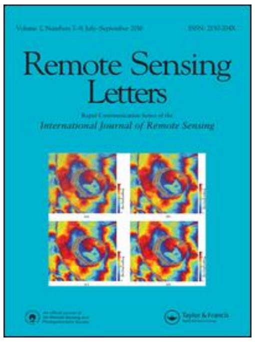

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Investigating the nature of an ash cloud event in Southern Chile using remote sensing: volcanic eruption or resuspension?

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ABSTRACT

On 14 December 2013, the Cooperative Institute for Meteorological Satellite Studies (United States) reported a volcanic ash cloud apparently emitted by the Puyehue Cordón Caulle Volcanic Complex (Chile) and indicated its cause was probably resuspension. The distinction of volcanic ash resuspension from volcanic eruptions is important because both processes pose different scenarios for civil protection authorities and besides, there is a special need of specific schemes for detecting and monitoring resuspension of volcanic ash. To this end, we intended to identify the cause of this event by using remote sensing technology. Remote sensing based volcanic ash products enabled us to confirm the presence of volcanic ash and observations on the Moderate Resolution Imaging Spectroradiometer (MODIS)–based cloud-integrated water path provided evidence in favour of a small and short-lived eruption. Thus, a volcanic eruption would constitute a plausible explanation for the cloud of 14 December 2013, but we were unable to discard resuspension. On the other hand, we found out that the water path product could constitute useful ancillary data to identify the origin of this kind of processes. The set of observations presented constitutes a good initial point towards the identification and subsequent development of decision support tools for the mitigation of the hazards posed by volcanic ash resulting from volcanic eruptions and resuspension.

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1. Introduction

On 14 December 2013, the Cooperative Institute for Meteorological Satellite Studies (CIMSS) reported an ash cloud drifting north to north-east from the Puyehue Cordón Caulle Volcanic Complex (PCCVC) (40°35′ S; 72°5′ W) (Figure 1). On 15 December 2013, the Volcano Discovery website reported that a 'significant' ash cloud could be spotted from Moderate Resolution Imaging Spectroradiometer (MODIS) and owing to the

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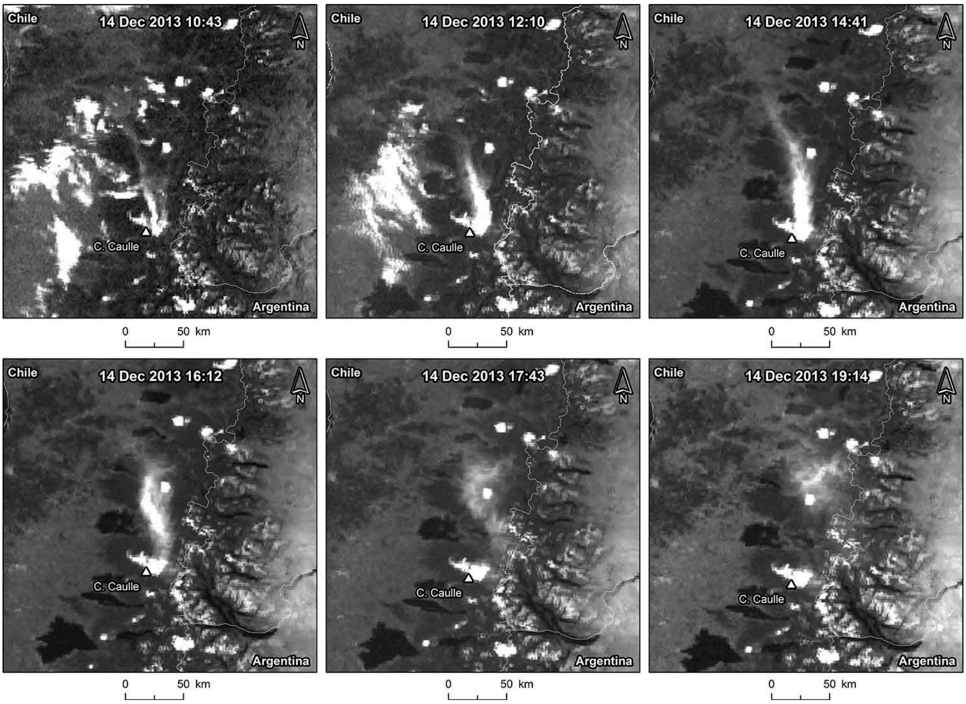

