigen Sichtweise. Anhand rekonstruierter Felder der Höhenzirkulation stellen wir fest, dass der erste Winter nach dem Krakatau-Ausbruch gut mit der heutigen Auffassung übereinstimmt. Die Analyse deutet auf einen verstärkten Polarwirbel in der arktischen Stratosphäre hin, während Europa am Erdboden einen warmen Winter erlebte. Der zweite Winter nach dem Ausbruch zeigt kein klares Signal mehr. Die Ergebnisse sind nicht zuletzt im Kontext der aktuellen Debatte um menschliche Eingriffe in das Klimasystem («geoengineering») von Interesse.

Key words: Volcanoes – Krakatoa – climate – reconstructions
Schlagwörter: Vulkane – Krakatau – Klima – Rekonstruktionen

1 INTRODUCTION

Major volcanic eruptions affect climate on a large scale and represent the most prominent natural climate forcing on interannual to decadal time scales. The global cooling induced by large eruptions (Robock, 2000) might temporarily counterbalance global warming trends. In fact, geoengineering methods mimicking a permanent volcanic eruption have been suggested to counter the anthropogenic greenhouse effect (Crutzen, 2006). However, the volcanic effect is more complex than a mere global cooling. Volcanic eruptions alter the atmospheric circulation, the hydrological cycle, stratospheric chemistry, and ocean heat content in a complex way for months to years to even decades after the eruption (Robock, 2000; Gleckler et al., 2006). Studying climatic impacts of volcanic eruptions therefore forces us to look at the global climate as part of the Earth's system (which is an important perspective also for assessing geoengineering methods) und promotes our understanding of this system. It also has a practical aspect: Should an eruption occur in the near future, climatic effects might be predicted.

The current knowledge on atmospheric effects of major eruptions is to a significant extent based on the eruption of Mount Pinatubo in June 1991. Despite the wealth of information (including satellite data) and the large number of studies, the question remains how representative the eruption was and how this compares with previous large eruptions, such as the one of Krakatoa in 1883.

Contrasting the eruptions of Mount Pinatubo 1991 and Krakatoa 1883 (the strongest eruption of the past 150 years) is appropriate because of their similarities: both volcanoes are located near the Equator and both ejected similar amounts of ashes and gases into the atmosphere. Observation-based data sets to study climate effects of the 1883 Krakatoa eruption exist, and a new upper-level data set covering this period has recently been finalised (Griesser et al., 2008). Another point makes the comparison of the two eruptions particularly interesting: Their role in our scientific understanding of volcanic effects. A large amount of contemporary literature, summarising various kinds of observations, is available for the Krakatoa eruption. For instance, colourful sunsets were observed all over the world during almost three years after the eruption (Zerefos et al., 2007). These observations and their interpretations were not only important for the history of atmospheric sciences (Symons, 1888): the works of geologists on the remaining of the Krakatoa volcanic complex built the foundations of modern volcanology (Verbeek, 1884).

In this paper we analyse the climatic effects of the 1883 Krakatoa eruption from a historical and present day perspective. We start with a short description on the volcanic eruption, a summary of what science has learnt from Krakatoa in the 1880s and how the discussion has evolved since. Then we analyse the Krakatoa eruption in a newly available dataset of upper-level fields that were specifically reconstructed for this time period. This serves as a test whether a strengthening of the stratospheric polar vortex due to increased volcanic aerosols (as hypothesised in studies on Pinatubo) can be observed in the reconstructions. We end with brief conclusions on open issues, which concern the life-cycle of the volcanic climate effect.

2 THE 1883 KRAKATOA ERUPTION

In 1883, Krakatoa was an unpopulated island composed of three volcanoes, Danan, Perbuatan and Rakata. It was located in the strait of Sunda (6°6' S, 105°25' E), between the islands of Java and Sumatra (see Fig. 1). Both islands belong to the arc of Sunda, where the Australian plate subducts under the lighter Eurasian plate. This region of the Earth undergoes an important tectonic activity and Indonesia experienced several major volcanic eruptions in its relatively short geological history: Toba (~71 000 years ago), Tambora (1815), Krakatoa (1883) and Agung (1963) are the best-known. These eruptions all had widespread climatic effects: the Toba eruption, with an estimated decrease of global temperature of about 3–3.5 °C likely affected human evolution (Ambrose, 1998). The famous «year without summer» in 1816 is associated with the Tambora eruption.

Three factors contribute to the large climate effect of volcanoes of the arc of Sunda. First, the volcanism associated with subduction zones is a very explosive one, allowing the ejected gases to reach the stratosphere. Secondly, the andesitic to dacitic lavas produced in the subduction zones are enriched in sulphur (in the form of SO_2 and H_2S), which in the stratosphere react to form sulphate aerosols. Thirdly, because the arc of Sunda is located near the equator, the stratospheric aerosols have a long life-time with respect to transport. In fact, the stratospheric aerosol cloud, which is zonally distributed around the whole globe within a few weeks, can spread meridionally over both hemispheres and remain in the stratosphere for 1–3 years before being transported to the troposphere and washed out.

