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Did sulfur-rich volcanic eruptions affect drought episodes in Taiwan?

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Abstract Precipitation change in Taiwan during the twentieth century is investigated. Six major drought episodes in Taiwan during the period from 1897 to 2001 are identified. They are 1899–1902, 1906–1910, 1913–1916, 1960–1965, 1978–1980 and 1993–1997. That there is one episodic high sulfur-rich volcanic eruption which corresponds to each drought event is intriguing. Sulfur-rich volcanic eruption forcing from the Pinatubo eruption in 1991 is evident in the drought episode of 1993–1997. The Agung eruption (1963) coincides with the centre of a drought episode (1960–1965) of about a half decade duration. Together with all the other eruptions, this indicates that high sulfur-rich volcanic eruptions bear some relationships to drought episodes in Taiwan with durations of from three years to six years.

Key words drought episodes; precipitation change; sulfur-rich volcanic eruptions; Taiwan

INTRODUCTION

The year of 1993 has caught the popular attention of the Taiwan atmospheric scientific and operational community. Models completely failed to simulate the 1993 severe Taiwan drought. Meanwhile there appear to be some abrupt changes in relatively large-scale Asian monsoon climate conditions, which is a major part of the global circulation system, around the year 1990. Taiwan, a subtropical island, is situated at the triple junction of the Pacific, Eurasia and South China Sea. Taiwan's topographical structure is unique. Somewhat SWS–NEN oriented mountains and hills cover more than 60% of Taiwan's area of 36 000 km^2. This central range forms the backbone. The surrounding oceans are important sources of water vapour for precipitation. More important is that Taiwan has been undergoing tremendous economic development, industrialization, and land-use change since the 1960s. Flood interspersed with extremely dry episodes in Taiwan ensued from 1960s. This study examines: (a) how precipitation change in Taiwan is manifest in the long-term precipitation record, and (b) how Taiwan drought episodes emerge in a time frame coincident with high sulfur-rich volcanic eruptions.

Change in the amount of incoming solar and outgoing longwave radiation, the so-called "radiative forcing", is crucial for climate change (IPCC, 1994, 2001). The enhanced greenhouse effect and global warming are pre-eminent research projects in this regard. An increase in atmospheric CO_2 concentration leads to a reduction in outgoing infrared radiation which results in a positive forcing. This positive forcing tends to raise surface and lower troposphere temperatures. Increase of anthropogenic emissions of CO_2 and other greenhouse gases due to industrialization and land-use change contribute to an enhanced greenhouse effect (IPCC, 2001). Furthermore, warmer ocean surfaces will increase the atmospheric water vapour content. Water vapour partially fills the intervening spectral regions where CO_2 is transparent. Water vapour feedback plays an important role in amplifying climate change (Twomey, 1991).

An equally important process is radiative forcing by aerosols: suspensions of particles in the atmosphere. Aerosols come into the atmosphere by anthropogenic processes and episodic major sulfur-rich volcanic eruptions. The radiative effects of aerosols are mainly negative because of their scattering of shortwave radiation and the resultant increase in planetary albedo. Aerosol forcing acts to mitigate greenhouse warming. Surface cooling will decrease the atmospheric water vapour content. The increase of aerosols can change the concentrations of cloud condensation nuclei, and in turn alter the hydrological cycle of the atmosphere (Twomey, 1991; Charlson *et al.*, 1992; Simpson & Wiggert, 1969). Aerosols act to inhibit precipitation in the sense that they reduce atmospheric precipitable water, decrease cloud droplet size and prolong cloud lifetime. Anthropogenic aerosols are relatively short-lived and sulfur-rich volcanic injection is an episodic phenomenon. Transient explosive eruption presumably will enhance the anthropogenic aerosol effect.

AEROSOLS FORCING

Clouds and radiation are key components of the hydrological cycle (Chahine, 1992). The factors that influence albedo are very important in determining the energy balance of the earth. By scattering and absorption of radiation, and interaction with clouds, aerosols can influence the thermal structure of the atmosphere.