Figure 1. GOES-13 Imager snapshots at 10:43, 12:10, 14:41, 16:12, 17:43 and 19:14 UTC on 14 December 2013 captured by the visible channel centred at 0.63 µm. The snapshots intend to summarize the animation posted in the CIMSS Satellite Blog. The location of PCCVC is 40°35′ S, 72°5′ W.

absence of other signals of volcanic activity (i.e., heat, eyewitness reports, webcam, observatory reports, etc.), its causes were attributed to remobilization (http://www.volcanodiscovery.com/puyehue/news/40224/Puyehue-Cordon-Caulle-volcano-Chile-possible-eruption-ash-plume-reported.html). On 30 December 2013, the report of the activity of PCCVC for December 2013 by the Volcanological Observatory of the Southern Andes (OVDAS) from the Chilean National Service for Geology and Mining (SERNAGEOMIN) mentioned gas columns composed predominantly by water vapour reaching 700 m height on 8 December 2013 (OVDAS 2013). The Buenos Aires Volcanic Ash Advisory Centre also reported emissions but yet on 23 December 2013 and then on 16 and 17 January 2014, where they indicated that weak emissions of steam, gas and volcanic ash had taken place (http://www.smn.gov.ar/vaac/buenosaires/productos.php?lang=es&anio=2013). Finally, in the report for January 2014, OVDAS mentioned a field campaign that took place between 17 and 22 January 2014 to continue with the follow-up of volcanic fluids that confirmed the absence of ash emissions at the crater and therefore attributed remobilization to be the cause of the emissions that had been reported previously (OVDAS 2014).

The implications for hazard mitigation of ash clouds due to resuspension are different from those of volcanic eruption clouds (i.e., dispersion and deposition patterns of both types of clouds are different; resuspension is typically restricted to the lowest layers of the atmosphere; small volcanic eruptions could constitute events of larger magnitude;

etc.). Moreover, improved tools for tracking volcanic ash clouds and in turn to increase the regional/local capabilities to cope with this kind of natural hazards are required. To this end, our aim is to build up tools for rapid decision support as regards the origin and evolution of volcanic ash clouds by using remote sensing technology. It is within this context that we intended to identify the cause of the event of 14 December 2013 by using data captured by the sensor Imager on board the Geostationary Operational Environmental Satellite (GOES-13) and by the MODIS on-board the satellites Terra and Aqua.

We evaluated the dynamics of the 14 December 2013 cloud and used standard image processing techniques to confirm if volcanic ash and/or sulphur dioxide (SO_2) were present and to estimate its height. We also investigated the MODIS-based cloud masks and cloud-integrated water path (King et al. 1997) to test if the volcano has emitted ash and water. Finally, we compared the products obtained for the cloud under question with six events of known origin, that is, three volcanic eruption clouds and three clouds of resuspended ash.

2. Methodology

For the identification of volcanic ash, we relied on the concept of reverse absorption, true colour composites and Ash & SO_2 products (Prata 1989a, 1989b, Pavolonis et al. 2006; Carn et al. 2009; Pavolonis 2010; Pavolonis, Heidinger, and Sieglaff 2013). The concept of reverse absorption refers to the lower emissivity of volcanic ash at 11 μm than at 12 μm, which results in that the brightness temperature difference between both bands ($BTD_{11–12\ \mu m}$) is negative in contrast to meteorological clouds that show positive values (Prata 1989a, 1989b). The Ash & SO_2 product, originally conceived by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), combines the $BTD_{12–11\ \mu m}$ in the red, the $BTD_{11–8.5\ \mu m}$ in the green and the brightness temperature at 11 μm ($BT_{11\ \mu m}$) in the blue channels, respectively. Red and magenta pixels identify volcanic ash, whereas yellow pixels indicate where both ash and SO_2 coexist. We evaluated all these products and looked into descriptive statistics of regions of interest (ROIs), that is, polygons based on visual interpretation of the products to cover the clouds.

We obtained the altitude of the cloud under question by using (i) the MODIS Cloud Product (MOD 06), which includes the cloud's height based on the CO_2 slicing method (Menzel, Smith, and Stewart 1983; King et al. 1997; Richards 2006) and (ii) the minimum $BT_{11\ \mu m}$ of the observed cloud and a nearby radiosonde from Puerto Montt (Chile). It was required to add 755 m to the height retrievals obtained by using the first method, since it corresponds to the average increase obtained by Richards (2006) for 15 cases by using the CO_2 slicing method but with emissivity ratios that contemplate the microphysics of the volcanic ash. As regards the second approach, we used the temperature vertical profile from the radiosonde to interpolate the cloud height that corresponds to the minimum $BT_{11\ \mu m}$.

