remote sensing

MDPI

Supplementary Materials

Table S1. Reference list for volcanological applications of satellite data to volcanic plumes.

Citation	Eruption	Sensor	Methods					
			BA	A/V	H(S)	H(T)	M	Others
Hanel (1961) [62]	Meteorological clouds	n/a						CO_2 absorption technique
Heiken & Pitts (1975) [63]	Sakurajima 1972	**Landsat 1**	X					Cloud discrimination
Kienle & Shaw (1979) [2]	Augustine 1976	AVHRR radar	X			X	X	Thermal energy
Krueger (1982) [64]	La Soufriere 1979	SMS	X	X				Possibility to obtain H
Barr & Heffter (1982) [65]	La Soufriere 1979		X			X		Mass flux
Krueger (1983) [66]	El Chichon 1982	TOMS	X					
Robock & Matson (1983) [67]	El Chichon 1982	AVHRR GOES	X					
Hanstrum & Watson (1983) [3]	Mt. Galunggung 1982	GMS	X			X		
Matson (1984) [68]	El Chichon 1982	AVHRR GOES	X			X		
Richardson (1984) [69]	El Chichon 1982	AVHRR						Atmospheric haze
Sawada (1985) [70]	Mayon 1984	GMS	X			X	X	Thermal energy
Prata *et al.* (1985) [71]	Lesser Sunda Islands 1982	AVHRR	X					
Malingreau & Kaswanda (1986) [72]	Colo 1983	AVHRR	X	X				
Sparks *et al.* (1986) [73]	St. Helens 1980	GOES	X		X?	X?		
Carey & Sigurdsson (1986) [74]	El Chichon 1982	GOES	X	X			X	H by lithic clast dispersal model
Sawada (1989) [75]	Pagan 1981 Soputan 1982 Colo 1983	GMS	X	X		X	X	Thermal energy
Prata (1989) [76]	Mt. Galunggung 1982	AVHRR	X					Discrimination plume/met. cloud
Glaze *et al.* (1989) [16]	Lascar 1986	**Landsat TM**	X		X	**X**		
Holasek & Rose (1991) [77]	Augustine 1986	AVHRR	X	X		X		Discrimination plume/met. cloud Eruption rate
Woods & Self (1992)[18]	St. Helens 1980 El Chichon 1982	AVHRR				X		Problems with H(T)
Koyaguchi & Tokuno (1993) [78]	Pinatubo 1991	GMS	X	X	X?	X	X	Cloud thickness
Dean *et al.* (1994) [38]	Redoubt 1990	AVHRR	X	X	X	X		H by wind altitude & pilot reports
Wen & Rose (1994) [79]	Crater Peak 1992	AVHRR	X				X	
Holasek & Self (1995) [39]	St. Helens 1980	GOES radar	X		X	X		H by radar Spreading speed
La Frulla *et al.* (1995) [80]	Hudson 1991	AVHRR	X			X		

Holasek *et al.* (1996) [19]	Pinatubo 1991	AVHRR GMS	X	X	X	X		Shadow over clouds, H errors
White & Hockey (1996) [81]	Mt. Ruapehu 1995	AVHRR	X		?	?		
Kinoshita (1996) [40]	Mt. Sakurajima 1993	**Landsat 5**	X		X	**X**		
Prata & Turner (1997) [54]	/	ATSR		X				H by stereoscopy Plume thickness
Denniss *et al.* (1998) [41]	Lascar 1993	AVHRR OPS	X		X			
Oppenheimer (1998) [7]	Review	AVHRR ATSR GOES HIRS SSM/I TOMS	X		X	X		Methodological problems of (H(S) and (H(T) Operational monitoring
Krotkov *et al.* (1999) [82]	Crater Peak 1992	AVHRR TOMS	X				X	
Glaze *et al.* (1999) [17]	Redoubt 1989	AVHRR						H by stereoscopy & photoclinometry
Schneider *et al.* (1999) [83]	El Chichon 1982	AVHRR TOMS	X				X	
Simpson *et al.* (2000) [84]	Soufriere 1982 Crater Peak 1992 Mt Augustine 1986 Mt Ruapehu 1996	AVHRR GMS GOES TOMS	X					Detection failures in wet ash clouds
Prata *et al.* (2001) [85]	Soufriere 1982 Crater Peak 1992 Mt Augustine 1986 Mt Ruapehu 1996	AVHRR GMS GOES TOMS	X					
Simpson *et al.* (2001) [86]	Hekla 2000	AVHRR GMS GOES TOMS	X					
Prata & Grant (2001) [42]	Mt Ruapehu 1996	AVHRR ATSR	X		X	X	X	H by stereoscopy Plume thickness
Prata & Grant (2001) [87]		AVHRR MODIS	X		X	X	X	
Aloisi *et al.* (2002) [4]	Etna 1998	Meteosat	X					
Bertrand *et al.* (2002) [88]	Etna 2002	Meteosat	X					Radiative flux
Tupper & Kinoshita (2003) [89]	Indonesia, Papua New Guinea, Vanuatu 1994-2002	AVHRR GMS	X		X	X		H by stereoscopy
Tupper *et al.* (2004) [43]	Russia, Japan, Indonesia, others 1997-2002	AVHRR GMS VISSR MODIS	X		X	X		
Tupper (2005) [90]	Pinatubo 1991	AVHRR GMS VISSR	X			X		H by radar
Richards *et al.* (2006) [91]	Anatahan, Manam, Etna 2001-2004	MODIS MISR						H by CO_2 absorption technique
Steffke *et al.* (2010) [92]	Tungurahua 2006-2008	GOES MODIS				X		H by velocity determination
Scollo *et al.* (2012) [93]	Etna 2000-2008	MIRS						H by stereoscopy