Aerosol effects on cloud droplet size are significant (Brêon *et al.*, 2002). Charlson *et al.* (1992) have discussed direct radiative, indirect radiative and cloud lifetime as three mechanisms by which aerosols affect the Earth's radiation budget. Aerosol and cloud condensation nuclei can scatter and absorb radiation. A chain process can occur in the atmosphere due to an increase in aerosol concentration. These sequential processes range from increasing the concentration of cloud condensation nuclei, decreasing the mean droplet size, inhibiting precipitation development, increasing cloud lifetime, disturbing water and heat content in the atmosphere, to the disturbance of the hydrological cycle. Simpson & Wiggert (1967) found a 72% decrease in precipitation fallout when enough small hygroscopic particles are added to maritime air. Twomey (1991) concluded that rain formation would become more difficult when aerosols increase.

SULFUR-RICH VOLCANIC ERUPTION FORCING

A climate model can be used to simulate the temperature changes that occur both from natural and anthropogenic forcing. Some evidence suggested that most of the warming observed over the last 50 years is attributable to human activities (IPCC, 2001). However, a notable difference exists between observations and simulations with only anthropogenic forcing, including greenhouse gases and an estimate of sulfur aerosols. Anthropogenic forcing alone is unlikely to explain the entire range of observed changes. Simulations with both natural (solar and volcanic) and anthropogenic forcing agree well with observations. While solar forcing is cyclic, volcanic forcing is transient. Surface temperature changes due to sulfur-rich gas ejected into the stratosphere from giant volcanic eruptions are in the same direction as anthropogenic aerosol concentrations and opposite direction to greenhouse gas concentrations (McCormick *et al.*, 1995; Robock, 1995).

It was Franklin (1974) who first recognized that reflection of sunlight by aerosols of the Icelandic volcano Laki reduced solar heating of the Earth and caused the bitter winter of 1783–1784 in northern Europe. Two huge volcanic eruptions in the 19th century are Tambora and Krakatau. The Tambora volcanic eruption in 1815 was followed by "the year without a summer" in the USA (Landsberg & Albert, 1974) and the Krakatau volcanic eruption in 1883 was followed by the coolest year (1884) for the period from 1880 to 1987 (Hansen & Lebedeff, 1987). Rampino & Self (1982) compared the Agung eruption (of 1963) with the Krakatau and Tambora eruption. While the Agung was a much smaller eruption in terms of fine ash, it had a comparable amount of sulfur aerosols. They concluded that a decrease in surface temperature of a few tenths of a °C for several years following these three volcanic eruptions were primarily a result of the sulfate aerosols. McCormick *et al.* (1995) have reviewed the atmospheric effect of the Mount Pinatubo eruption. Several years of globally warm surface temperature was stopped by the radiative effect of the ejected particles. The important role on surface cooling played by the sulfate aerosols of major volcanic eruptions during the 20th century has been addressed in numerous papers (Rampino & Self, 1984a,b; Kelly & Sear, 1984; Hansen *et al.*, 1978, 1992).

Global water vapour reduction was found after the eruption of Mount Pinatubo in June 1991 (Soden *et al.*, 2002). Positive water vapour feedback will enhance a substantial climate response of aerosol forcing (Del Genio, 2002). Together with a drier atmosphere, volcanic aerosol settling will prohibit precipitation. Precipitation is a regional and noisy parameter. If one focuses on a smaller spatial scale than the global scale, a precipitation–volcanism relationship should emerge. Less water vapour will be evaporated from oceans after major sulfur-rich volcanic eruptions because of the sea surface cooling effect. Taiwan is a small island surrounding by water surface. Lower sea surface temperature reduces the moisture sources for precipitation in Taiwan, and in turn volcanic eruption acts to enhance the aerosol effect on rainfall prohibition.

