‘Major’ volcanic eruptions since 1883 and East Asian Monsoon variability

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1. Introduction

The injection of tephra, water vapour and gases into the stratosphere during ‘major’ volcanic eruptions is a possible cause of monsoon variability mainly because of the reduction in solar heating. In the present study, 13 ‘major’ volcanic eruptions defined by a Volcanic Explosivity Index (VEI) of 5 and above shown in ***Table 1*** and located in ***Fig. 1*** are investigated for their role in East Asian Monsoon variability in southern China. The Hong Kong Station on the coast of southern China with continuous temperature and rainfall records since 1884 except for the period 1940-1946 was selected for analysis because the location is sensitive to wind shifts. The annual mean temperature record of the station particularly after the Second World War is however known to be influenced by the heat island effect (Koo, 1990) to increase by about 1°C.

Volcano	Latitude & longitude	Main eruption date	VEI	Volume of tephra	Ranking
Krakatau, Indonesia	6°6’6”S 105°25’22”E	August 27, 1883	6	$2.0 \pm 0.2 \times 10^{10}$ m^3	=2
Okataina, New Zealand	38°7’0”S 176°30’0”E	June 10, 1886	5	2.0×10^9 m^3	10
Santa Maria, Guatemala	14°45’21”N 91°31’6”W	October 24, 1902	6?	2.0×10^{10} m^3	=2
Ksudach, Russia	51°48’0”N 157°32’0”E	March 28, 1907	5	2.4×10^9 m^3	8
Novarupta, USA	58°16’0”N 155°9’24”W	June 6, 1912	6	2.8×10^{10} m^3	1
Cerro Azul, Chile	35°39’12”S 70°45’39”W	April 10, 1932	>5	9.5×10^9 m^3	5
Kharimkotan, Russia	40°7’0”N 154°30’30”E	January 8, 1933	5	1.0×10^9 m^3	13
Bezymianny, Russia	55°58’42”N 160°35’12”E	March 30, 1956	5	2.8×10^9 m^3	7
Agung, Indonesia	8°20’30”S 115°30’30”E	March 17, 1963	5	$>1.0 \times 10^9$ m^3	12
St. Helens, USA	46°12’0”N 122°11’0”W	May 18, 1980	5	1.2×10^9 m^3	11
El Chichón, Mexico	17°21”36”N 93°13’40”W	April 4, 1982	5	2.3×10^9 m^3	9
Pinatubo, Philippines	15°8’0”N 120°21’0”E	June 15, 1991	6	$1.1 \pm 0.5 \times 10^{10}$ m^3	4
Cerro Hudson, Chile	45°54’0”S 72°58’0”W	August 12, 1991	5	4.3×10^9 m^3	6

Table 1 *Chronological list of the 13 ‘major’ volcanic eruptions investigated showing their location, first eruption date, VEI, volume of tephra and ranking. Source: Global Volcanism program.*

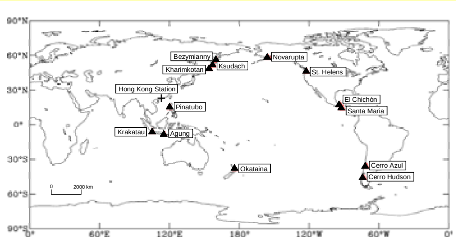

Fig. 1 *Location map of the 13 ‘major’ volcanic eruptions at the Hong Kong Station.*

2. Temperature, rainfall and monsoon onset record

Table 2 provides a summary of annual mean temperatures, annual rainfall and East Asian monsoon onset dates where available during the years of the 13 ‘major’ eruptions. Some of the coldest years have occurred early in the record of the Hong Kong Station while many of the ‘major’ eruptions with one exception were low rainfall years including the driest year since record began in 1963. Furthermore East Asian summer monsoon onset may be earlier or later because of the timing of volcanic eruptions.

Table 3 provides a comparison of annual mean temperature(s) in degrees centigrade at the Hong Kong Station before, during and after the eruption year in 1883, 1902, 1933, 1982 and 1991. It can be seen that the 1883 Krakatau eruption was responsible for the most significant cooling suppressing annual mean temperatures for18 years. This is followed by the 1902 Santa Maria eruption and the 1991 Pinatubo eruption.