After over 2000 years of silence, the Perbuatan volcano erupted in 1680 leading to devastation of the island's vegetation. On the 20th of May 1883 Perbuatan showed again signs of activity: an 11 km long ash and water vapour column could be seen from Java and Sumatra. During the three following months small eruptions accompanied by earthquakes occurred from time to time. Surprisingly, this bothered neither the Indonesian nor the Dutch colonists: they even organised trips to Krakatoa Island to have a picnic beside the erupting volcano. Albeit the people remem-

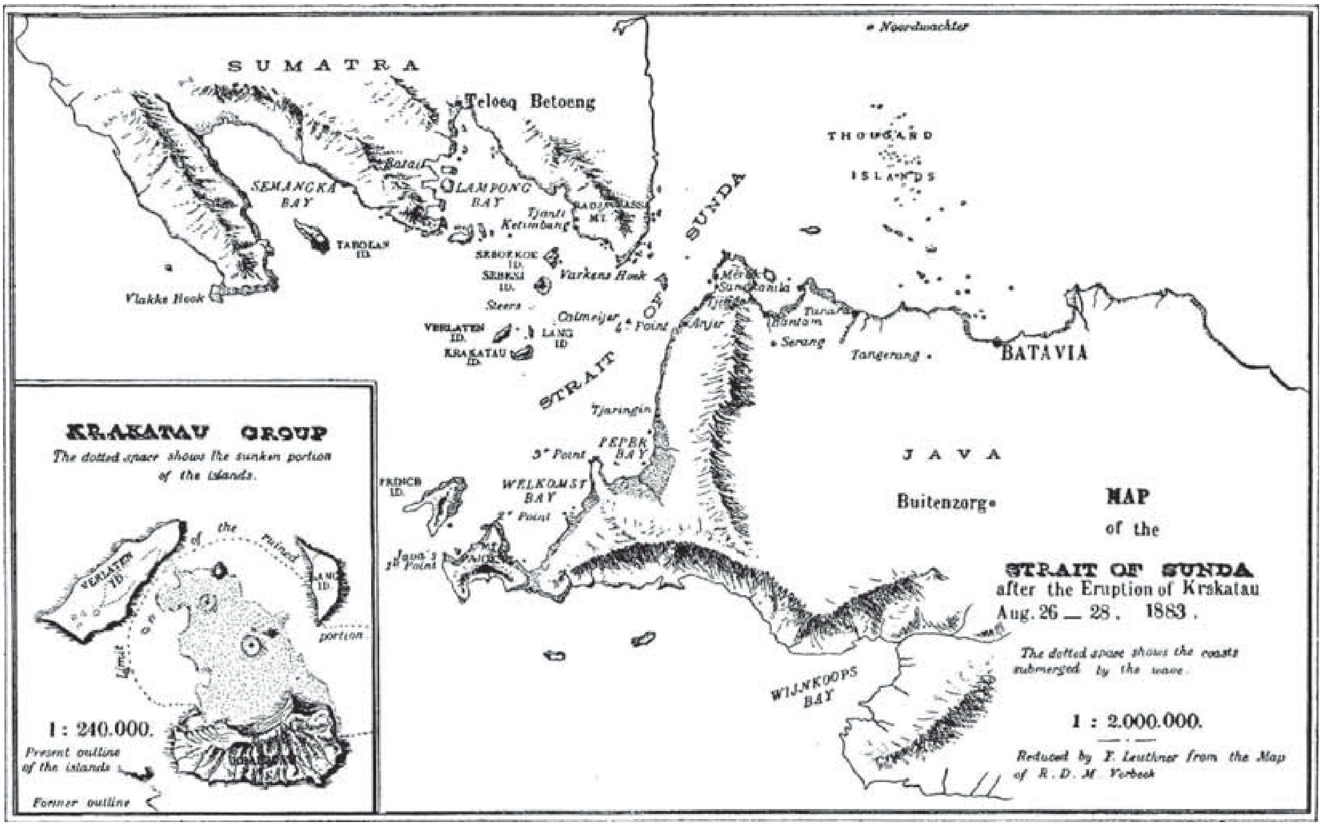

Fig. 1. Map of the Sunda Strait after the eruption of Krakatoa (HURLBUT and VERBEEK, 1887).
Abb. 1. Karte der Sundastrasse nach dem Krakatau-Ausbruch (HURLBUT und VERBEEK, 1887).

bered the destroying Tambora eruption in 1815 and realised similarities, the Perbuatan volcano was considered too small to be dangerous. Only later it was recognised that the three volcanoes were actually three volcanic cones related to the same huge magma chamber. The main eruption occurred on the 26th and the 27th of August 1883 (Fig. 2). The lava and gases were ejected from both the Perbuatan and the Danan volcano to approximately 50 km height. The magma chamber emptied itself very quickly and collapsed, such that only half of the Rakata volcano remained. The coasts of Java and Sumatra experienced severe damages due to tsunamis and pyroclastic flows; more than 30000 people died during the Krakatoa eruption.

The 1883 Krakatoa eruption was important also in terms of perception (of volcanic eruptions and of geosciences) as it was the first eruption that found a media echo all over the world. Telegraphy allowed up-to-date news coverage, and the aerosol cloud fashioned colourful sunsets and moonlight worldwide during more than two years.