At present, there are more than 600 active volcanoes distributed around the world and the eruptions occur every year (Tilling, 1990). Several major eruptions occurred in the periods 1883 to 1912, and 1963 to 1991. Six major sulfur-rich volcanic eruptions during the 20th century were identified from excerpts and records in the existing literature (e.g. Newhall & Self, 1982; Mass & Portman, 1989; among others).

Table 1 presents the selected six sulfur-rich volcanoes together with their geo-location, activity date, volcanic explosivity index (on the scale of explosive eruptions), stratospheric H_2SO_4 aerosol loading, and the northern hemisphere temperature change in the year follow the eruption. The Ksudach eruption on 28 March 1907 was also included in the list. While ice core evidence is lacking, the eruption is vigorous (VEI of 5).

Table 1 Six selected sulfur-rich volcanic eruptions during the 20th century. VEI: volcanic explosive index.

Eruption	VEI	Stratospheric H_2SO_4 aerosols (g)	Northern hemisphere temperature change (°C)
Santa Maria 14.8°N, 91.6°W; October 1902	6	$\leq 2 \times 10^{13}$	–0.4
Ksudach 51.8°N, 157.5°E; March 1907	5	–	–
Katmai 58.3°N, 155.2°W; June 1912	6	$\leq 2 \times 10^{13}$	–0.2
Agung 8.3°S, 155.5°E; March/May 1963	4	$1\sim2 \times 10^{13}$	–0.3
St Helens 46.2°N, 122.2°W; May 1980	5	$\sim3 \times 10^{11}$	0 to –0.1
El Chichon 17.3°N, 93.2°W; March/April 1982	4	$\sim2 \times 10^{13}$	–0.4 to –0.6
Pinatubo 15.1°N, 120.2°E; June 1991	6	$\sim3 \times 10^{13}$	–0.7

The volcanic explosivity index (VEI), developed by Newhall & Self, is a general indicator of the explosive character of an eruption. They used one or more criteria, including volume of ejecta, column height, qualitative restriction, classification, duration of continuous blast, maximum explosivity, tropospheric injection, stratospheric injection, to assign an eruption to a scale of 0 to 8. Scale 8 indicates the most energetic eruption; scale 7 is the second most energetic and so on. While this index gives the explosivity degree, it does not contain the sulfate input to the stratosphere. The H_2SO_4 loading included in Table 1 indicates the amount of sulfur content.

PRECIPITATION RECORD IN TAIWAN

Precipitation and rain day records for eight stations during the twentieth century were obtained from the Central Weather Bureau, Taiwan. These eight selected stations are located on the coastal plain (Fig. 1). Their World Meteorological Organization (WMO) station number, year of record commencement, latitude and longitude, altitude, climatological annual mean precipitation and standard deviation are presented in Table 2.

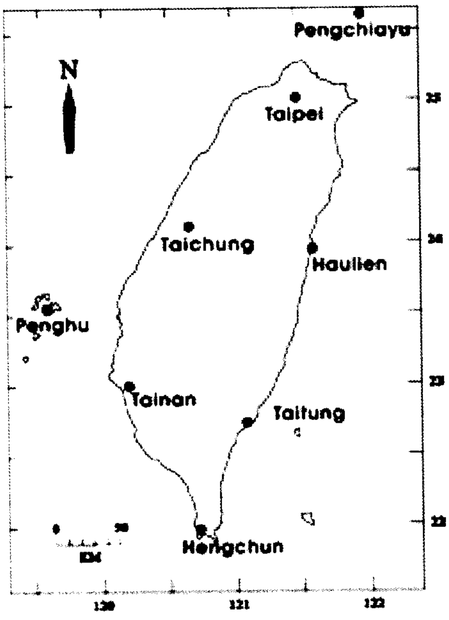

Fig. 1 Schematic map of eight meteorological stations in Taiwan.