Volcanic eruption	Annual mean temperature (°C)	Annual rainfall (mm)	Monsoon onset date[a]	Comment
8/1883 Krakatau	N/A	N/A	-	Year following lowest annual mean temperature on record (21.3°C)
6/1886 Okataina	21.4	1756.9	-	Equal second coldest year on record (21.4°C)
10/1902 Santa Maria	23.0	2477.2	-	-
3/1907 Ksudach	22.3	2377.7	-	-
6/1912 Novarupta	22.2	1625.2	-	Ninth driest year on record
4/1932 Cerro Azul	22.3	2325.9	-	-
1/1933 Kharimkotan	22.5	1585.2	-	Eighth driest year on record
3/1956 Bezymianny	22.6	1649.3	31/5-4/6	Eleventh driest year on record; late monsoon onset
3/1963 Agung	23.3	901.1	25-30/5	Driest year on record, 41.4% of average
5/1980 St. Helens	23.0	1710.6	11-15/5	Seventeenth driest year on record; early monsoon onset
4/1982 El Chichón	22.9	3247.5	31/5-4/6	Second wettest year on record, 145.7% of average; late monsoon onset
6/1991 Pinatubo / 8/1991 Cerro Hudson	23.5	1639.1	5-9/6	Tenth driest year on record, 75.1%; late monsoon onset

N/A – not available; a Commencement of East Asia summer monsoon after Wang et al. (2004).

Table 2 *Mean annual temperature and annual rainfall at the Hong Kong Station and East Asian summer monsoon onset during the year of the ‘major’ volcanic eruptions shown in* ***Table 1****. The average mean annual temperature and average annual rainfall is 22.62°C and 2227.9 mm.*

Volcano(es)	Month and eruption year	AMT before year	AMT during year	AMT after 1 year	Difference from eruption year	AMT after 2 years	Difference from eruption year	Number of years with successive lower AMT
Krakatau	8/1883	22.6[b]	N/A	21.3	-1.3[c]	21.6	-1.0[c]	18
Santa Maria	10/1902	22.3	23.0	21.9	-1.1	22.0	-1.0	11
Kharimkotam	1/1933	22.3	22.5	21.9	-0.6	22.4	-0.1	3
El Chichón	3/1982	23.1	22.9	23.0	+0.1	22.5	-0.4	3[d]
Pinatubo / Cerro Hudson	6/1991 & 8/1991	23.1	23.5	22.8	-0.7	23.1	-0.4	2

AMT – Annual mean temperature; b – Annual mean temperature in 1880 (Peterson and Vose, 1997); c – 1880 and d – after second year.

Table 3 *Comparison of annual mean temperature(s) in °C at the Hong Kong Station in 1883, 1902, 1933, 1982 and 1991 unless specified. The influence of the heat island effect on the annual mean temperatures of the Hong Kong Station before the Second World War is not expected to be significant.*

The annual rainfall of the 12 years of volcanic eruptions shown in ***Table 2*** has included the driest, eight driest, ninth driest, tenth driest, eleventh driest and seventeenth driest years since record began. A weakening of East Asian summer monsoon is therefore common. An exception is 1982 the second wettest year since record began. This exceptionally wet year is explained by the westward spread of the El Chichón eruption cloud across the Pacific Ocean under the influence of the jet streams (***Fig. 3***). The cloud reached the South China Sea by ca. 16th April 1982 resulting in 1041.2 mm rainfall during the period 22nd April to 31st May 1982 (***Fig. 4***). The unseasonal early heavy rainfall, the abnormally low surface humidity observed during April and the bimodal peaks of monthly rainfall in May and August can be explained by the influence of the stratospheric eruption cloud from the eruption which provided condensation nuclei.

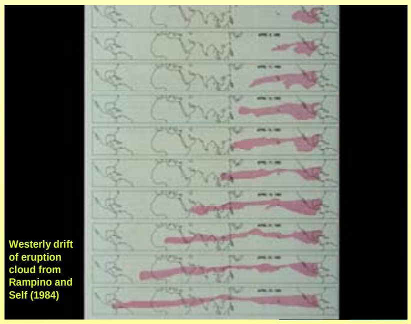

Fig. 3 *Maps showing the spread of the El Chichón eruption cloud during the first 3 weeks after the eruption made by combining information from satellites. Source: Robock & Matson (1983). Heavy rain fell over Hong Kong 17 days after the April 4th eruption.*

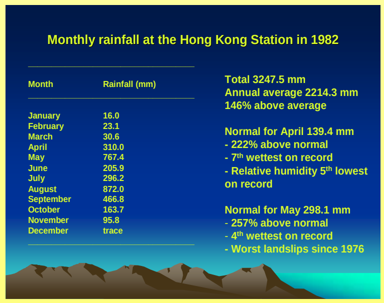

Fig. 4 *Distribution of monthly rainfalls in 1982 and rainfall-related statistics at the Hong Kong Station during April.*