3 HISTORICAL LITERATURE

Rogier D. M. Verbeek was a Dutch geologist doing survey in Indonesia at the time of the Krakatoa eruption and was also the first man to dock on the remains of the Krakatoa Island a few months after it. In his first paper about the eruption (VERBEEK, 1884), he was already able to give detailed scientific information on the ejected materials, and compared it with the Tambora eruption. The volume of material ejected by the Krakatoa volcano was about 20 km^3, around ten times less than the Tambora eruption. The darkness caused by the ash rain persisted for three days after the onset of the Tambora eruption, in contrast to only a few hours after the Krakatoa eruption. Verbeek further wrote that the ejected gases and ashes were pushed into the upper-air currents, in 15–20 km height, where they would freeze and then travel as tiny crystals around the globe. He thought that these crystals were the cause of the colourful sunsets, since particles with the same composition as the Krakatoa's ashes were found in the falling snow in Spain.

The eruption had a «peculiar» effect on atmospheric pressure, showing a shock wave travelling around the globe. Corresponding papers were presented in front of the Royal Society and led to the creation of a special committee to investigate causes and effects of the eruption by compiling independent observations, comments and hypothesis from scientists from all around the world (see: The Royal Society, Collection of the Month – Krakatoa Committee, January 2006, http://royalsociety.org/page.asp?id=3987). The report, published in 1888 (SYMONS, 1888), also discussed atmospheric effects. Around half of the observers did not attribute the observed effects (such as colourful sunsets) to the eruption; others developed inventive theories on the phenomena. Interestingly, one observer mentioned the possibility of sulphuric acid being responsible, but this hypothesis was abandoned until the 1970s. Another interesting analysis concerned the propagation of the ash cloud which circled the globe from east to west within about two weeks (see Fig. 3). Though the stratosphere as an isothermal or inversion layer had not yet been discovered, the notion that strong (>30 m/s) upper-level winds existed began to form, which became known as «Krakatoa easterlies» (HASTENRATH, 2007). From hindsight, we can interpret these winds as an easterly phase of the Quasi Biennial Oscillation (QBO). Interestingly, the report mentions that ashes travelled from east to west also after the Tambora eruption, thus pointing to an easterly phase also during this eruption.

The interest in understanding the atmospheric effects of volcanic eruptions (including Krakatoa) was further boosted after the eruption of Mount Katmai in Alaska in June 1912. Here, in particular, the change in solar radiation was analysed. ABBOT and FOWLE (1913) compiled solar radiation measurement and published time series of the solar radiation, sunspot numbers and temperature back to 1880 (see Fig. 4), thus including the Krakatoa eruption. They calculated that solar radiation decreased by around 10% after the eruption (ABBOT and FOWLE, 1913). A few months later, HUMPHREYS (1913) related the ice ages to volcanic eruptions in a fundamental paper. It was already known at that time that the atmosphere can be subdivided into tropo-

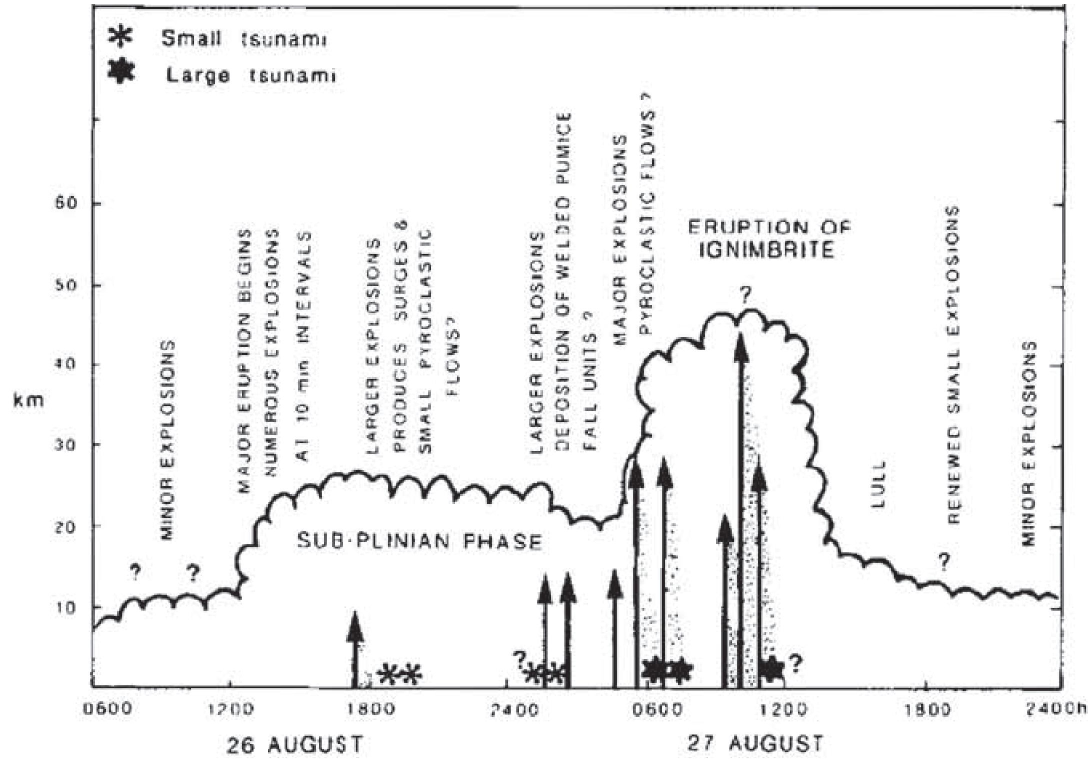

Fig. 2. Chronology of the Krakatoa eruption during its most active phase on 26 and 27 August 1883. In the beginning the eruption was plinian, later Ignimbrit-forming. The thin (bold) asterisks stand for small (large) tsunami events (SELF and RAMPINO, 1981). Reprinted by permission from Macmillan Publishers Ltd: Nature, © 1981.