Table 2 Eight selected stations with their WMO station number, latitude and longitude of geolocation, altitude, year of record commencement, climatological mean precipitation and standard deviation.

Station no.	Station name	Latitude °N	Longitude °E	Altitude (m)	Year of commencement	Annual precipitation (mm)	Standard deviation (mm)
6950	Pengchiayu	25.6	122.1	101.7	1910	1785	378
6920	Taipei	25.0	121.5	5.5	1897	2168	372
7490	Taichung	24.2	120.7	84.0	1897	1714	454
6990	Haulien	24.0	121.6	16.1	1901	2067	464
7350	Penghu	23.6	119.6	10.7	1897	1008	301
7410	Tainan	23.0	120.2	13.8	1897	1744	518
7660	Taitung	22.8	121.2	9.0	1901	1836	494
7590	Hengchun	22.0	120.7	22.3	1897	2182	534

Both the northeast and southwest monsoons influence weather and climate in Taiwan. The northeast monsoon from Asia prevails in winter, while its weather patterns during summer are influenced by the southwest monsoon and subtropical high. In general, rainfall in Taiwan can be classified into five seasons, i.e. winter, spring, Mai-Yu, typhoon, and autumn, instead of the conventional four seasons. Seasonal and regional variations in monthly precipitation are evident. Month to month variations for Taipei and Pengchiayu are smaller than for other stations. Mai-yu and typhoon rain are important to Taichung, Tainan and Hengchun. Taitung and Haulien have a higher autumn rainfall. These characteristics are all related to the moisture sources for each month and station.

PRECIPITATION, RAIN DAY AND RAINFALL INTENSITY ANOMALIES IN TAIWAN

Precipitation change is investigated using precipitation amount and rain day averaged from all eight selected stations. Rainfall intensity is derived from dividing precipitation amount by rain day. Hereafter precipitation, rain day and rainfall intensity are referred to as the annual value of the eight stations average. Figure 2 shows the time series for annual precipitation (top panel), rain day (middle panel) and rainfall intensity (lower panel) anomalies for the period from 1897 to 2001. Anomalies are calculated with respect to the mean for the period 1961–1990 for each variable.

Table 3 lists the first seven wettest and driest years in Taiwan during the 20th century along with associated precipitation anomalies. The seven driest years during the twentieth century are (in order of dryness) 1923, 1993, 1963, 1980, 1907, 1936 and 1902. Five of the seven driest years coincide with volcanic eruptions.

Table 4 lists the first seven least and most rain-day years in Taiwan during the 20th century along with associated rain-day anomalies. The seven least rain-day years (in order) during the twentieth century are 1963, 1993, 1902, 1995, 1994, 1987 and 1980. Excepting the sixth least rain-day year, 1987, major volcanic eruptions occurred on or immediately before all other six least rain-day years. All the seven most rain-day years occurred during the period from 1920 to 1953, a period when no major volcanic eruptions occurred and before the rapid economic development.