Finally, the MODIS-based cloud-integrated water path is derived at 1 km spatial resolution using the visible, near-infrared and shortwave infrared bands. Water paths are in grams per square metre for pixels previously classified as cloudy by the MODIS-based cloud mask (King et al. 1997). We hypothesized that it would be reasonable to expect the absence of water in resuspended ash clouds and in turn to lack positive water path retrievals. Thus, we evaluated if the cloud masks detected the clouds of all the events and based on the ROIs, we estimated the proportion of pixels classified as cloudy and from this subgroup of pixels we calculated the percentage pixels with valid water path retrievals (i.e., those larger than zero) and the average water path.

For the comparison with the reference events, we used MODIS 5-min tiles available from the Level 1 and Atmosphere Archive and Distribution System of the Goddard Space Flight Center at NASA (https://ladsweb.nascom.nasa.gov/). The area covered by these tiles corresponds to 5 min of acquisition by the MODIS instrument. The tiles covered (i) two ash clouds of 20 June 2011 (14:30) and 26 June 2011 (18:15) of the 4 June 2011 eruption of PCCVC with and without SO_2 signal, respectively; (ii) an eruption cloud from PCCVC on 4 July 2013 (14:30) that consisted of fine ash and water vapour (Villarosa 2013); (iii) a cloud of resuspended ash of PCCVC on 14 October 2011 (18:25) that corresponded to a significant and confirmed event of resuspension, well documented by previous studies (e.g., Folch et al. 2014); (iv) a resuspension event eyewitnessed by Dr. Villarosa (INIBIOMA-CONICET) on 16 March 2015 (14:55) with its source possibly located at the volcanic complex and (v) the resuspension case of volcanic ash from Katmai volcano, near Anchorage (Alaska, USA) on 22 September 2013 (22:30). The ash was from the 1912 eruption of Katmai volcano (e.g., Hildreth and Fierstein 2012; CIMSS Satellite Blog: http://cimss.ssec.wisc.edu/goes/blog/archives/13992).

3. Results

The animation based on GOES-13 Imager visible data posted in the CIMSS Satellite Blog (http://cimss.ssec.wisc.edu/goes/blog/archives/14569) and further summarized by the snapshots in Figure 1 shows a cloud apparently 'attached' to the source area at PCCVC that initially moved towards the north-west and then changed sharply its direction towards the east. At about 14:00–15:00 UTC, it reached a simile oval shape that pointed towards the north and later at 19:00 UTC, it appeared 'diluted' and 'detached' from the 'source'.

The MODIS acquisition on 14 December 2013 at 15:05 provided one of the best views of the event under study while the scene at 19:15 was close to the end of this short-lived event (Figures 1 and 2). In both cases, the ash-contaminated pixels were considered to be those with a $BTD_{11-12\ \mu m} < -0.3$ K, while the mean values of this parameter were of −1.3 and −1.1 K for the 15:05 and 19:15 clouds, respectively (Figure 2). Thus, these observations indicate that the cloud consisted of volcanic ash. The Ash & SO_2 products provided additional evidence in these respects; magenta colour of the pixels reflects the presence of volcanic ash and the absence of SO_2 (Figure 2).

The MODIS-based altitude of the cloud at 15:05 was 2.9 km above sea level (ASL) and 1.0 km above the summit of the PCCVC, respectively. The second method provided heights of 3.2 km and 1.0 km ASL and above the summit of the volcanic complex, respectively.

The true colour composites plus the $BTD_{11-12\ \mu m}$ elaborated for the reference events showed clear ash clouds in all cases except for the one of 4 July 2013 (Figure 3). The concept of reverse absorption did not work in this latter case because of the high levels of water vapour emitted by the volcano plus the presence of