Abb. 2. Chronologie des Krakatau-Ausbruchs während der aktivsten Phase am 26. und 27. August 1883. Am Anfang war die Eruption plinianisch und in einer zweiten Phase wurde sie Ignimbrit-bildend. Die feinen (fettgedruckten) Sternchen stehen für schwache (starke) Tsunamis (SELF und RAMPINO, 1981). Abgedruckt mit Bewilligung von Macmillan Publishers Ltd: Nature, © 1981.

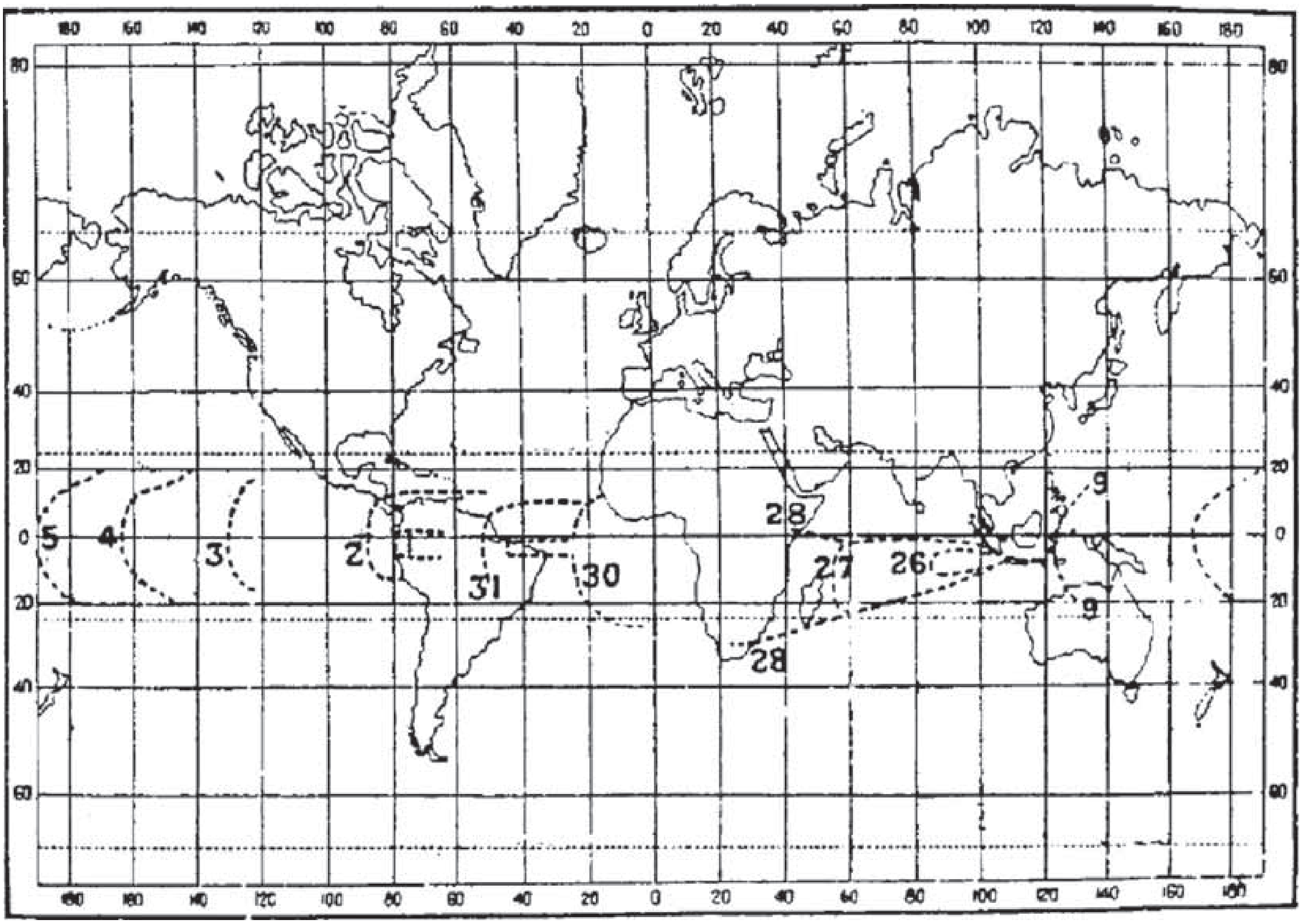

Fig. 3. Observed extent from east to west of the ash cloud after the Krakatoa eruption. Numbers give the dates of observations (26 August to 9 September 1883) (from SYMMONS, 1888).

