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VOLCANIC ERUPTIONS IN ICELAND — HISTORICAL EFFECTS AND FUTURE FORECASTS

INTRODUCTION

Volcanic eruptions have long been considered a possible cause of considerable changes of weather and climate. Over 2000 years ago, Plutarch and others (FORSYTH 1988) suggested that the Etna eruption of 44 BC shaded the sun, causing cooling and a subsequent decrease in the harvest, resulting in famine in Rome and Egypt. In the XVIII century, after the eruption of Lakagigar (Laki) FRANKLIN (1784) suggested that a very cold summer and a severe winter in 1783/1784 might have been caused by the Icelandic eruption. HUMPHREYS (1913) was the first to relate long cool weather periods to the radiation effect of stratospheric aerosols. However, he did not posses long enough data series to evaluate that relationship. A large number of studies have now been published describing the influence of volcanic eruptions on climate (LAMB 1970, TOON and POLLACK 1980, TOON 1982, ASATUROV *et al.* 1986, KONDRATYEV 1988, ROBOCK 1989). One of the most interesting is the publication of ROBOCK (2000). He presented a thorough and complex characterization of the influence of volcanic eruptions on climate change, including a review of the methods used in current research on this topic.

In a number of publications, the eruption of the volcano Tambora in 1815 is regarded to be the largest in recent times. The effects of that eruption could be discerned everywhere on Earth. Enormous amounts of dust rose into the stratosphere, the eruption column reaching over 43 km (OPPENHEIMER 2003). Small particles of volcanic ashes stayed at a height of 10-30 km above the Earth's surface for a few months to a few years (STOTHERS 1984), causing a strong radiation effect on the global scale. In the years following that eruption, a decrease of the average annual air temperature was observed. The year after the eruption was called the year without a summer (STOMMEL and STOMMEL 1983).

The eruption of Pinatubo, Philippines, in 1991 provided a considerable amount of scientific information on the environmental aspects of eruption. In particular, remote sensing provided a large amount of data that allowed the testing of new scientific hypotheses and a better understanding of the relationships between the physical processes involved. Among others, the influence of the eruption of Pinatubo on the Arctic Oscillation was studied (STECHNIKOV *et al.* 2002). A related problem studied in depth was the influence of volcanic eruptions on changes in atmospheric circulation and, in particular, the quasi-two-year oscillations of the equatorial winds (THOMAS *et al.* 2009).

The influence of volcanic eruptions on climate has been widely discussed in the literature. The influence of volcanic ash and gases can be divided into three basic classes: radiation, dynamic and chemical. From the point of view of climate changes, the first two are the most important. Sulphur dioxide, emitted during the early stages of the eruption high into the stratosphere, is as a result of chemical reactions transformed into sulphuric acid aerosols that efficiently diffuse or reflect sun rays, decreasing solar radiation fluxes within its visual spectrum that reaches the Earth surface. This process causes a decrease of temperature in the near-surface atmosphere, and is known as the radiation effect. At the same time, the sulphuric acid aerosols absorb very well the solar radiation within its near-red and sub-red spectrum range, causing the warming of these parts of the atmosphere where they are confined. In the case of volcanic eruptions situated in low geographical latitudes, where the solar radiation is larger, the aerosols more strongly warm up the lower levels of the atmosphere. This leads to an increase in the longitude gradient of temperature in these lower-atmosphere regions. This in turn causes changes in the atmospheric circulation patterns of the Northern Hemisphere. This process is called a dynamic response of the climate system. It is characterised by positive phases of the North Atlantic Oscillation and Arctic Oscillation, with relatively mild winters on the Northern Hemisphere after large volcanic eruptions in lower latitudes. On the other hand, the radiation effect is responsible for very cold summers.

In the case of volcanic eruptions in higher geographical latitudes, the response of the climatic system is rather different. The dynamic effect is not well pronounced, but there is a strong radiation effect present during the warm part of the year (OMAN *et al.* 2005).

In this paper, we shall analyse the mechanisms of transport of toxic particles from Iceland after the eruption of Laki and present possible scenarios of transport for the eruptions of similar or larger magnitude in present-day Europe. Apart from the literature-based discussions we present the analysis of air temperature changes over Europe in the years following Laki eruption and relate them to the volcanic influence. The first section presents the geographical and geological setting of Iceland and the second section gives a short summary of the history of volcanic eruptions in the vicinity of Iceland. The third section discusses the influence of Icelandic eruptions on Europe, with Laki as an example. The fourth section summarises the influence of Icelandic eruptions on the European climate. The fifth section presents the influence of eruptions on the air temperature in Europe and the sixth section describes the possible future scenarios based on the very recent eruption of Eyjafjöll. The last section presents the conclusions.

GEOGRAPHIC LOCATION OF ICELAND AND GEOLOGICAL CONDITIONS

Iceland is situated on that part of the Mid-Atlantic Ridge extending above the sea level, about 1000 km from the Scandinavian Peninsula. It has been built up during the past 16 million years by basaltic volcanism caused by the spreading of the Eurasian and North American plates over the so-called Iceland Hotspot (SAEMUNDSSON 1974). The island's landscape is formed by a system of volcanoes along the rifts (among others, Laki) (Fig. 2, 3), elongated depressions transformed into glacier formations during the Pliocene and nowadays used by rivers and partly occupied by lakes. Spreading along the Mid-Atlantic Ridge causes volcanic activity in the area, accompanied by earthquakes and volcanic eruptions. The highlands and lava plateau are between 700-1000 m a. s. l. and dominate an area covered with erupted lava and volcanic ash. Lowlands form only a small part of the island and are situated at its south and south-west coastal areas. The glaciers form about 12% of the island's surface.

The specific location of Iceland at the junction of tectonic plates is the reason for the high levels of volcanic activity. There are about 130 volcanoes on the main island and surrounding small islands, of which 18 have been active since the habitation of Iceland in 874.

It is estimated that the amount of lava erupted from Icelandic volcanoes during the last 500 years equals half of the total amount of lava erupted in the same time onto the entire Earth surface. It is worth mentioning that the largest amounts of lava outflow in the historic times was during the eruption of volcano Laki that lasted 8 months in the years 1783–1784.

Volcanic activity of Iceland, apart from its location over the Mid-Atlantic Ridge, is also related to the existence of the Iceland

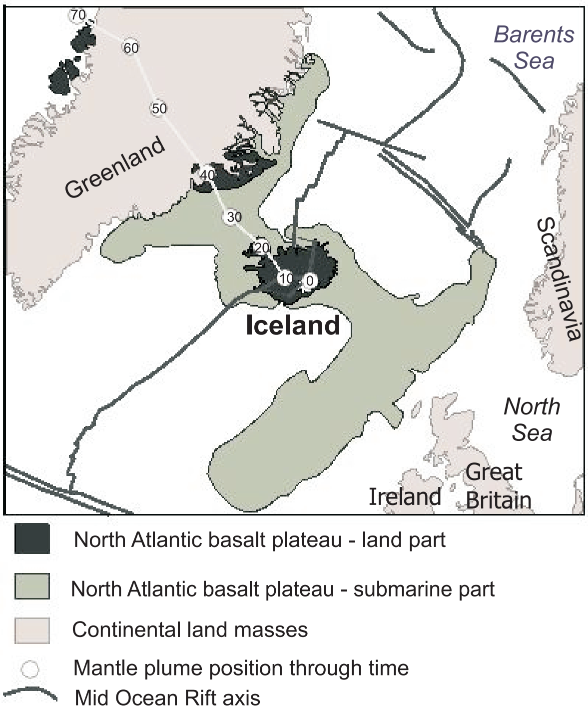

Fig. 1. System of rifts and the location of the Iceland Hotspot (modified from THORDARSON and LARSEN 2007).