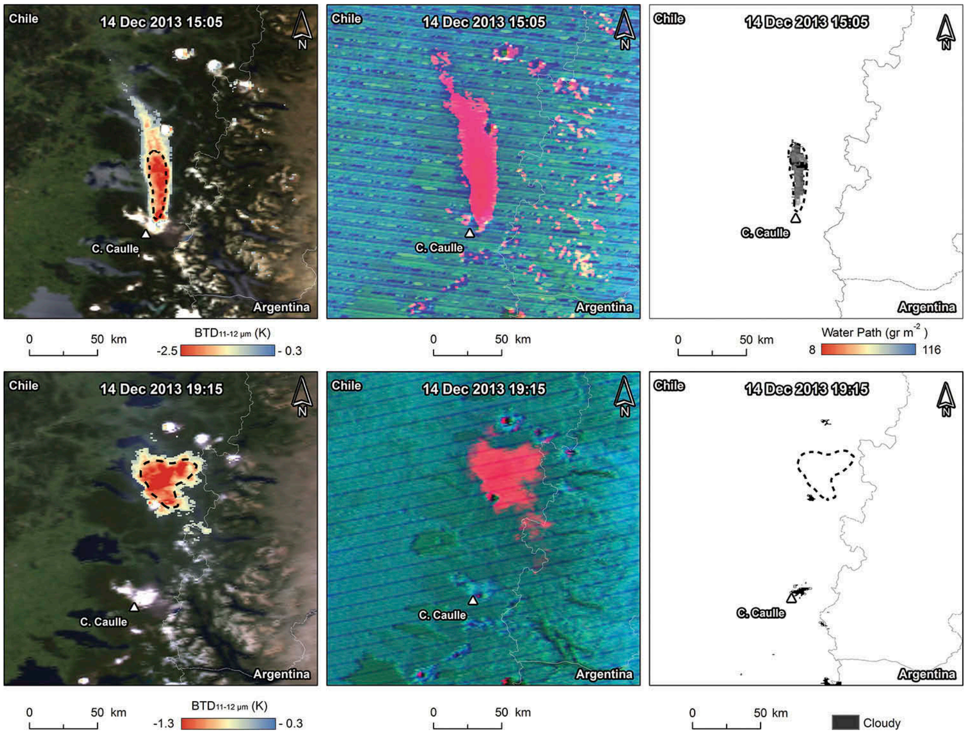

Figure 2. Col. 1 shows $BTD_{11-12\ \mu m}$ and sample polygons (dashed) overlain onto true colour composites of 14 December 2013 at 15:05 UTC and at 19:15 UTC at the top and bottom, respectively. Col. 2 shows Ash & SO_2 products for both data sets (the stripping is due to the band centred at 8.5 µm). Col. 3 shows the cloud-integrated water path for the cloud on 14 December 2013 at 15:05 at the top. At the bottom, the scene at 19:15 shows cloudy pixels in black. No positive water path retrievals were obtained in this case. The location of PCCVC is 40°35′ S, 72°5′ W.

meteorological clouds. Thus, the 4 July 2013 mean $BTD_{11-12\ \mu m}$ was positive (i.e., 0.6 K), whereas the means for the eruption clouds of 20 and 26 June and for the proximal sample of the 14 October 2011 resuspension case were −1.2, −1.6 and −1.8 K, respectively. The distal sample of 14 October 2011 and the 16 March 2015 remobilization case showed mean values of –0.6 and –0.3 K, respectively. Finally, the cloud of resuspended ash from Katmai volcano showed an average $BTD_{11-12\ \mu m}$ of −0.6 K (Figure 3). The Ash & SO_2 products showed magenta-coloured clouds for the resuspension cases and the eruption case with no SO_2 signal. When SO_2 was present, pixels were yellow/orange (Figure 4).

On 14 December 2013 at 15:05, the water path product showed a cloud surrounded by a clear atmosphere that agrees with the cloud identified by the volcanic ash products (Figure 2). From this cloud, 99% of the ROI included pixels that classified as cloudy. Almost 90% of these pixels contained valid water path retrievals; the mean value was of 29 gr m^{-2}. There were no valid water path retrievals in the cloud at 19:15; clear pixels covered 97% of the ROI in this case (Table 1; Figure 2).