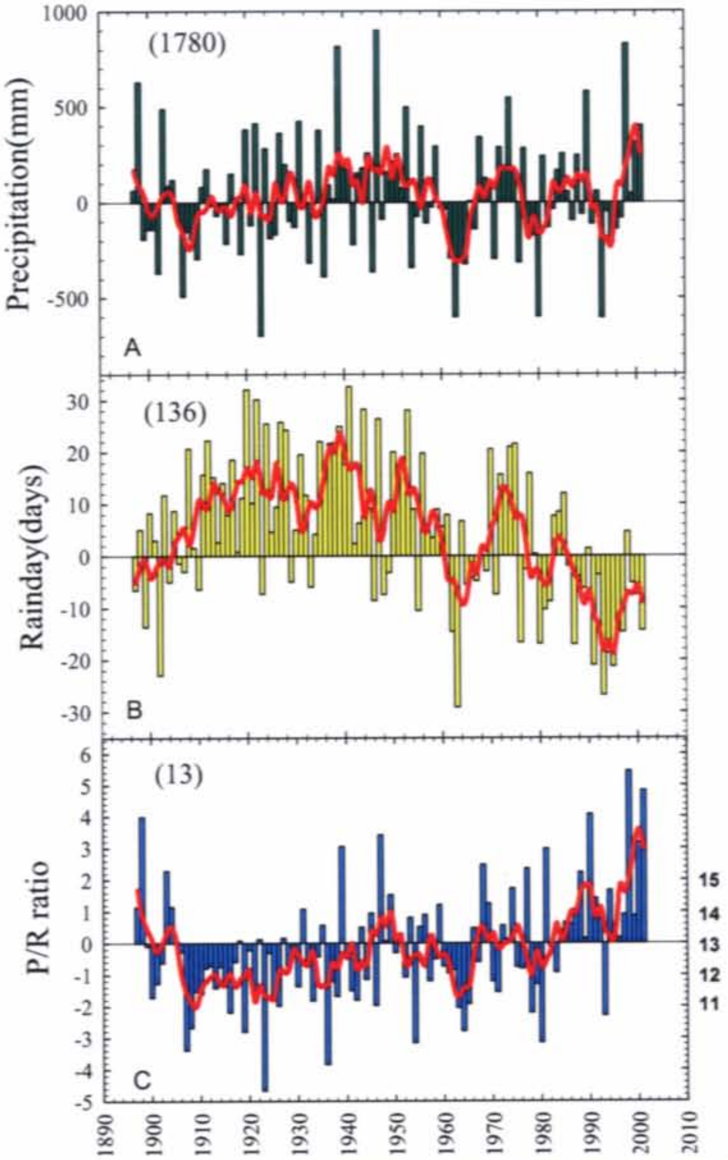

Fig. 2 Top panel: annual precipitation anomaly averaged from all eight stations, and its associated five-year running mean time series. Middle panel: same as top panel but for rain day. Lower panel: same as top panel but for rainfall intensity anomaly is calculated with respect to the mean for the period 1961–1990.

Drought is characterized by prolonged rainfall deficit. Six episodes are characterized by three or more consecutive years with below normal precipitation (Table 5). They are 1899–1902, 1906–1910, 1913–1916, 1960–1964, 1978–1980 and 1993–1997. Each episode corresponds to one volcanic eruption listed in Table 1. Only El Chichõn does not seem related to the dry episode. Note that 1982–1983 is an unusual ENSO year.

Figure 2 (bottom panel) indicates that rainfall intensity reaches a maximum for 1998. Above normal rainfall intensity is observed for the period 1983–2001 except in 1993. Over the last twenty years rainfall intensity has increased drastically. As the rainfall intensity is getting stronger, Taiwan is more prone to floods and droughts.

Table 3 First seven wettest and driest years in Taiwan along with associated precipitation anomalies.

Seven wettest years			Seven driest years		
Rank	Year	Precipitation anomaly (mm)	Rank	Year	Precipitation anomaly (mm)
1	1947	899	1	1923	–699
2	1998	828	2	1993	–604 (Pinatubo)
3	1939	817	3	1963	–601 (Agung)
4	1898	629	4	1980	–599 (St Helens)
5	1990	579	5	1907	–493 (Ksudach)
6	1974	546	6	1936	–389
7	1953	497	7	1902	–372 (St Maria)

Table 4 First seven least and most rain-day years in Taiwan along with associated precipitation anomalies.