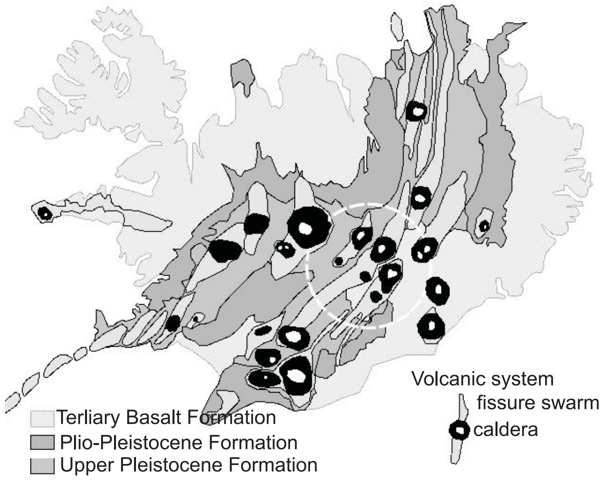

Fig. 2. Distribution of active volcanic systems (large open circle indicates approximate centre of the Iceland Hotspot in the mantle) (modified from THORDARSON and LARSEN 2007).

Hotspot, shown in Figures 1 and 2. Nevertheless, most of the volcanoes are situated along the border of tectonic plates, stretching from the south west of the island to north-east (Fig. 2).

HISTORY OF VOLCANIC ACTIVITY IN ICELAND

Volcanic activity in Iceland varied over time (Fig. 3). The historical records and data obtained from ice cores provide evidence of activity cycles with growing amplitude. The increase in the number of volcanic eruptions may be explained by climatic change. It has been estimated that the volcanic activity has increased 30 times since the last ice age, due to the decrease of pressure of the Earth's surface on the mantle (PAGLI *et al.* 2007).

Volcanic eruptions in Iceland are closely related to the processes in the mantle. Adiabatic decompression of the ascending hot spot results in the formation of magma which may lead to an eruption. Volcanoes covered with ice are the most affected by the changes of pressure in the upper mantle. In Iceland, the changes of volcanic activity are related to ice cover losses. Iceland glaciers have been undergoing intensive melting since 1890 and nowadays their retreat is estimated as 20 mm/yr (SIGMUNDSSON *et al.* 2010). Since the XIX century, the ice cover in Iceland has decreased in volume by 10%.

The effect of pressure on the lower part of the Earth's crust depends on the spatial scale of the area from which the ice cover disappears. The decrease of ice cover of a range of few kilometres has influence only on the volcanic systems of the Earth crust.

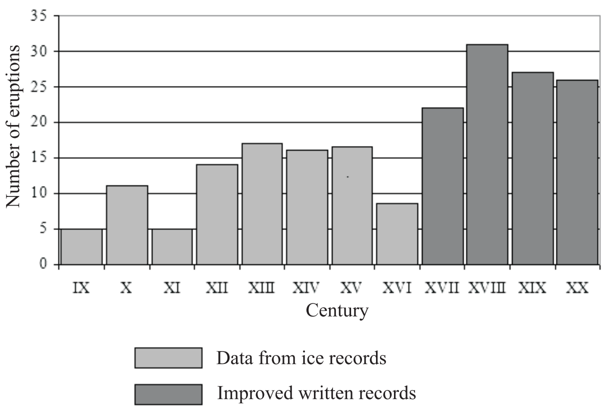

Fig. 3. Frequency of eruptions of Iceland volcanoes in the past (THORDARSON and LARSEN 2007).

In the case when the range of the area where from ice has disappeared is larger than few tens of kilometres, deeper layers of the Earth's interior are affected, including also the mantle (SIGMUNDSSON *et al.* 2010). Present research concentrates on models that could help in better understanding of these processes.

Regarding the deeper layers of the Earth's interior, the models estimate that since 1890 a large amount of magma has been generated, with the rate of 0.014 km^3 per year (SIGMUNDSSON *et al.* 2010). This amount of surplus magma may result in an increase of volcanic activity in the region. Therefore we might soon witness more frequent eruptions of higher intensity.

Research on the periodicity of volcanic eruptions in Iceland has been performed by many scientists, including Prof. Larsen from the University of Iceland in Reykjavik. With his team, he studied lava samples, ice cores and historical records and showed the existence of cycles of low and high volcanic activity in Iceland (LARSEN *et al.* 1998). High activity periods are accompanied by an increased number of earthquakes that release the pressure formed at the tectonic faults near the island.

The strong periodicity of the activity is related to the pulsation of magma released from the mantle, changes of pressure at the Earth surface caused by the ice melt and geothermal activity.

The team led by Prof. Larsen has shown that in the region of the glacier Vatnajokull with the two most active volcanoes Grimsvotn and Bardarbunga, there are 6–11 eruptions per 40 years, which is considered to be a period of high activity. In comparison, in a period of low volcanic activity, there are a maximum of 3 eruptions per 40 years. The other regions of Iceland show a similar regularity.

Forecasts regarding the changes of volcanic activity in Iceland are very interesting. Thordarson claims that according to the newest observations of volcanic and seismic activity in the region, Iceland is moving into a high activity phase (RAVILIOUS 2010).

THE INFLUENCE OF ICELANDIC VOLCANOES ON EUROPE WITH LAKI AS AN EXAMPLE

Apart from the fact that continental Europe lies at a distance from Iceland, due to the prevailing circulation patterns in the North Atlantic, and particularly during the positive phase of NAO, Europe remains under the influence of air masses from the west, and therefore from Iceland. The last large volcanic eruption in Iceland, in 1783, showed how large an influence such an eruption can have on European countries.

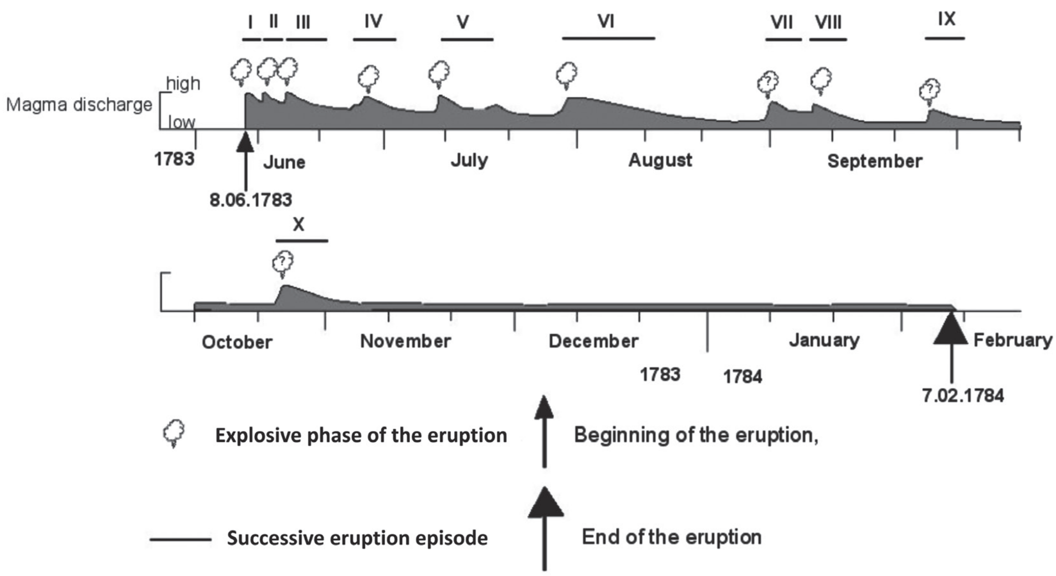

Fig. 4. Episodes of activity of volcano Laki during the eruption in 1783 (modified from THORDARSON and SELF 2003).