The MODIS cloud mask facilitated the identification of the three eruption clouds and the percentage of valid water path retrievals were about 80–90%. The ash/water vapour

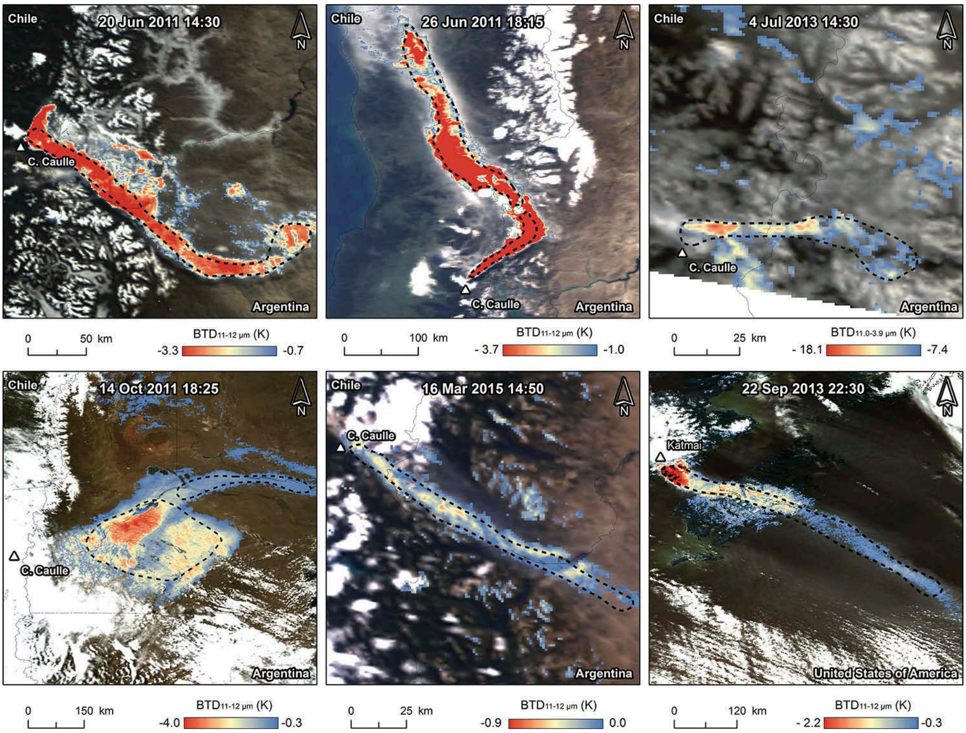

Figure 3. $BTD_{11-12\ \mu m}$ and sample polygons (dashed) overlain onto true colour composites of the reference data sets. The cloud of resuspended ash of 14 October 2011 includes two ROIs, one closer and the other one farther away from the source. In the 4 July 2013 case, the $BTD_{11-3.9\ \mu m}$ replaces the $BTD_{11-12\ \mu m}$, since the concept of reverse absorption does not work in this case (see text for more details). The location of PCCVC is 40°35′ S, 72°5′ W.

cloud of 4 July 2013 showed the highest average value of this parameter, while the June 2011 eruption clouds exhibited average values of about 40 gr m^{-2} (Table 1; Figure 5).

Regarding the resuspension cases, the MODIS mask identified as cloudy about 80–90% of the proximal sample polygon of the 14 October 2011 case and of the cloud at Katmai. Approximately half of the proximal sample contained positive water path retrievals while the average water path was of 11 gr m^{-2}. At Katmai, the proportion of pixels with positive retrievals and the average water path were very low. The MODIS cloud mask failed to detect the distal sample of the October 2011 cloud of resuspended ash and finally, it detected about 50% of the 16 March 2015 cloud from which one third had positive retrievals (Table 1; Figure 5).

4. Discussion

The satellite imagery and the animation fitted better an eruption, since between the beginning of the event and until about 17:00 UTC, the ash cloud dispersed and appeared to be ‘attached’ to the source of the volcanic complex (Figures 1 and 2). The cloud altitude of 1 km above ground level at 15:05 and its associated uncertainty of about 1 km are not conclusive, however, as regards the origin of the event.