Seven most rain-day years			Seven least rain-day years		
Rank	Year	Rain-day anomaly (day)	Rank	Year	Rain-day anomaly (day)
1	1941	32.7	1	1963	–29.1 (Agung)
2	1920	32.1	2	1902	–23.0 (St Maria)
3	1922	30.2	3	1993	–23.0 (Pinatubo)
4	1944	28.3	4	1995	–21.3 (Pinatubo)
5	1953	28.1	5	1994	–18.7 (Pinatubo)
6	1947	26.4	6	1987	–17.1
7	1927	25.8	7	1980	–16.9 (St Helens)

FIVE-YEAR RUNNING MEAN PRECIPITATION AND TEMPERATURE ANOMALIES

In order to remove the fluctuations resulting from the year-to-year variation, quasi-biennial oscillation and El Niño Southern Oscillation, a five-year running mean was applied to the time series. The five-year running mean time series for precipitation, rain day and rainfall intensity are plotted as curves against their annual bar time series in Fig. 2. The five-year running mean precipitation anomaly time series is transcribed to Fig. 3. The alternation of dry and wet episodes after 1960 emerged clearly in the precipitation anomaly five-year mean time series. Four major drought episodes are 1906–1910, 1961–1964, 1978–1982 and 1993–1995. The centres of each dry episode are 1908, 1963, 1980 and 1993. The symbol 🌋 locates the timing of six selected major sulfur-rich volcanic eruptions (see Table 1) during the 20th century.

The drought episode of 1906–1910 appears related to the 1907 Ksudach eruption. Northern Hemisphere sea surface temperature dropped after the 1902 St Maria eruption and lasted for several years (Newhall & Self, 1982). There is no ice core record for Ksudach, however its VEI is 5. The drought episode 1961–1964 coincides with the 1963 Agung eruption. The St Helens and El Chichõn eruptions occurred with the drought episode 1978–1982. The evidence that the Pinatubo eruption in 1991 caused the drought episode 1993–1995 is strong. Our precipitation record agrees well with the observed global precipitable water decrease (Soden *et al.*, 2002). The coupled occurrences of episodic sulfur-rich volcanic eruptions and drought episodes are intriguing. The El Chichõn eruption of 1982 competes with the unusual 1982–1983, and appears a more subtle influence on precipitation. The El Niño Southern Oscillation (ENSO) is the strongest natural fluctuation that can induce large variations in weather

Table 5 Dry periods in Taiwan along with associated precipitation and rain-day anomalies. Six periods with three or more consecutive years below normal precipitation.

Period	Year	Precipitation anomaly	Rain-day anomaly	Comment
1	1899	−192.3	−13.7	
	1900	−142.7	8.3	
	1901	−140.3	3.0	
	1902	−372.7	−23.0	Santa Maria erupted on 24 October 1902
2	1906	−56.1	−1.3	
	1907	−493.1	−3.0	Ksudach erupted on 28 March 1907
	1908	−152.8	20.7	
	1909	−193.8	1.5	
	1910	−295.7	−6.5	
3	1913	−18.9	15.2	Katmai erupted on 6 June 1912
	1914	−69.6	2.7	
	1915	−24.9	14.1	
	1916	−215.6	7.9	
4	1960	−32.2	5.7	
	1961	−36.7	7.9	
	1962	−295.2	−14.6	
	1963	−601.3	−29.1	Agung erupted on 17 March 1963
	1964	−313.6	6.7	
	1965	−324.6	−5.4	
5	1978	−130.5	15.9	
	1979	−173.4	0.4	
	1980	−598.9	−16.9	St. Helens erupted on May 18 1980
6	1993	−604.2	−26.8	Pinatubo erupted on June 15 1991
	1994	−49.1	−18.7	
	1995	−209.4	−21.3	
	1996	−141.5	−12.4	
	1997	−81.4	−14.7	