3. Explanation

The possible mechanisms of ‘major’ volcanic eruptions include:
(a) A reduction in solar radiation received causing cooling (***Fig. 5***). This effect is greater for tropical eruptions than high latitude eruptions. The result is normally a weakening in the summer monsoon.
(b) The eruption cloud is responsible for transferring significant quantities of water vapour from the troposphere into the stratosphere changing their ‘normal’ composition (***Fig. 6***).
(c) The eruption cloud transported by jet streams interferes with the ‘normal’ atmospheric circulation (***Fig. 6***). Based on the common occurrence of drought years during years of ‘major’ eruptions in southern China there is a weakening of the East Asian summer monsoon.
(d) Because the ‘major’ volcanic eruptions differ in their composition, geographical location and their eruption timing, the East Asian summer monsoon onset is affected.
(e) The quantities of water vapour transferred from the troposphere into the stratosphere is likely to be dependant on the geographic location of the volcano and as well as the meteorological conditions at the time of the volcanic eruption. Volcanic eruptions located on islands including those involving ice and snow cover such as Eyjafjallajökull in Iceland are expected to have a greater moisture supply than inland volcanoes. The timing of the 1991 Pinatubo eruption coincided with the passage of Typhoon Yunya (***Fig. 7***) causing even greater moisture transfer from the troposphere into the stratosphere.

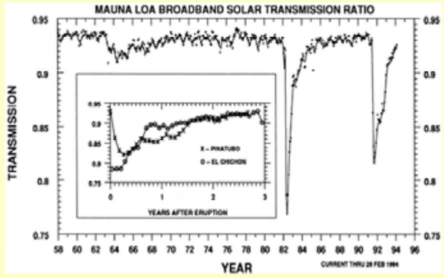

Fig. 5 *Solar radiation at Mauna Loa from 1958 to February 1994 showing the impact of the 1963 Agung eruption, the 1982 El Chichón eruption and the 1991 Pinatubo/Cerro Hudson eruptions.*

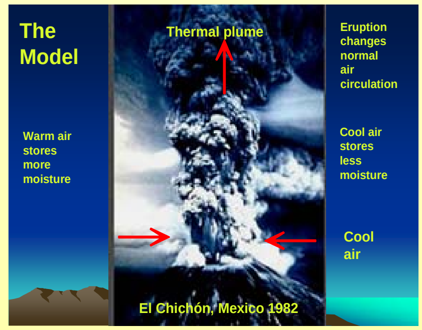

Fig. 6 *Model showing how a ‘major’ volcanic eruption interferes with normal atmospheric circulation to affect incoming solar radiation and moisture distribution.*

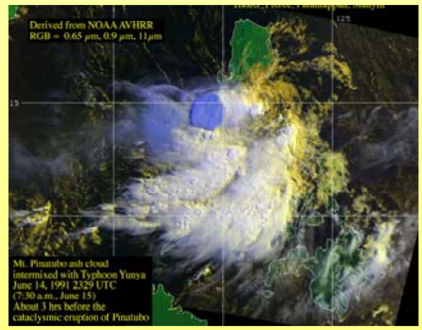

Fig. 7 *Satellite image of the Pinatubo eruption ash cloud and Typhoon Yunya about 3 hours before the main eruption. Yunya dissipated into a tropical depression within 2 days.*

4. Conclusions

The main conclusions drawn are:
(1) ‘Major’ volcanic eruptions usually result in dry years (East Asian summer monsoon weakening) with one known exception.
(2) The second wettest year since record began in 1982 at the Hong Kong Station was caused by the El Chichón eruption cloud transported across the Pacific Ocean by jet streams (East Asian summer monsoon strengthening).
(3) The timing of ‘major’ volcanic eruptions may affect East Asian summer monsoon onset.
(4) In spite of the pronounced heat island effect on the annual mean temperatures of the Hong Kong Station evidence for cooling can be found in 9 of the 13 ‘major’ eruptions. Most significant cooling was caused by the 1883 Krakatau eruption followed by the 1902 Santa Maria eruption and the 1991 Pinatubo eruption. Volcanic eruptions located in the tropics have greater impact in reducing solar heating than those from higher latitudes.
(5) Similar studies should be carried out on ‘modern’ volcanic eruptions in other monsoonal regions.

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