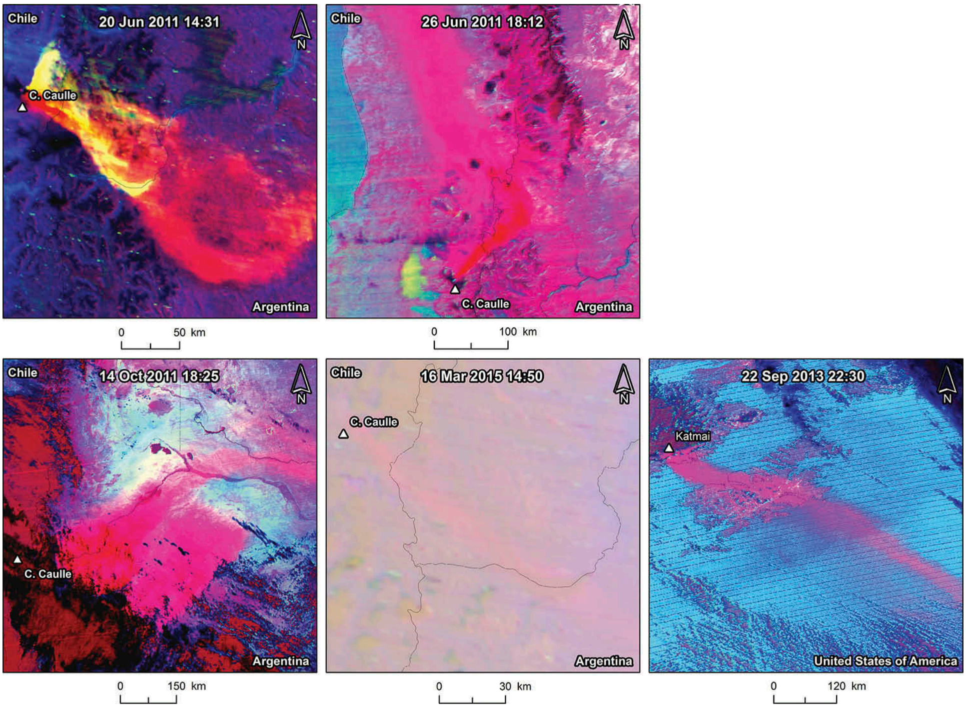

Figure 4. Ash & SO_2 products for all reference cases but the 4 July 2013 one. The $BTD_{11-12\ \mu m}$, the $BTD_{11-8.5\ \mu m}$ and the $BT_{11\ \mu m}$ were assigned to the red, green and blue channels, respectively. The location of PCCVC is 40°35′ S, 72°5′ W.

Table 1. Proportion of pixels classified as cloudy percentage with valid water path (WP) retrievals and average WP for all the cloud events.

Event	Date	Time	Cloudy (%)	Valid WP (%)	Mean WP (gr m^{-2})
Ash cloud event	14 December 2013	15:05	99	87	29
Ash cloud event (diluted)	14 December 2013	19:15	3	–	–
Eruption cloud/ash and water vapour	4 July 2013	14:30	100	89	92
Eruption cloud/with SO_2	20 June 2011	14:30	100	91	45
Eruption cloud/no SO_2	26 June 2011	18:12	92	83	35
Resuspension PCCVC (p)*	14 October 2011	18:25	80	48	11
Resuspension PCCVC (d)*	14 October 2011	18:25	8	3	0.2
Resuspension PCCVC	16 March 2015	14:55	49	33	7
Resuspension Katmai volcano	22 September 2013	22:30	85	13	3

* There were two sample polygons for the remobilization case on 14 October 2011, one closer (p: proximal) and the other farther (d: distal) from the area of the source (Figures 3 and 5).

Conventional remote sensing methods such as the $BTD_{11-12\ \mu m}$ and the Ash & SO_2 product enabled us to confirm that the 14 December 2013 cloud was of volcanic ash and the absence of SO_2 signal. While the latter could be interpreted as support to the hypothesis of remobilization, volcanic eruption clouds may lack SO_2, among other possible interpretations.

Thermal anomalies (Wright et al. 2002) could be identified at the source of PCCVC during the first fortnight of December 2013, but their presence was discontinuous in time and in turn did not contribute towards the eruption hypothesis.