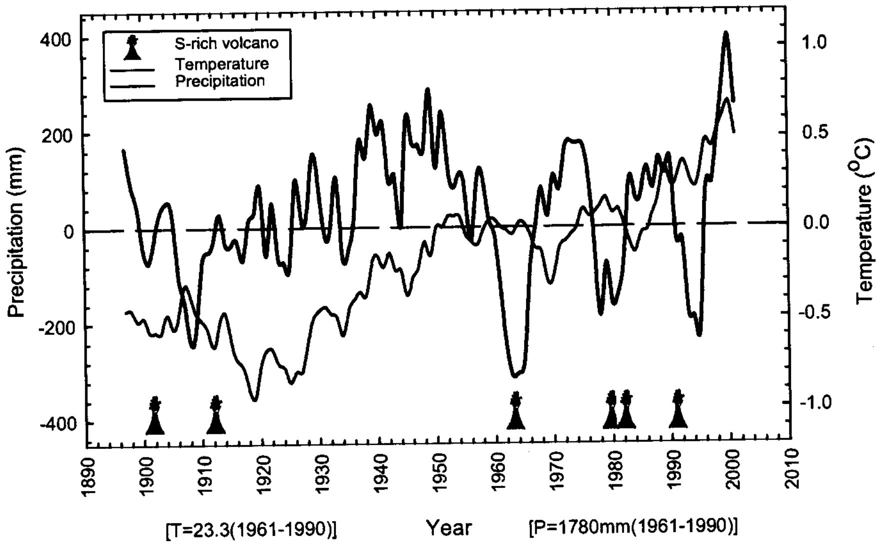

Fig. 3 Time series of five-year running mean precipitation and temperature anomalies averaged from eight station records for the period from 1897 to 2001.

and climate. There are droughts and floods around the world that are associated with El Niño and La Niña (Rasmusson & Wallace, 1983; Trenberth & Branstator, 1992; Trenberth & Guillemont, 1996). Drought initiation, maintenance and withdrawal are complex hydrological and dynamic processes involving the atmosphere, land surface, ocean, radiative forcing and bio-ecosystem interaction (Chang & Smith, 2001). The coupled occurrence of drought episodes in Taiwan and sulfur-rich volcanic eruptions, and the inferred consequence of enhanced greenhouse and anthropogenic aerosols on precipitation variability is woven in a complicated web. The synergies presented of sulfur-rich volcanic eruption and drought episodes provide the evidence that sulfur-rich volcanic forcing influences Taiwan's drought episodes.

CONCLUSIONS

Strong rainfall intensity and large rainfall variability emerged from five-year running mean precipitation anomaly time series in Taiwan. These trends ensued with rapid economic development and urbanization in the 1960s. The observed increase of rainfall variability and intensity during the last four decades is inferred to be a consequence of greenhouse warming and anthropogenic aerosol forcing. Four major drought episodes during the 20th century are observed in the five-year running mean precipitation anomaly time series. They are 1906–1910, 1961–1966, 1978–1982 and 1993–1995. They occurred in the two periods that major sulfur-rich volcanic eruptions occurred, 1902–1912 and 1963–1995. The coupled occurrence of drought episodes and episodic eruptions is intriguing. The Agung in 1963 coincides with the 1961–1966 drought, the St Helens in 1980 and the El Chichõn in 1982 coincide with the 1978–1982 drought, and the Mount Pinatubo in 1991 coincides with the 1993–1995 drought. The evidence for the Pinatubo 1991 effect on the drought in 1993–1995 is significant. The Agung, St Helens and El Chichõn coincide with the drought episode of about a half decade duration that began before their eruption. The salient features of precipitation change and synergies of droughts and high sulfur-rich volcanic eruption in Taiwan during the 20th century illustrate the impacts of sulfur-rich volcanic eruption and anthropogenic process.

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REFERENCES

Brĕon, F.-M., Tanrĕ, D. & Generoso, S. (2002) Aerosol effect on cloud droplet size monitored from satellite. *Science* **295**, 834–838.

Chahine, M. T. (1992) The hydrological cycle and its influence on climate. *Nature* **359**, 373–380.

Chang, F.-C. & Smith, E. A. (2001) Hydrological and dynamical characteristics of summertime droughts over US Great Plains. *J. Climate* **14**, 2296–2316.

Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley Jr, J. A., Hansen, J. E. & Hofmann, D. J. (1992) Climate forcing by anthropogenic aerosols. *Science* **255**, 423–430.