Abb. 3. Beobachtete Ausdehnung von Osten nach Westen der Aschewolke nach dem Krakatau-Ausbruch. Die Zahlen geben das Datum der Beobachtungen an (26. August bis 9. September 1883) (aus SYMMONS, 1888).

sphere and stratosphere and that the volcanic particles (even if their nature was still unclear) reach the stratosphere. It was also well accepted, that volcanic eruptions tend to cool the global climate because of the absorption of the direct solar radiation by the particles. Based on the measurements of Abbot and Fowle, Humphreys calculated that a global decrease of the solar constant of 10% would correspond to a global cooling of about 6.4 °C (HUMPHREYS, 1913), which is quite an overestimation.

Only later it was recognised that volcanic eruptions can also alter the atmospheric circulation. In a pioneering article on atmospheric circulation over the North Atlantic, DEFANT (1924) defined an index of the zonal flow (similar to the currently used North-Atlantic Oscillation index) which he compared with time series of volcanic eruptions. His analysis revealed that during the winter 1884, following the Krakatoa eruption, the atmospheric circulation was strengthened (corresponding to a positive NAO phase) and the temperatures were exceptionally warm over Europe. A few years later, ÅNGSTRÖM (1935) summarized this in an apt statement: *«Thus a change in the solar radiation reaching the lower air layers, – it may be produced by a change of the solar constant or by a variation of the transmission of the atmosphere – must naturally be expected to produce an increase in the temperature contrast between equator and pole and in this connection also an increase in the atmospheric circulation.»* (ÅNGSTRÖM, 1935)

He estimated the global cooling caused by volcanic eruptions to be of the order of 0.5–1 °C, which is more realistic than the numbers suggested by ABBOT and FOWLE (1913) and HUMPHREYS (1913).

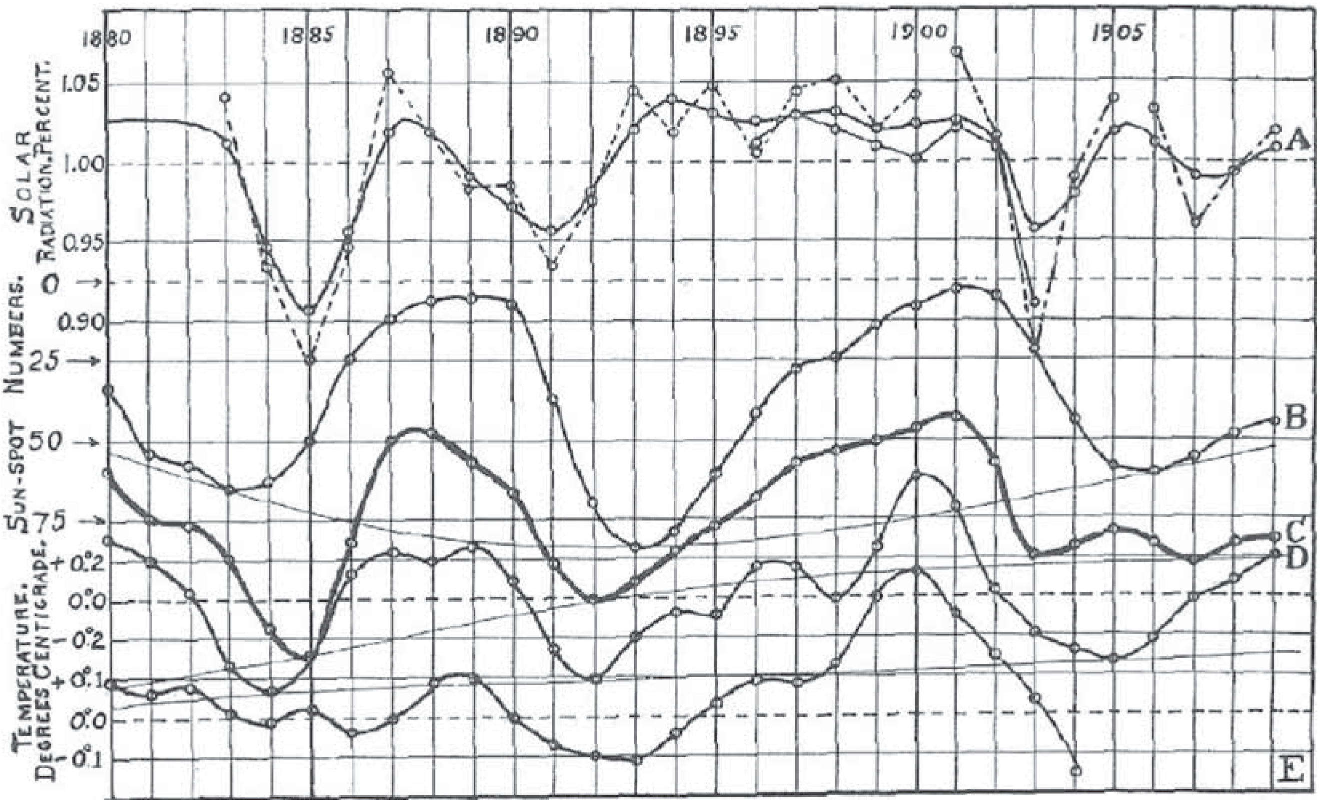

Fig. 4. Solar radiation, sunspot number, and temperature from 1880 to 1910. A. Observed and smoothed annual mean noon solar radiation. B. Wolf's smoothed sun-spots numbers. C. Combined solar radiation and sun-spot numbers. D. Smoothed annual mean departures, United States maximum temperatures (15 stations). E. Smoothed annual mean departures, world temperature (47 stations) (from ABBOT and FOWLE, 1913).