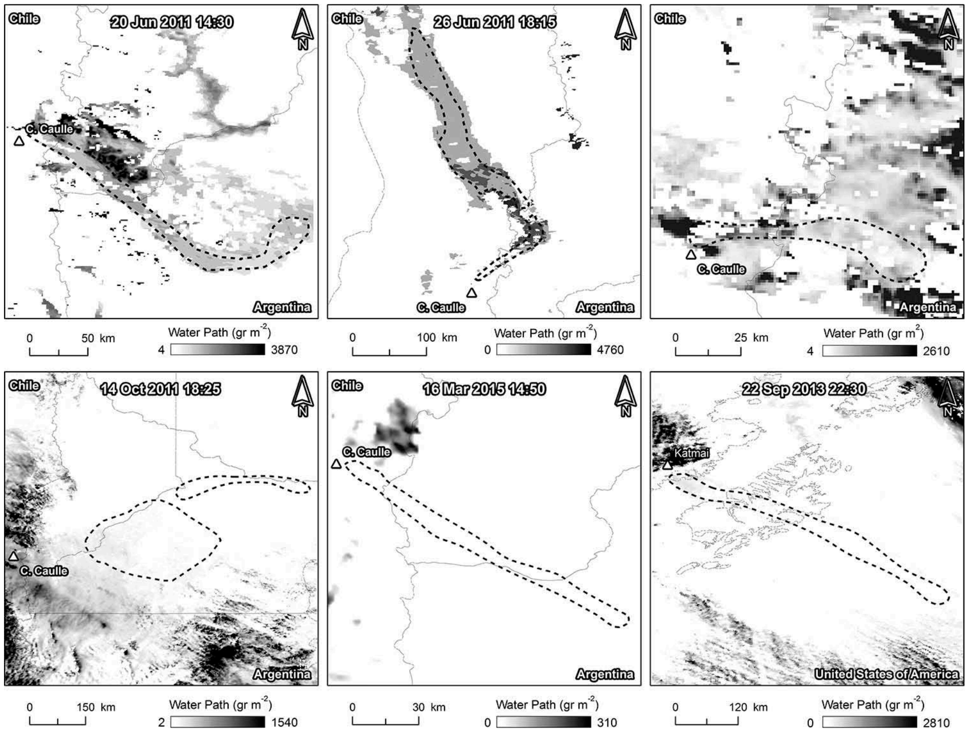

Figure 5. Cloud-integrated water path (gr m^{-2}) for all the reference events. The location of PCCVC is 40°35′ S, 72°5′ W.

The cloud masks facilitated the identification of all the ash cloud cases, except for the cloud under question on 14 December 2013 at 19:15, the distal polygon sample of the cloud of 14 October 2011 and about 50% of the cloud of resuspended ash of 16 March 2015. The cloud dynamics constitutes the best explanation for the lack of detection of the cloud under study in the evening of 14 December 2013. By that time, the cloud had almost dissipated (Figures 1 and 2). On the other hand, artefacts in the algorithm of the cloud mask product may have resulted in the failure to detect both this and the other two cases (Table 1; Figure 5).

The proportion of positive water path retrievals on 14 December 2013 at 15:05 was in agreement with the ones obtained for the eruption cases; average values ranged between 29 and 82 gr m^{-2}. The resuspension clouds in contrast showed proportions of positive water paths and average values that were much lower (Table 1; Figure 5). Thus, these observations suggest that clouds of resuspended ash could be 'dryer' than eruption clouds, as hypothesized earlier. On the other hand, it would be reasonable to interpret that the eruption cases contained water most probably from the eruption. The fact that a clear atmosphere surrounded the cloud at 15:05 on 14 December 2015 would support the hypothesis that the cause of this event was an eruption (Figure 2). Finally, despite the influence of the meteorological clouds in the south-west, the percentage pixels with positive water path retrievals and the average values obtained for the proximal polygon sample of 14 October 2011 were much lower than the values obtained for the eruption cloud cases (Figure 5; Table 1).

5. Conclusions

The initial observations based on satellite imagery suggested the cloud of 14 December 2013 was the result of an eruption of fresh volcanic material. Based on the volcanic ash products, we were able to confirm that the cloud consisted of volcanic ash. Besides, the low MODIS-based altitudes and their associated uncertainties agree with either a resuspension event or a weak eruption.

The analysis of the cloud masks and water paths provided evidence in favour of an eruption. More research will be required to investigate if the low water path retrievals in the case of resuspension events in contrast to those of eruption clouds constitute a pattern. On the other hand, lack of cloud detection by the MODIS algorithm may be the result of artefacts that should be also investigated. Eventually, the water path product might prove useful as ancillary data to assist operational forecasters in the identification of these kinds of processes in near real time.

In summary, while a volcanic eruption constituted a plausible explanation for the cloud of 14 December 2013, we were not able to discard resuspension. The set of observations presented constitutes a good initial point towards the identification and subsequent development of decision support tools for the mitigation of the hazards posed by volcanic ash resulting from volcanic eruptions and resuspension.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Carn, S., A. J. Krueger, N. A. Krotkov, K. Yang, and K. Evans. 2009. "Tracking Volcanic Sulfur Dioxide Clouds for Aviation Hazard Mitigation." *Natural Hazards* 51: 325–343. doi:10.1007/s11069-008-9228-4.