Del Genio, A. D. (2002) The dust settles on water vapor feedback. *Science* **296**, 665–666.

Franklin, B. (1784) Meteorological imagination and conjectures. *Manchester Literary and Philosophical Society Memoirs and Proceedings* **2**, 122.

Hansen, J. E. & Lebedeff, S. (1987) Global trends of measured surface air temperature. *J. Geophys. Res.* **92**, 13345–13372.

Hansen, J. E., Wang, W. C. & Lacis, A. A. (1978) Mount Agung eruption provides test of a global climatic perturbation. *Science* **199**, 1065-1068.

Hansen, J., Lacis, A., Ruedy, R. & Sato, M. (1992) Potential climate impact of Mount Pinatubo eruption. *Geophys. Res. Lett.* **19**, 215–218.

IPCC (1995) *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* (ed. by J. T. Houghton, L. G. Meria Filho, J. Bruce, H. Lee, B. A. Callander, E. Haites, N. Harris & K. Maskell). Cambridge University Press, UK.

IPCC (2001) *Climate Change 2001: The Scientific Basis* (ed. by J. H. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Lindon, X. Dai, K. Maskell & C. A. Johnson). Cambridge University Press, UK.

Kelly, P. M. & Sear, C. B. (1984) Climatic impact of explosive volcanic eruptions. *Nature* **311**, 741–743.

Landsberg, M. E. & Albert, J. M. (1974) The summer of 1816 and volcanism. *Weatherwise* **27**, 63–66.

Mass C. F. & Portman, D. (1989) A. Major volcanic eruptions and climate: a critical evaluation. *J. Climate* **2**, 566–593.

McCormick, M. P., Thomason, L. W. & Trepte, C. R. (1995) Atmospheric effects of the Mt Pinatube eruption. *Nature* **373**, 399–404.

Newhall, R. E. & Self, S. (1982) The volcanic explosivity index (VEI): an estimate of explosive magnitude of historic eruptions. *J. Geophys. Res.* **87**, 1231–1238.

Rampino, M. R. & Self, S. (1982) Historic eruptions of Tambora (1815), Karatau (1883), and Agung (1963), their stratospheric aerosols, and climatic impact. *Quatern. Res.* **18**, 127–143.

Rampino, M. R. & Self, S. (1984a) The atmospheric effect of El Chichon. *Scientific American* **250**, 34–43.

Rampino, M. R. & Self, S. (1984b) Sulfur-rich volcanic eruptions and stratospheric aerosols. *Nature* **310**, 677–679.

Rasmusson, E. M. & Wallace, J. M. (1983) Meteorological aspects of the El Ninõ/Southern Oscillation. *Science* **222**, 1195–1202.

Robock, A. (1995) The volcanic contribution to climate change of the past 100 years. In: *Greenhouse-Gas-Induced Climate Change: A Critical Appraisal of Simulations and Observations* (ed. M. E. Schesinger), 429–443. Elsevier, New York, USA.

Simpson, J. & Wiggert, V. (1969) Models of precipitating cumulus towers. *Monthly Weather Rev.* **97**, 471–489.

Soden, B. J., Wetherald, R. T. & Stenchikov, G. L. (2002) Global cooling after the eruption of Mount Pinatubo: a test of climate feedback by water vapor. *Science* **296**, 727–730.

Tilling, R. I. (1990) Coping with volcanic hazards: a global perspective. *Earthquakes and Volcanoes* **22**, 154–160.

Trenberth, K. E. & Branstator, G. W. (1992) Issues in establishing causes of the 1988 drought over North America. *J. Climate* **5**, 159–172.

Trenberth, K. E. & Guillemont, C. J. (1996) Physical processes involved in the 1988 drought and 1993 floods in North America. *J. Climate* **9**, 1288–1298.

Twomey, S. (1991) Aerosols, clouds and radiation. *Atmos. Environ.* **25A**, 2435–2442.