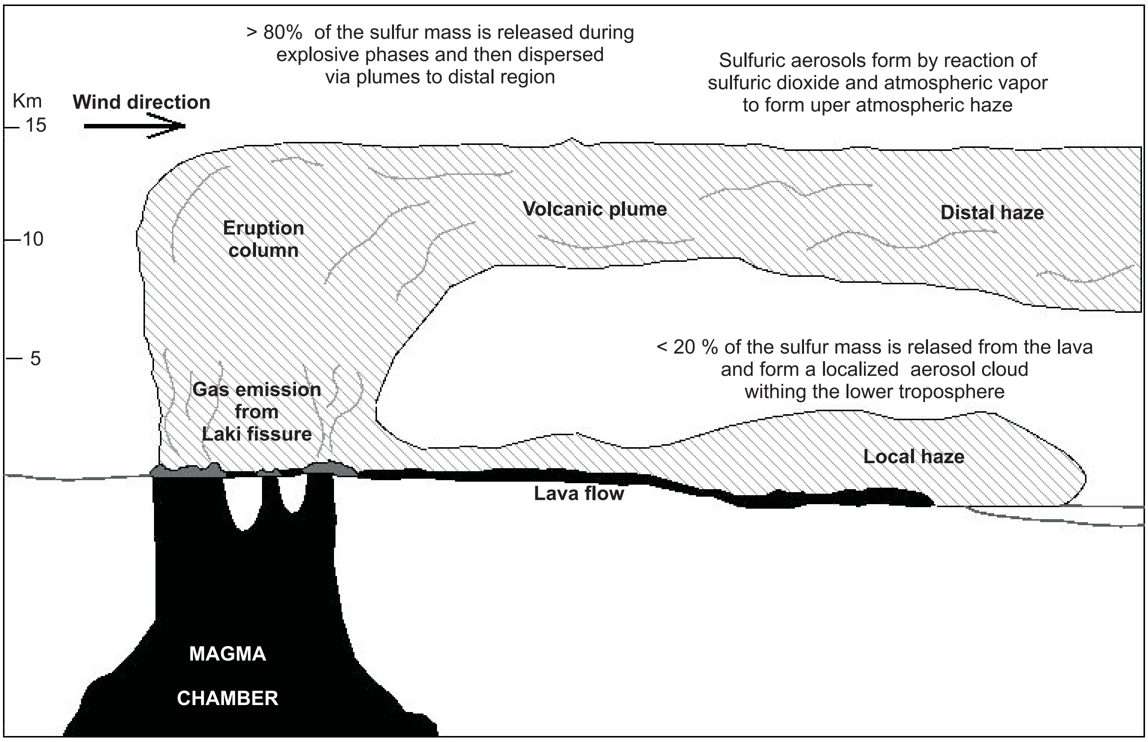

Fig. 5. Dispersion and the range of influence of toxic gases (modified from THORDARSON and SELF 2003).

In 1783, the fissure volcano Laki, neighbouring Grimsvotn, became active. Lava and clouds of ashes were erupting from over 100 craters for eight months (8.09.1783–7.02.1784). During the first five months of the eruption, 10 episodes of volcanic activity were observed, each starting with a short explosive phase followed by longer periods of lava flow (Fig. 4). The volcano showed the most intense activity during the first months of the eruption – in June and in the first half of July. The periods between each episode increased in length with the progress of the eruption. The last period, lasting about 3.5 months, was characterised by slow lava flow and degassing.

The influence of toxic ashes and gases released during the eruption of the volcano had local (degassing of lava in near-surface layer of the atmosphere) and regional (transport to long distances of ash particles and gases, injected into the upper troposphere and lower stratosphere) effects (Fig. 5). The damaging power of lava was limited to the island itself.

Iceland was the region most affected by the eruption. Toxic sulphur dioxide caused the death of the local population and domestic animals, lava and falling ash totally damaged the harvest and the pastures, causing famine and death of about 10 thousand people (about 25% of the population). A large part of the environment was totally devastated, earlier agricultural land was lost forever. The activity caused the death of 76% of the sheep, 76% of the horses and 50% of the cattle (GRATTAN and BRAYSHAY 1995).

The influence of ash and gases was not restricted to Iceland. A large cloud of chemical compounds of volcanic origin, released during the explosive phases of the eruption (Fig. 4), reached heights of 9–13 km, thus reaching the atmospheric stream current formed at these latitudes in higher troposphere and lower stratosphere and was quickly transported to the northern parts of Europe. Sulphur dioxide reacted with water vapour in the atmosphere and formed a vast cloud of sulphuric acid aerosols. Under the synoptic conditions present at that time, the toxic cloud moved south, south-east and reached the lower layers of the atmosphere, embracing most of Europe.

A detailed analysis of the weather conditions prevailing at the time of the eruption and their quantitative assessment was possi-

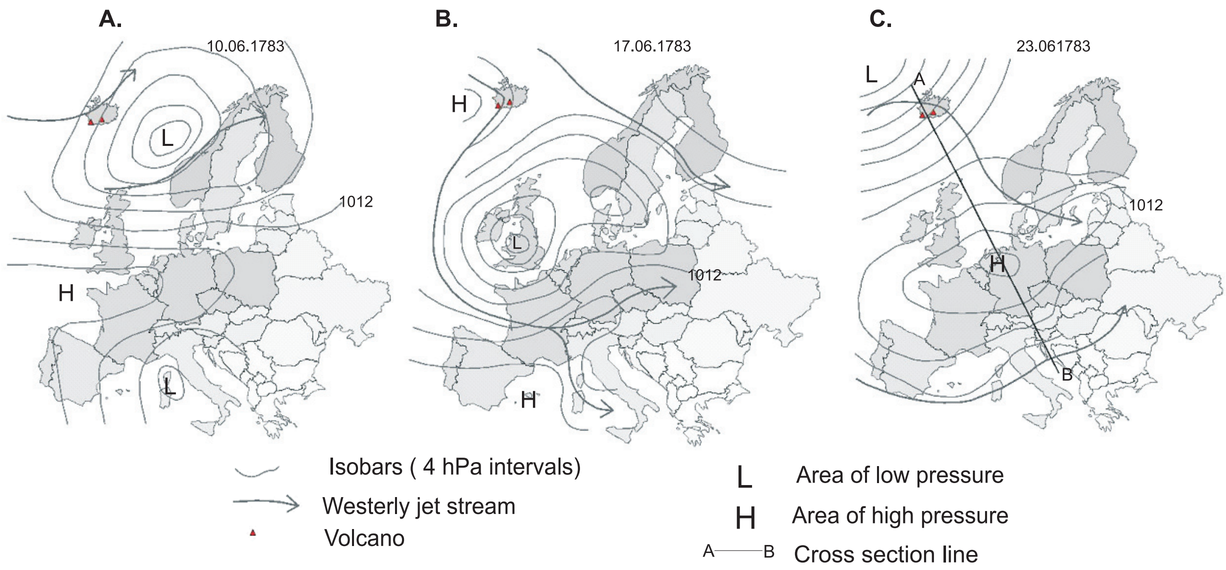

Fig. 6. Reconstruction of synoptic maps from June 1783 showing the weather and circulation conditions over Europe during the period of 8–12.06, 15–19.06 and 22–25.06. (modified from THORDARSON and SELF 2003).

ble thanks to the data published by KINGTON (1988). The synoptic maps that he produced for the 80's of the XVIII century are a valuable source of information allowing the circulation conditions to be traced, and therefore also the routes of the transport of volcano-derived toxic material.