Folch, A., L. Mingari, M. S. Osores, and E. Collini. 2014. "Modeling Volcanic Ash Resuspension – Application to the 14–18 October 2011 Outbreak Episode in Central Patagonia, Argentina." *Natural Hazards and Earth System Science* 14 (1): 119–133. doi:10.5194/nhess-14-119-2014.

Hildreth, W., and J. Fierstein. 2012. "The Novarupta-Katmai Eruption of 1912: Largest Eruption of the Twentieth Century: Centennial Perspectives." U.S. Geological Survey Professional Paper 1791, 259 p. http://pubs.usgs.gov/pp/1791/

King, M. D., S. Tsay, S. E. Platnick, M. Whang, and K. Liou. 1997. "Cloud Retrieval Algorithms for MODIS: Optical Thickness, Effective Particle Radius, and Thermodynamic Phase." MODIS Algorithm Theoretical Basis Document No. ATBD-MOD05-MOD06 – Cloud Product. NASA Goddard Space Flight Center.

Menzel, W. P., W. L. Smith, and T. R. Stewart. 1983. "Improved Cloud Motion Wind Vector and Altitude Assignment Using VAS." *Journal of Applied Meteorology* 22: 337–384.

OVDAS (Observatorio Volcanológico de los Andes del Sur). 2013. “Reporte de Actividad Volcánica (RAV).” Región de los Lagos, Año 2013 Diciembre - Volumen 10, Red Nacional de Vigilancia Volcánica (RNVV), Servicio Nacional de Geología y Minería (SERNAGEOMIN), December 30. http://www.sernageomin.cl/reportesVolcanes/20140111012049907000001 8548-RAV_Los_Lagos_2013_Diciembre_puyehue_vol_10.pdf

OVDAS. 2014. “Reporte de Actividad Volcánica (RAV).” Región de los Lagos, Año 2014 Enero - Volumen 1, Red Nacional de Vigilancia Volcánica (RNVV), Servicio Nacional de Geología y Minería (SERNAGEOMIN), February 5. http://www.sernageomin.cl/reportesVolcanes/20140211080513574RAV_Los_Lagos_2014_Ene_vol_1.pdf

Pavolonis, M. J. 2010. “Advances in Extracting Cloud Composition Information from Spaceborne Infrared Radiances—A Robust Alternative to Brightness Temperatures. Part I: Theory.” *Journal of Applied Meteorology and Climatology* 49: 1992–2012. doi:10.1175/2010JAMC2433.1.

Pavolonis, M. J., W. F. Feltz, A. K. Heidinger, and G. M. Gallina. 2006. “A Daytime Complement to the Reverse Absorption Technique for Improved Automated Detection of Volcanic Ash.” *Journal of Atmospheric and Oceanic Technology* 23: 1422–1444. doi:10.1175/JTECH1926.1.

Pavolonis, M. J., A. K. Heidinger, and J. Sieglaff. 2013. “Automated Retrievals of Volcanic Ash and Dust Cloud Properties from Upwelling Infrared Measurements.” *Journal of Geophysical Research: Atmospheres* 118: 1436–1458. doi:10.1002/jgrd.50173.

Prata, A. J. 1989a. “Observations of Volcanic Ash Clouds in the 10–12 μm Window Using AVHRR/2 Data.” *International Journal of Remote Sensing* 10: 751–761. doi:10.1080/01431168908903916.

Prata, A. J. 1989b. “Infrared Radiative Transfer Calculations for Volcanic Ash Clouds.” *Geophysical Research Letters* 16: 1293–1296. doi:10.1029/GL016i011p01293.

Richards, M. S. 2006. “Volcanic Ash Cloud Heights Using the MODIS CO_2-Slicing Algorithm.” MSc. Thesis in Atmospheric and Oceanic Sciences, Univ. Wisconsin-Madison

Villarosa, G. 2013. “Evento de emisión de gases y cenizas del Cordón Caulle en julio de 2013.” INIBIOMA CONICET-Universidad Nacional del Comahue. San Carlos de Bariloche, Río Negro, Argentina: Inédito.

Wright, R., L. P. Flynn, H. Garbeil, A. J. L. Harris, and E. Pilger. 2002. “Automated Volcanic Eruption Detection Using MODIS.” *Remote Sensing of Environment* 82: 135–155. doi:10.1016/S0034-4257(02)00030-5.