Abb. 4. Normalisierte Sonneneinstrahlung, Anzahl Sonnenflecken und Temperatur von 1880 bis 1910. A. Beobachtetes und geglättetes Mittel der jährlichen Sonnenstrahlung am Mittag. B. Wolfs Sonnenfleckenzahl (geglättet). C. Kombination von Sonnenstrahlung und Sonnenflecken. D. Geglättete Anomalien der jährlich gemittelten Tagesmaximaltemperatur in den USA (15 Stationen). E. Geglättete globale Abweichungen der Jahresmitteltemperatur (47 Stationen), aus ABBOT und FOWLE (1913).

The interest in the volcanic effect on climate was revived again from the 1970s on (LAMB, 1970), in the context of historical climatology, the eruptions of Mt. Agung and later El Chichón and Pinatubo, and in the 1980s discussion about the «nuclear winter». The Krakatoa eruption was dealt with in a book by SIMKIN and FISKE (1983). The latest re-emergence of interest is due to geoengineering proposals such as the one by CRUTZEN (2006), which aim at producing a perpetual volcanic eruption by artificially injecting sulphur into the tropical stratosphere.

4 THE CURRENT VIEW OF VOLCANIC EFFECTS ON CLIMATE

The present day knowledge of atmospheric processes related to volcanic eruptions is summarised in ROBOCK (2000) and was significantly shaped by the eruption of Pinatubo in 1991. It is now understood that the blocking of shortwave radiation reaching the ground (leading to a cooling) makes up only part of the volcanic signal. Volcanic aerosols in the stratosphere also absorb radiation and thus heat up the stratosphere. This leads to differential heating between the (sunlit) tropical-to-midlatitude stratosphere, which after tropical eruptions is rich in aerosols, and the (dark) polar stratosphere during winter. The altered temperature gradient acts to strengthen the polar vortex in the stratosphere. Through mechanisms of downward propagation (BALDWIN and DUNKERTON, 2001), it is believed that the strengthened vortex also strengthens the zonal circulation in the troposphere over the North Atlantic (as found by DEFANT, 1924) and leads to mild winters in Europe. This was also confirmed by means of historical climate reconstructions (FISCHER et al., 2007). However, the mechanisms are still not fully clear. For instance, model studies with a simplified volcanic forcing (reducing total solar irradiance) have produced a similar climate signal over Europe (Yoshimori et al., 2005) without invoking stratospheric heating. In turn, recent model studies with more realistic forcing do not reproduce the main features very well (Stenchikov et al., 2006). One reason for this might be the apparent coincidence of El Niño events and volcanic eruptions (see also Brönnimann et al., 2007), another reason might be the lack of comparability of different volcanic eruptions. Therefore, for a better assessment of the effects, case studies of strong eruptions are necessary.

5 DATA AND METHODS

For the following analyses we use the sea-level pressure (SLP) data set HadSLP2 (Allan and Ansell, 2006), the surface-air temperature data set HadCRUT3v (Brohan et al., 2006) as well as reconstructions of upper-level circulation (Griesser et al., 2008). The reconstructions include temperature and geopotential height up to 100 hPa (i.e., the lower stratosphere) for the extratropical northern hemisphere back to 1880. They are based on principal component regression and were calibrated and validated in ERA-40 reanalysis data (Uppala et al., 2005) in a similar way as described in Brönnimann and Luterbacher (2004). For the period considered here, the reconstructions are based only on data from the Earth's surface (station temperature series and SLP fields). Hence, they represent sophisticated interpretations of surface data rather than original upper-level information. Still, they provide useful information as they indicate which state of the stratosphere is consistent with the surface data. As in Brönnimann and Luterbacher (2004), low reconstruction skill (reduction of error <0.2 determined in split sample validations) is indicated in the figures by grey shading.

We analysed winter (Dec. to Mar., labelled with the year starting in Jan.) and summer (Jun.–Sep.) of the years 1884 and 1885, i.e., one and two years after the eruption, respectively. All fields are presented as anomalies with respect to the period 1880–1909, but after removing other volcanically perturbed winters as well as strong El Niño and La Niña events according to Brönnimann et al. (2007). The remaining winters were: 1880–83, 1888, 1894–96, 1898–99, 1901–02, and 1905–09, the summers: 1880–83, 1887, 1893–95, 1897–98, 1900–01, and 1905–08. Note that due to the shortness of the reference period, no missing values