Fig. 6 presents synoptic maps for June, the time when the eruption had the greatest intensity and the largest amounts of toxic material entered the atmosphere. The position of the atmospheric stream that quickly transported ash particles and gases from the eruption over long distances, reaching even the regions of temperate climate, is denoted by arrows.

The aerosol cloud reaching Europe at the end of June (Fig. 6C) met a well developed anti-cyclone on its way. As a result of the convergence of the air stream in the Tropopause, moving over the European continent, sulphuric acid aerosol was sucked into the high pressure cell localised over Europe and transported back to the lower atmosphere by the suspending air masses (Fig. 7). In these times, a strange fog was observed over all of Europe, called the "dry fog".

The appearance of enormous amounts of aerosol under very unfortunate weather conditions (anti-cyclone over Europe) resulted in a dense fog in the near-surface layer of the atmosphere that for many months covered the whole Western Europe. As a result, from the summer of 1783 until the winter of 1784, thousands of people died. The fog was so dense that ships had to be docked in ports of the whole of Europe. The clouds of aerosol resulted in large economical losses for Great Britain.

Extreme weather conditions prevailing after the Laki eruption had their effect on demography (WITHAM and OPPENHEIMER 2004). Looking at the data of death rates in Great Britain (Fig. 8), there are seen two phases of increase in death numbers – in the summer of 1783 (the direct influence of the toxic aerosol) and during the winter of 1784 (very hard winter due to the weather

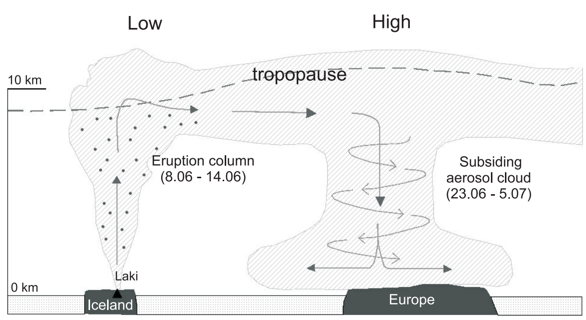

Fig. 7. The simplified cross-cut (A–B from Fig. 6 (C.)) through Iceland and middle Europe showing the dispersion and development of the dust cloud during the first 3-4 weeks of the eruption (modified from THORDARSON and SELF 2003).

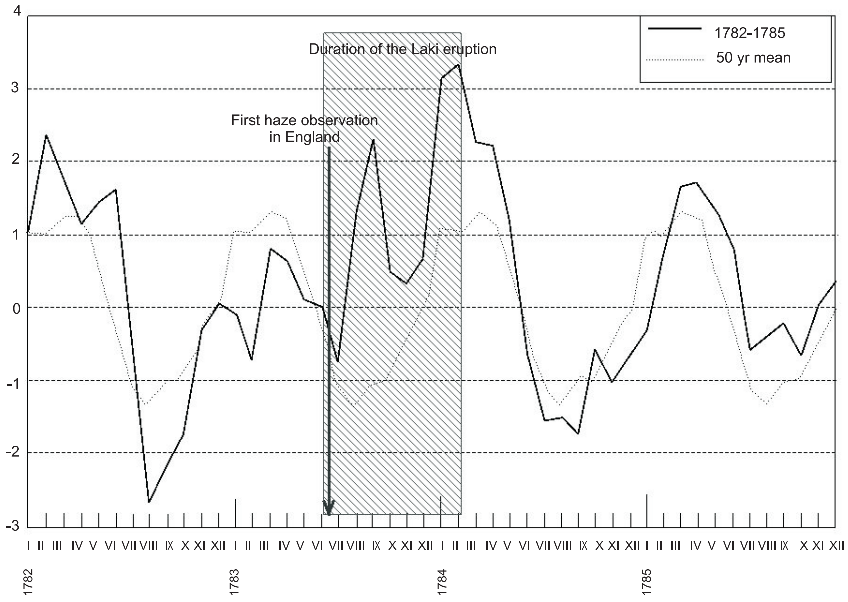

Fig. 8. Comparison of monthly average death rates in Great Britain from the period 1782–1785 with the average monthly death rates from the years 1759–1808 (modified from WITHAM and OPPENHEIMER 2004).

anomaly resulting from the volcanic eruption and the weakening of population due to the break down of the harvest). It is worth noticing the shape of the death rate curve (Fig. 8) averaged over 50 years (dashed line). There is a natural periodicity in the death rate, higher in the winter and lower in the summer times. Therefore, a very high death rate during the summer 1783 confirms the influence of toxic gases on the health of the human population.

In Poland "a strange fog" was observed. Based on observational records from Żagan[1] (PRESUS 1783), the time of its occurrence over Poland can be traced:

- 17.06 1783 the first occurrence of a strange fog, a hygrometer did not register any humidity in the air (further on the observer uses the name dry fog)
- Since 17.06.1783 fog could be observed through the whole July, August, September, October, November with a varying intensity
- Even intensive, big rain had no influence on its presence in the air
- During some days in July sun was hardly visible, in the morning and in the evening it had red colour, and in the middle of the day it was of yellow-green shade
- In September the intensity of the fog increased, colouring nearly the whole sky in the west red
- In October the fog could be observed only in the middle atmosphere (clouds of non-natural red colour)
- On the 5th of November the fog was observed for the last time.

INFLUENCE OF ICELANDIC VOLCANOES ERUPTION ON CLIMATE OF EUROPE

Climate and weather patterns in Europe are controlled by two pressure centres: the Icelandic Low and Azores High. The specific wind direction related to the existence of the Low Pressure Centre above Iceland conditions the characteristic flow of air masses from north-west to south-east, exposing the European continent to the influence of ashes from Icelandic eruptions. When the positive phase of the North Atlantic Oscillation occurs, the intensity of the air flow from the west is increased.

The analysis of the NAO index data from the period 1825–2010 shows that the positive NAO phases are more frequent than the negative phases (Fig. 9). As mentioned, when the positive phase is observed, the ashes and gases originating in Iceland that reached a specific height are more likely to be transported towards the continental

[1]The only location within the borders of present-day Poland that was the part of the palatine network, where regular measurements of the weather were undertaken. The station was active in the years 1783–1795.