Spinetti *et al.* (2013) [94]	Eyjafjallajökull 2010	MODIS **ASTER**	X		X	**X**		
Ekstrand *et al.* (2013) [95]	Redoubt 2009	AVHRR MODIS				X		Problems with H(T) H by stereoscopy
Zaksek *et al.* (2013) [20]	Eyjafjallajökull 2010	MODIS Aqua SEVIRI				X		Underestimations by H(T) H by photogrammetry
Marchese *et al.* (2014) [21]	Shinmoedake 2011	GMS lidar	X	X		X	X	Underestimations by H(T), transparent cloud problem Thermal activity
De Michele *et al.* (2016) [55]	Holuhraun 2010	**Landsat 8**						H by PEM
Corradini *et al.* (2018) [35]	Etna 2011-2015	SEVIRI				X		
De Michele *et al.* (2019) [44]	Etna 2013	**Landsat 8**						H by PEM

A/V = extraction of area/volume, ASTER = Advanced Spaceborne Thermal Emission and Reflection, ATSR = Along Track Scanning Radiometers, AVHRR = Advanced Very High Resolution Radiometer, BA = basic observations, GMS = Geostationary Meteorological Satellite, GOES = Geostationary Operational Environmental Satellite, H = volcanic plume or cloud height, H(S) = volcanic plume or cloud height obtained thanks to the height-from-shadow technique, H(T) = volcanic plume or cloud height obtained thanks to the height-from-temperature technique, HIRS = High-resolution Infrared Radiation Sounder, LIDAR = Laser Imaging Detection And Ranging, M = mass, MIRS = Operational Microwave Integrated Retrieval System, MISR = Multiangle Imaging SpectroRadiometer, MODIS = Moderate-Resolution Imaging Spectroradiometer, OPS = Optical Sensor from Japan Earth Resources Satellite (JERS-1), SEVIRI = Spinning Enhanced Visible and Infrared Imager, SMS = Synchronous Meteorological Satellite, SSM/I = Special Sensor Microwave/Imager, TOMS = Total Ozone Mapping Spectrometer, VISSR = Visible-Infrared Spin Scan Radiometer, TM = Thematic Mapper. The column and lines of interest, respectively for articles measuring H(S) and using high-spatial resolution images, are highlighted in light grey. When these lines and columns cross, they are highlighted in dark grey, figuring the articles measuring plume height by the shadow technique using high-spatial resolution images.

Step 1: Sun-Earth geometry calculations

All formulas for the following parameters are listed in Chapter 1 of Iqbal (1983) [47].

Table S2. Sun-Earth geometry calculations.

Parameters Needed	Calculations (In Order)
Local standard time of satellite scene Standard longitude of satellite scene Local longitude (each point of interest) Local latitude (each point of interest)	Solar declination Equation of time E_T Longitude correction Local Apparent Time (LAT) Hour angle ω Solar elevation α Solar azimuth ψ

Step 2: Intersection line

The shape of the intersection line that will define the height profile location is manually selected. The objective of this step is to obtain the longitude and latitude of each intersection point on the intersection line related to each point of interest on the shadow outline, as follow:

- Retrieval of each coordinate set of the line segment ends,
- Calculation of the line equation for each line segments,
- Calculation of the line equation for each point of interest with the vertical direction,
- Calculation of the coordinate set for each intersection point from the 2 previous line equations.

Step 3: Distance from the vent

The distance between the vent and each intersection point on the future height profile can be calculated taking into account their longitude/latitude coordinates and the Earth curvature.

Step 4: Shadow Length Measurement and pixel size

Parameters needed
Swadth (pixels) Scan increment angle Satellite altitude

We now need the distance between the shadow outline and the intersection point of each point of interest. The main steps are as follow

- Retrieval of the number of pixels corresponding to the distance, for each point of interest,
- Calculation of the pixel number coordinates for nadir position (using the geometry of the image acquisition),
- Calculation of pixel number coordinates for each point of interest (using the geometry of the image acquisition),
- Calculation of the scan angle (cf. Harris (2013) [48]),
- Calculation of the pixel size in the cross- and along-scan direction for each corresponding point of interest and point on the intersection line (cf. Harris (2013) [48]),
- Assuming that the difference in pixel size between these two points is negligible for Low Earth Orbital sensors, an average pixel size for each distance of interest can be used,
- The Shadow Length Measurement is the number of pixels multiplied with the pixel size for each distance of interest.

Step 5: Topography effect

The topography on the path between the shadow outline and the intersection line needs to be taken into account. This is possible as follow:

- Retrieval of the elevation of each couple of shadow outline point of interest and associated point on the intersection line,
- Calculation of the slope for each point of interest,

- Calculation of the plume altitude using equations 2 and 3.

Step 6: Spherical geometry effect

If applicable, the cloud maximum height H_{max} can be calculated when assuming a spherical geometry of the convective ash puffs, as follow:

- Retrieval of the plume width at each point of interest (in pixels and then in meters),
- Calculation of Hmax using equations 5 and 6.