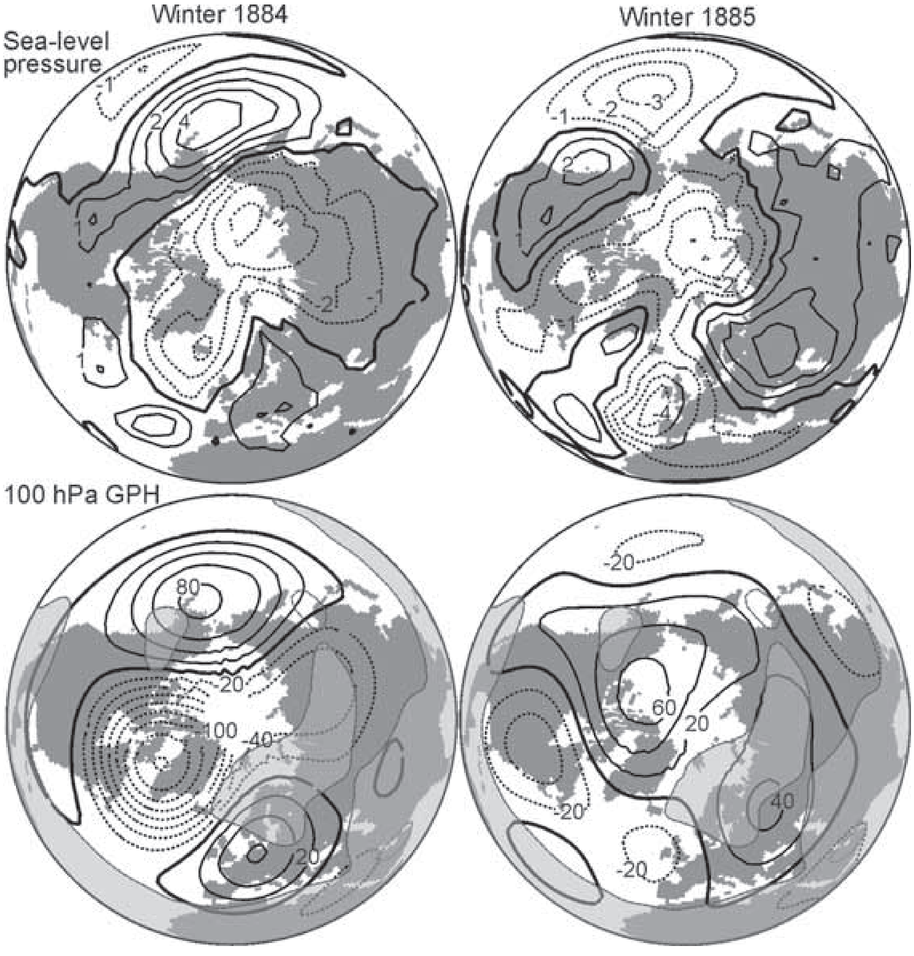

Fig. 5. Anomalies (with respect to a climatology, see text) of sea-level pressure (top) and 100 hPa geopotential height (bottom) during the winters (Dec.–March) of 1884 (left) and 1885 (right). Shaded areas denote low reconstruction skill.

Abb. 5. Abweichungen (bezüglich einer Klimatologie, vgl. Text) des Luftdrucks auf Meereshöhe (oben) und der geopotentiellen Höhe auf 100 hPa (unten) während der Winter (Dez.–März) von 1884 (links) und 1885 (rechts). Schattierungen zeigen Regionen mit niedriger Rekonstruktionsgüte.

were allowed, which reduces the temperature field considerably.

6 RESULTS AND DISCUSSION

Figure 5 shows the fields of SLP and 100 hPa geopotential height for the two winters following the eruption. The SLP field for the winter of 1884 exhibits a pattern resembling the positive mode of the North Atlantic Oscillation. Icelandic low and Azores high were well developed, leading to a strengthened zonal circulation over the Atlantic. Over the Pacific, in contrast, the Aleutian low was weaker than normal. The stratospheric reconstructions point to a strong polar vortex, with a shift of the vortex centre towards Greenland. Surface air temperatures (Fig. 6) show a pronounced winter warming over Europe during the first winter and low temperatures in North America. The second winter was different in many respects. Over the North Pacific, the Aleutian low was strengthened, which could have been due to a moderate El Niño event. The SLP anomaly in the Arctic basin was similar as in the previous winter, but the pressure distribution over the North Atlantic was different, with