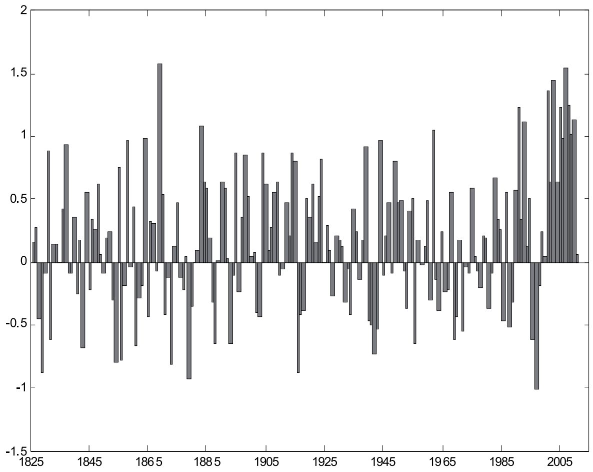

Fig. 9. North Atlantic Oscillation index (NAO) from the period 1825–2010 (Climatic Research Unit (CRU) data: http://www.cru.uea.ac.uk/cru/data/nao/).

Europe. The probability of volcanic ashes reaching Europe related to the probability of the occurrence of the positive NAO phase is estimated to 59%. It is worth noting that in the last twenty years (1990–2010) positive NAO phases have been more frequent. In that period the probability of NAO positive phases was as much as 85%.

It is well known that the direction of wind in the near-surface atmosphere layer depends to large extent on local factors, such as the shape of the terrain, the distance from water reservoirs and the land cover. In the case of Iceland, the characteristic of the wind in the lower troposphere is very important from the point of view of contaminant dispersion on the local scale. Fig. 10 presents the average annual wind direction frequencies for the specific Icelandic locations. The shape of the wind

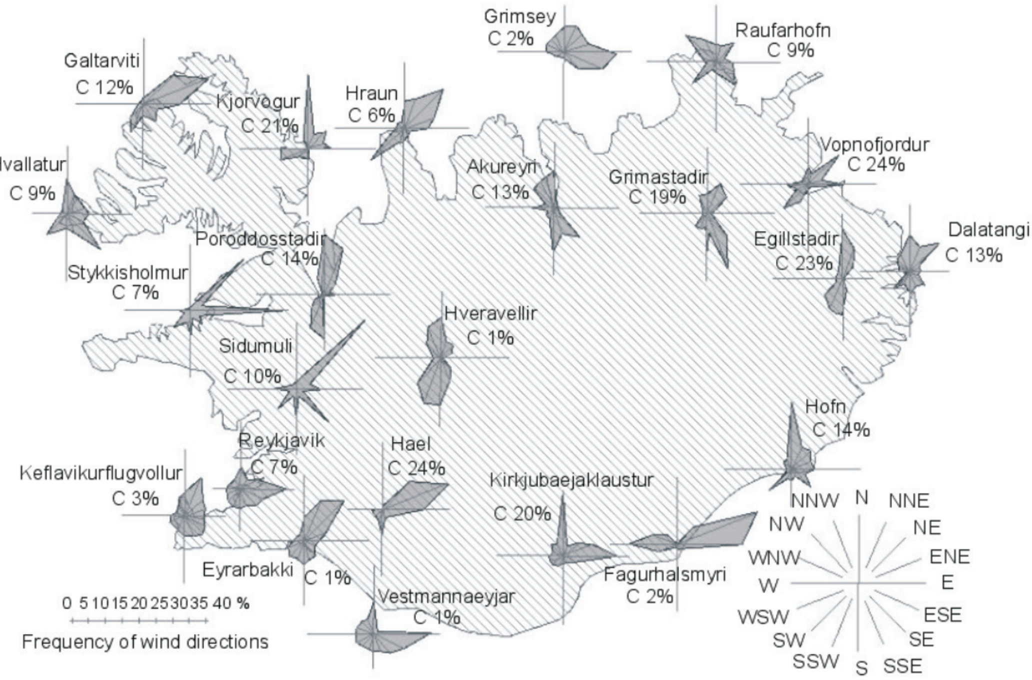

Fig. 10. Wind roses for specific Iceland stations (data for the period 1960–1990) (modified from EINARSSON 1984).

roses clearly indicates the influence of the local terrain characteristics.

The influence of volcanoes situated in the higher latitudes on the European climate is characterised mainly by the so-called radiation effect, depending on the transport of volcanic ashes to the European continent. The volcanic dust either disperses or reflects the sun radiation, limiting the solar energy flux to the Earth's surface. These processes disturb the energy balance in the region, which causes short-time climate changes, best observed in variations in temperature data.

The scale of the influence of Icelandic volcanoes on European climate depends on the amount of volcanic ash and gases that reached the higher layers of the atmosphere and their further propagation.

INFLUENCE OF VOLCANIC ERUPTIONS ON TEMPERATURE

The processes involved in volcanic eruptions and their influence on climate are very complex because they act on a range of climatic factors at different spatial and time scales. In this section we focus on the extraction of the signals related to volcanic eruptions in temperature data from 12 European observation stations. The analysis was performed on the 10-years long temperature observations after the Laki eruption, taking into account the seasonality of the data series. The station in Milano, situated most southerly, was used as a reference point, i.e. it was assumed that the influence of the eruption decreased with distance.

Figures 11 and 12 present average air temperature data for 10 year period (1781–1790) for 11 stations situated nearest to the eruption centre (Laki) that took place in June 1783, and for the reference station in Milan. Annual, summer and winter averages are shown. In the temperature data series, the eruption is most apparent in the short time periods after it took place. There is a clearly visible decrease in the annual average temperature, equal to about 2°C. This result is in agreement with previous studies reported by ANGELL and KORSHOVER (1985).

The minimum temperature occurred in the year after the eruption in stations situated in Northern Europe, nearer to the source of the ash and gases, and in two years after the eruption for the stations situated in Western and Middle Europe. The temperature returns to the values before the eruption in about 4 years after the eruption. It is interesting to note that the variations of average annual temperature at the reference station in Milan are very small.

Looking at the seasonal variations, some patterns can be observed. The summer season is characterised by a considerable decrease of temperature in the years following the eruption. In winter times, the average temperature increases (Figs. 11 and 12).

In summer of the year after the eruption, the temperature was lower by about 1.5°C. This decrease in temperature was maintained for the following 3–4 years, with the minimum mostly in the third year after the eruption. The average temperature for the summer months returned to the pre-eruption level in about five years after the eruption. At the reference station, a small increase of average summer temperature in the years following the eruption was observed.

When analysing the winter season, it is worth noting that the eruption started in summer and until the winter period started, it had already lasted for 6 months. There-

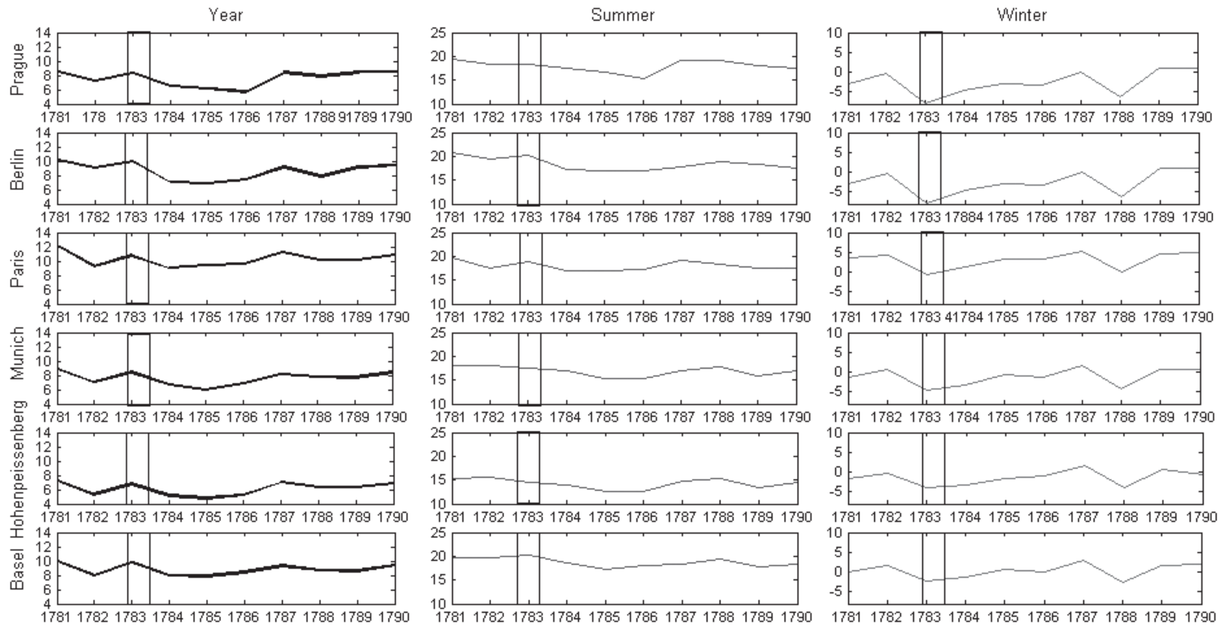

Fig. 11. Annual, summer and winter average air temperatures for the period 1781–1790 for the stations at Prague, Berlin, Paris, Munich, Hohenpeissenberg and Basel.

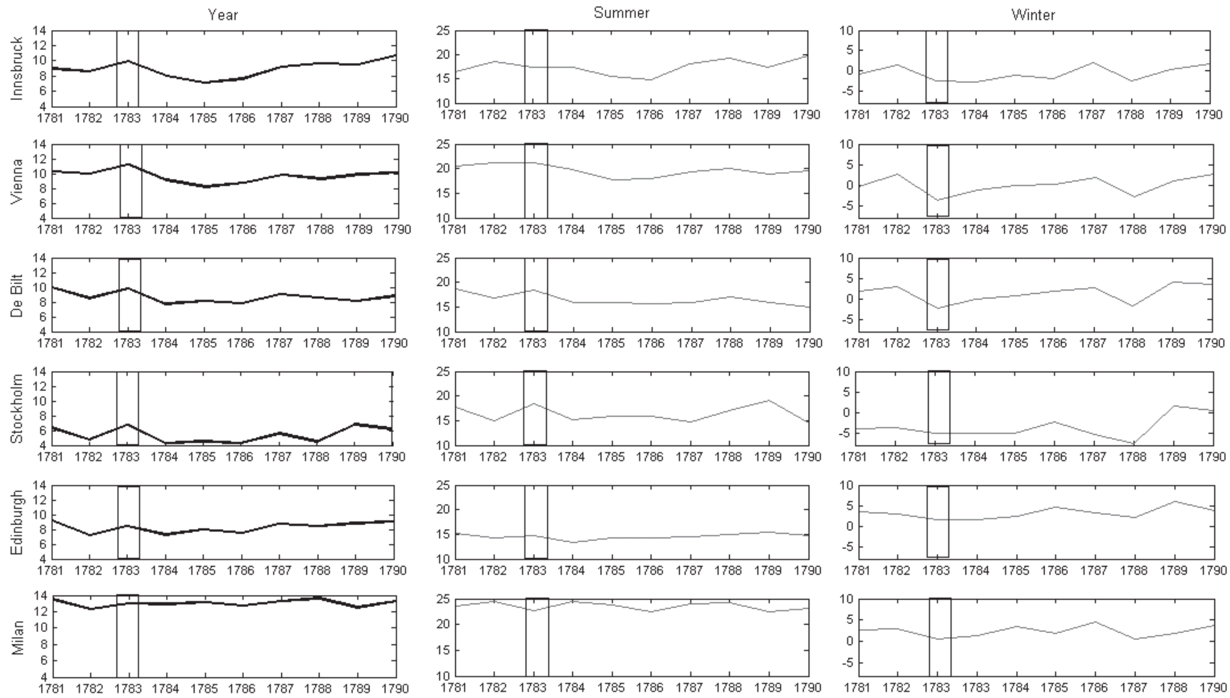

Fig. 12. Annual, summer and winter average air temperatures for the period 1781–1790 for the stations at Innsbruck, Vienna, De Bilt, Stockholm, Edinburgh and Milan.

fore, the climate system was already out of balance when the winter started. Extremely low temperatures were observed during the winter of 1783/1784. They were lower on average by 4.6°C than the values from the winter of 1782–1783. The largest temperature decrease (> 6°C) between two consecutive years was observed at stations situated in middle Europe, whilst the lowest temperature decrease (about 1.4°C) was noted in northern Europe. The cool period initiated in 1783 slowly disappeared during the following four years. The initial temperatures before the volcano eruption occurred were reached in 1787.

We compared differences between the annual average temperature at the stations and temperature averaged over 10 years for the period 1781–1790 for the years after the volcano eruption in order to analyse spatial differences in temperature variations. In the year of eruption, the average annual temperatures at all stations were not much different from those averaged over 10 years.

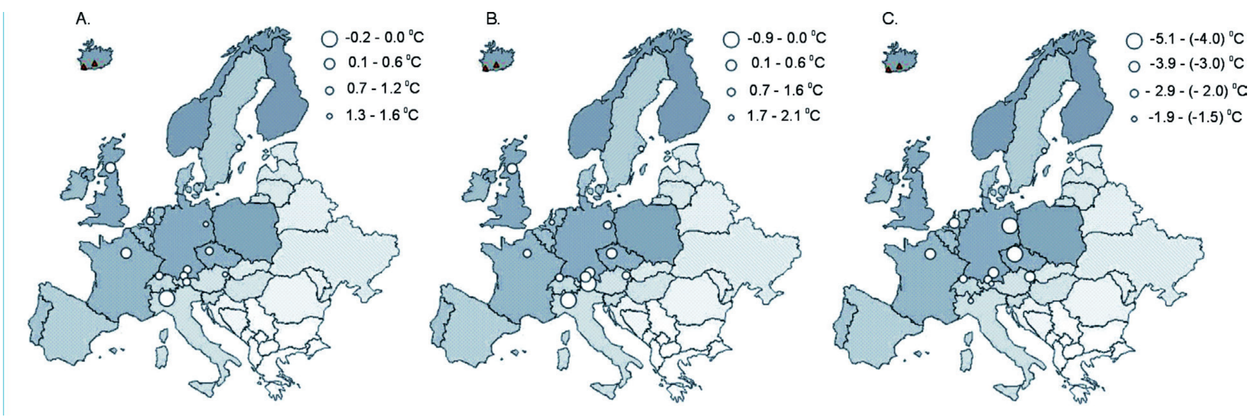

Fig. 13. Temperature anomaly for the period 1781–1790 in relation to 1783 (A. annual average B. summer, C. winter).