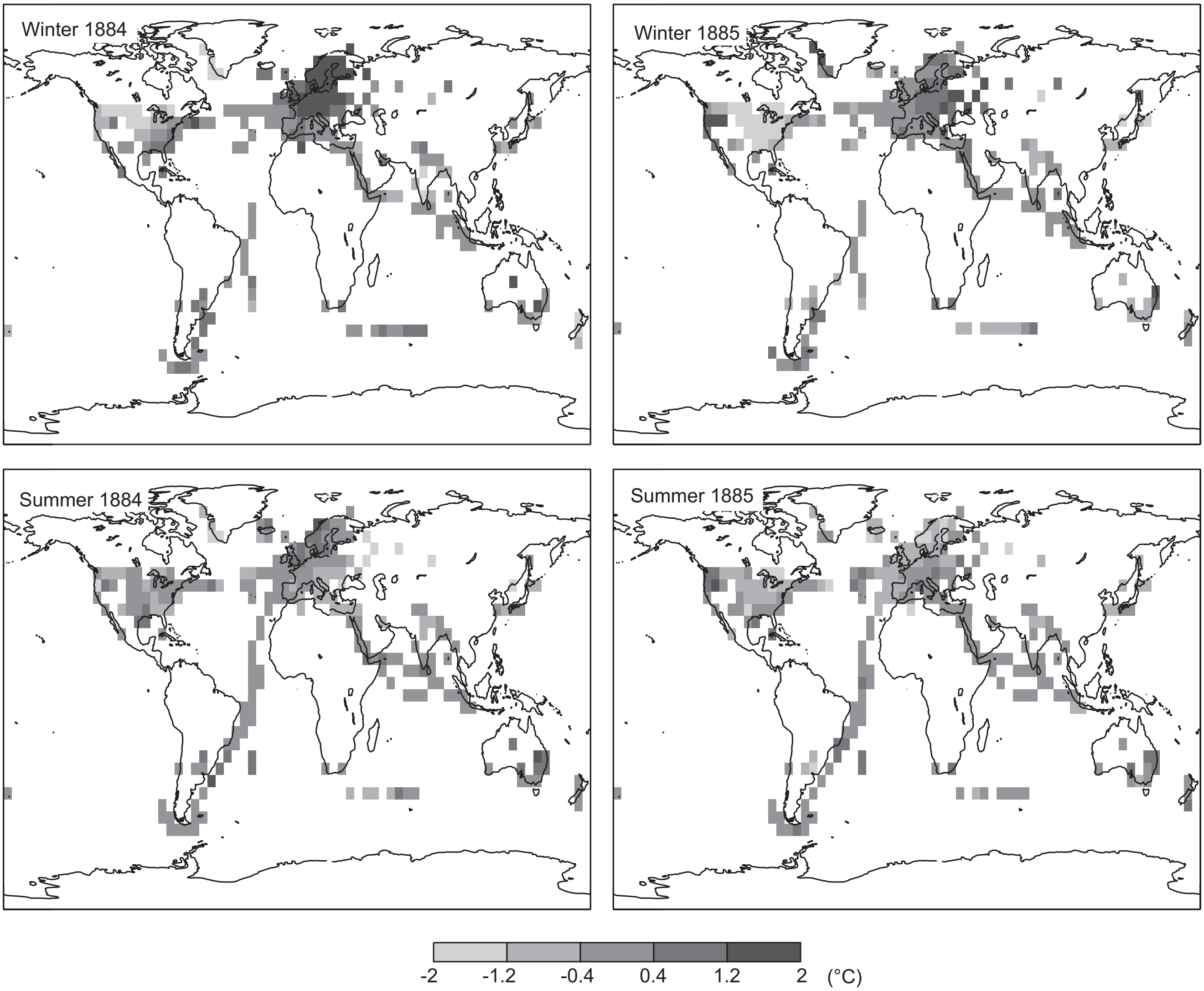

Fig. 6. Anomalies (with respect to a climatology, see text) of surface air temperature during the winters (Dec.–Mar, top) and summers (Jun.–Sep., bottom) of 1884 (left) and 1885 (right).

Abb. 6. Abweichungen (bezüglich einer Klimatologie, vgl. Text) der Lufttemperatur am Erdboden während der Winter (Dez.–März, oben) und Sommer (Juni–Sept., unten) von 1884 (links) und 1885 (rechts).

pronounced negative anomalies over the Bay of Biscay and near-neutral conditions with respect to the North Atlantic Oscillation. Temperatures in Europe were above climatological values, but by much less than the year before, while North America was still cooler than in the reference climatology. Surface air temperature anomalies in summer show a slight cooling in both years.

The pattern found in observations and reconstructions during the first winter after the Krakatoa eruption is very similar to the one observed after the Pinatubo eruption and hence supports a volcanic winter effect via the stratosphere. The aerosols likely strengthened the meridional temperature gradient in the stratosphere, giving rise to a strong vortex, which via downward propagation might have acted on the tropospheric circulation and caused a strengthened zonal flow over the North Atlantic and a winter warming of the European continent. Similarly, surface air temperature in summer exhibits a slight cooling, as is expected from the reduced short-wave radiation. The second year, however, shows a different pattern. We find no sign of the volcanic effect described above (although European winter temperatures remain high; see also FISCHER et al., 2007, who found significant volcanic effects also in the second winter after an eruption). There are at least two possible causes: The volcanic effect decreases in strength and other processes (i.e., variability) take over, or the volcanic effect itself changes as it undergoes a life cycle. The former might also be related to a weaker than commonly expected Krakatoa forcing. Its lavas were much poorer in sulphur (150 ppmv) than those of Tambora (380 ppmv) and Agung (800 ppmv) (RAMPINO and SELF, 1982). The latter might be related to the stratospheric aerosol distribution, which certainly changed from the first to the second winter, or an oceanic response (including possible volcano-triggered El Niño conditions). In any case, if this is a life cycle effect, then it is important with respect to geo-engineering projects.

7 CONCLUSIONS

The major tropical volcanic eruptions Krakatoa and Pinatubo have both considerably advanced our understanding of the climate system. After the Krakatoa eruption (1883), radiative properties of volcanic aerosols, blocking short-wave radiation and possibly cooling the Earth's surface were established. First ideas on effects on the mid-latitude zonal circulation, published 40 years later, also had their seeds partly in the Krakatoa eruption. A century later, the Pinatubo eruption (in 1991) played a similar role for climate science, demonstrating the importance of stratospheric processes and their coupling with climate near the ground. Revisiting the Krakatoa eruption using newly available stratospheric reconstructions confirms that Pinatubo might be, after all, quite representative for strong tropical eruptions. This is especially true for the first year of the eruption and might help to understand past climate variability, to assess climate models, or to predict climate following future volcanic eruptions. However, further studies are necessary to more fully analyse the possible «life cycle» of volcanic effects (already hinted at in historical work, see DEFANT, 1924). This is particularly important with respect to geoengineering applications.

8 ACKNOWLEDGEMENTS

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