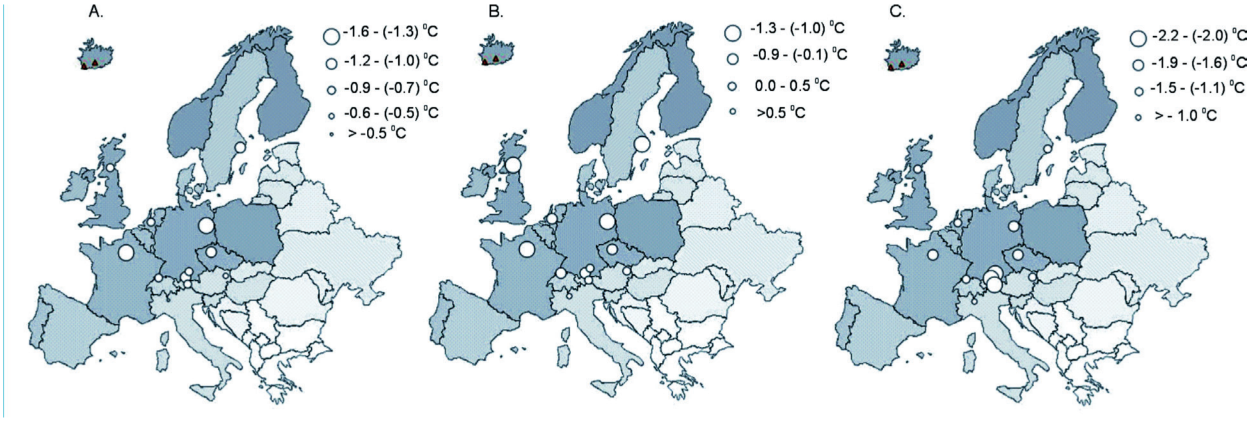

Fig. 14. Temperature anomaly for the period 1781–1790 in relation to 1784 (A. annual average, B. summer, C. winter)

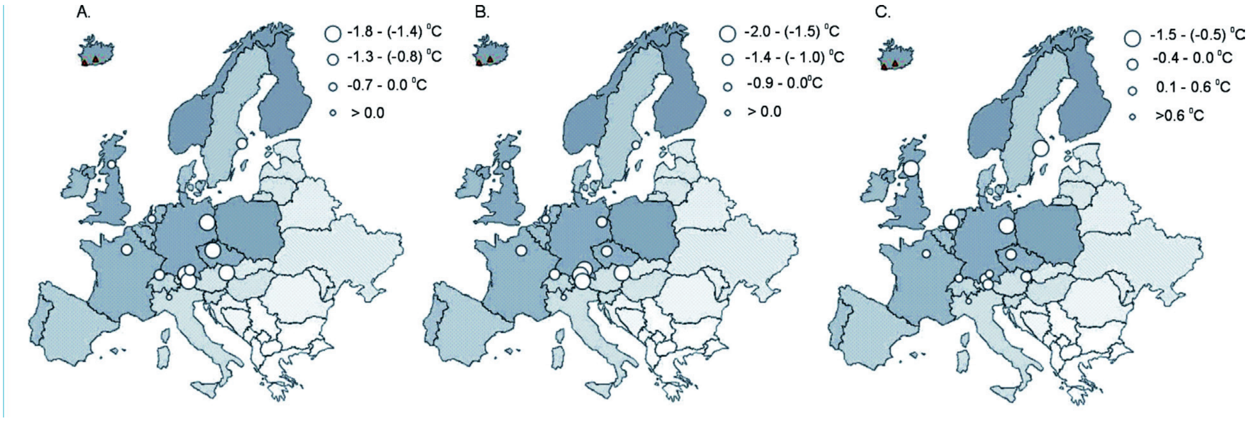

Fig. 15. Temperature anomaly for the period 1781–1790 in relation to 1785 r. (A. annual average, B. summer, C. winter)

At the reference station in Milano, the differences were the smallest (nearly equal to 0°C), and somewhat larger in the Western Europe (Paris and Edinburgh). The largest differences were observed in central and northern Europe. The summer season showed similar patterns. The winter of 1783 was particularly cold. Negative deviations from the average temperature from the years 1781–1790 varied between 5.1°C and –1.5°C. The largest decreases of temperatures (from 5.1°C to 4.0°C below average) were observed in Berlin and Prague. In general, central Europe and continental part of Western Europe were the coldest areas in the analysed region. The smallest decreases of temperature were observed in northern Europe, southern Europe and on the British Islands (> –2°C).

In the years following the eruption (1784, 1785 and 1786), considerable increases of negative deviations from the average temperatures on the annual scale and in the summer periods were observed. The largest decreases of temperatures below the long-term average varied within 2°C. In the summer periods, the largest deviations occurred in 1786 and the largest annual decreases were found in 1785 and 1786. Winter periods showed deviations from the pre-eruption temperatures decreasing with years.

Figures 13–16 present temperature anomalies for the period 1781–1790, related to temperature averages for the years 1783, 1784, 1785 and 1786, respectively. The figures show regional differences in the influence of the Laki eruption on Europe's temperatures. This influence also varies with time; at the beginning it was most pronounced in central Europe and in the continental part of Western Europe. The temperature changes in the region of northern Europe and British Islands reacted with some delay — the largest negative deviation was recorded in Britain three years after the volcano eruption.

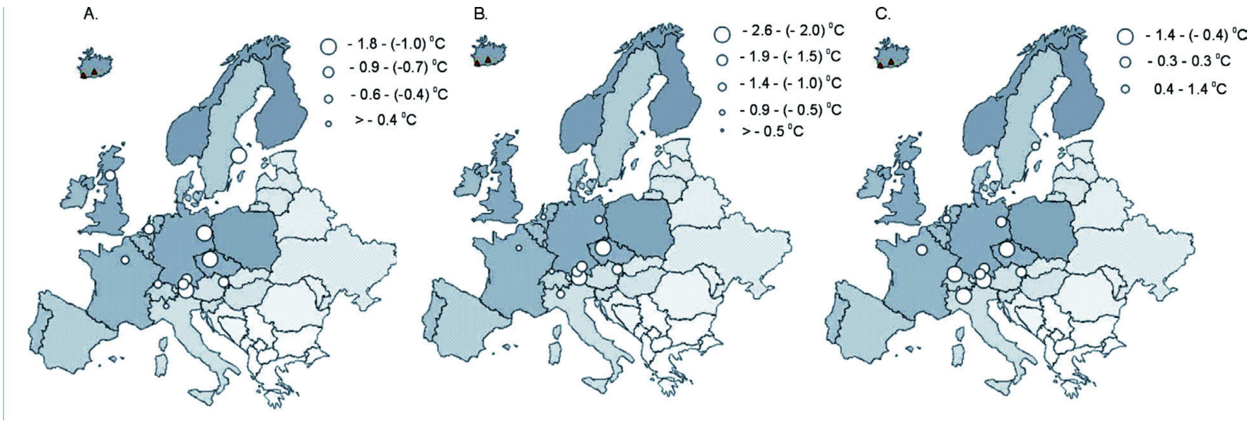

Fig. 16. Temperature anomaly for the period 1781–1790 in relation to 1786 r. (A. annual average, B. summer, C. winter)

This analysis of deviations from the average temperature values for the period 1781–1790 shows that the distance from the eruptive centre had no direct influence on the decrease of temperatures below the 10-years averages. The response of the climatic system of that region remained under the strong influence of circulation patterns from the North Atlantic.

DISCUSSION ON POSSIBLE FUTURE SCENARIOS WITH THE VOLCANO EYJAFJÖLL ERUPTION AS AN EXAMPLE

In the light of recent observations of increased volcanic activity in Iceland, the tragic eruption of Laki in 1783 that caused death of thousands of people in Iceland and also had a tragic influence on people's lives in large parts of Europe, can provide important information on possible future scenarios of volcanic eruptions in Iceland and their influence on Europe.

An example of possible problems was given by the eruption of the Iceland volcano Eyjafjöll in 2010. During historic times (last 500 years), this volcano erupted in 1612 and 1821. The eruption in 1821 (similar to Laki in 1783), lasted a long time – from December 1821 until January 1823. It is worth noting that both eruptions (from 1612 and 1821) were connected to eruptions of Katla, a much larger and more dangerous volcano than Eyjafjöll. The most recent eruption started on the night of 13 and 14 April 2010 and lasted over a few months, with varying intensity. The ash cloud reached a height of 9–10 km at the beginning of the eruption. The mechanism of its transport and dispersion was very similar to that from the Laki eruption. The atmospheric circulation patterns prevailing at the time of the eruption at North Atlantic were very suitable for the transport of pollutants of volcanic origin towards continental Europe. The cloud of ashes and gases quickly reached the northern parts of Europe (similar to the Laki eruption). Within a few hours, it reached large parts of Europe.

In the moderate climate regions of the Earth, the flow of air is mostly laminar (along lines of latitude). In Europe the winds blow mostly from the west. Therefore, the probability of the delivery of pollutants of volcanic origin from Iceland is very high. The synoptic conditions prevailing in a critical time of eruption and the general air circulation patterns are responsible for the transport of ash cloud over European countries, the speed of ash delivery and the extent. Available on-line synoptic maps are a very valuable source of information on possible directions of pollutant cloud propagation. They can be used to estimate the direction and time of delivery of volcanic ash and gases from Iceland.

One can assume that frictional forces are negligible at the heights into which the ash cloud was ejected and the wind at higher layers of troposphere is approximately parallel to the isobars. Under the permanent low pressure centres at Iceland, the air masses will move towards the east, south-east and north-east.

The negative impact of the volcano Eyjafjöll eruption had a slightly different character than that of Laki. The Laki eruption in 1783 was more dangerous to the health and life of the European population. The toxic cloud of aerosols formed due to the volcanic eruption reaching the lower layers of the atmosphere, polluting the natural environment of Europe for a long time. Eyjafjöll caused serious socio-economic problems. Due to present-day social and economic conditions, the scale of its influence was comparatively much bigger.

When comparing the eruption of both volcanoes, one should take into account the socio-economical development that has taken place since the XVIII century. Now we live in a world that is spatially interconnected; what happens in one part of the world influences regions over hundreds of kilometres. During the Eyjafjöll eruption, the real endangering of flights in the region of North Atlantic caused communication chaos that had a negative impact on international trade, aviation and tourism (WILSON *et al.* 2011). The scale of the negative impact can be estimated from the number of people directly employed in the aviation sector. Namely, there are about 5.5 million people working in this sector and it brings enormous income to the global Gross Domestic Product (GDP).Taking into account the chain of interconnections with other industry sectors, among others tourism, it generates 33 million work places. Moreover, air transport has a 33% share of global trade transport. Therefore, the disruptions caused by Eyjafjöll eruption had an enormous socio-economic impact that can be still seen in some branches of the global economy.

CONCLUDING REMARKS

Analysis of the causes of the eruptions of both volcanoes shows that Europe lies within the range of their influence, as well as the influence of other potential eruptions in Iceland. This situation is caused by the large-scale air movement in the region of North Atlantic. In the case of a large volcanic eruption in Iceland, there is a danger of the occurrence of similar ash cloud transport scenario to that which took place during the Laki eruption in 1783, or Eyjafjöll in 2010.

If an eruption similar to Laki took place nowadays, and sulphuric acid aerosols were transported to the lower layers of the atmosphere (Fig. 7), millions of people in Europe would be directly exposed to contact with the aerosol. This situation would be particularly dangerous for old people and children. Apart from the direct health hazard, the negative impact would include also aviation, fuel supplies and critical infrastructure, i.e. those factors that are essential for the functioning of society and the economy (WILSON *et al.* 2011). These include electricity, water supplies, land and air transport and communication.

ERUPCJE WULKANÓW NA ISLANDII — KONSEKWENCJE HISTORYCZNE I PROGNOZY NA PRZYSZŁOŚĆ

Streszczenie

Erupcje wulkanów należą do zjawisk ekstremalnych w istotny sposób zakłócających równowagę ekosystemów, w których żyjemy. Stanowią bardzo ważną naturalną przyczynę zmian klimatu. Reakcje sytemu klimatycznego powstałe na skutek wybuch wulkanu można obserwować w różnych skalach czasowych biorąc pod uwagę odległość od miejsca erupcji, ekspozycję na przeważające kierunki wiatru jak również sam czas trwania tego zdarzenia i jego siłę.

W badaniu wpływu erupcji wulkanicznych na klimat bardzo ważne jest uchwycenie zależności jakie mają miejsce w środowisku przyrodniczym. Interakcje powstałe na skutek eksplozji wulkanu wytrącają system klimatyczny z równowagi. Kluczową kwestią są zmiany w dostawie energii słonecznej docierającej do powierzchni Ziemi, pociągające za sobą zakłócenia w bilansie energetycznym powierzchni globu, czego przejawem są zmiany w średniej temperaturze.

Niniejsza praca stanowi studium przypadku wpływu wybuchu Islandzkiego wulkanu Laki z 1783 r jak również wulkanu Eyjafjöll z 2010. Jest ona próbą rekonstrukcji mechanizmów przenoszenia toksycznych pyłów znad Islandii po wybuch wulkanu Laki, jak również próbą pokazania możliwych scenariuszy wypadków dla erupcji o podobnej bądź większej sile rażenia we współczesnej Europie.

VOLCANIC ERUPTIONS IN ICELAND — HISTORICAL EFFECTS AND FUTURE FORECASTS

Summary

Volcanic eruptions include extreme events that strongly influence the balance of ecosystems. They are also a very important natural cause of climate change. Responses of climate systems to eruptive centre can be seen at different time scales, depending on the distance from the eruptive centre, the dominant wind directions and the duration and intensity of the eruption.

The study of influence of volcanic eruptions on climate should include the interactions between natural processes taking place in the environment. The eruption introduces changes that affect the natural energy balance. The main disruptions are caused by changes in solar energy fluxes reaching the surface of the earth, manifested in changes of average air temperature.

The aim of the paper is to study the influence on the environment of the eruptions of the Icelandic volcano Laki in 1783 and the volcano Eyjafjöll in 2010. We try to reconstruct the mechanisms of transport of toxic gases from Iceland after the Laki eruption and present possible scenarios of the influence of similar scale eruptions on Europe.

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