Space-borne Products for Operational Volcanic Ash Cloud Monitoring in Argentina

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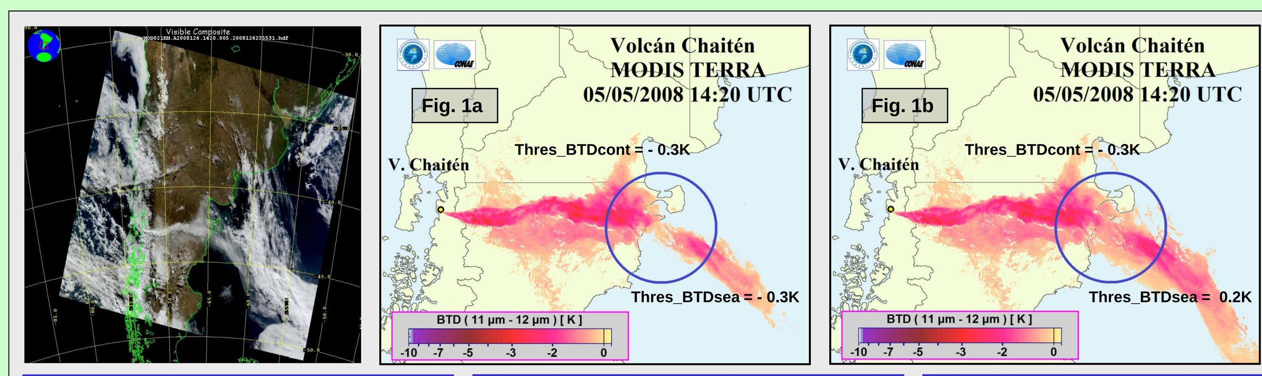
Abstract

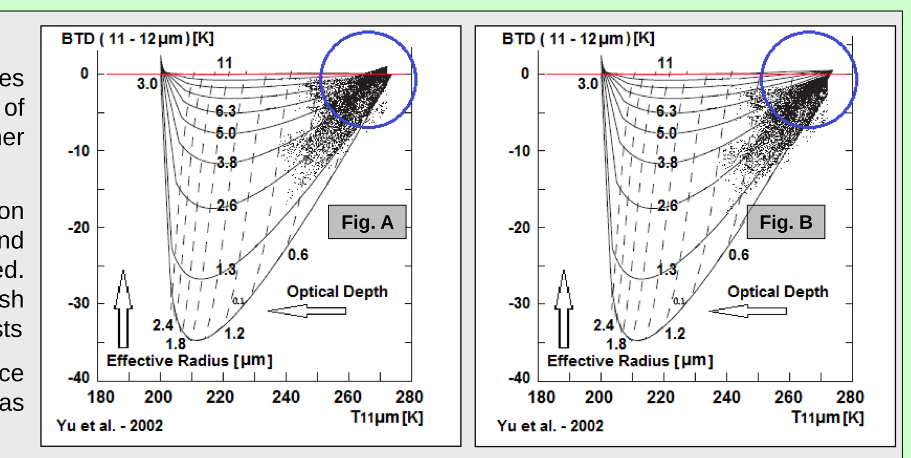
Starting from the operational implementation at CONAE's Ground Segment of the concept of reverse absorption, an extensive review of the ash detection algorithms available has been carried out, which use features of the spectral behavior of both ash and SO_2 such as those present at 11.0 and 12.0, 8.5, 4.0 and 0.65 µm. We present here example applications of such algorithms on the eruptions of Puyehue Cordón Caulle Volcanic Complex and Volcán Chaitén in June 2011 and May 2008, respectively, and the first results of a statistical analysis of brightness temperatures, radiances and spectral indices using data captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the satellites TERRA and AQUA on the eruption of Puyehue Cordón Caulle Volcanic Complex in June 2011. We expect to replicate this analysis in space and time in order search for patterns that will facilitate the adjustment of a volcanic ash identification scheme specific for the context of Argentina. We also show preliminary tests of quantitative retrievals and we look forward to completing these exercises for the eruption of Cordón Caulle and to extending it to other eruptions, to consider other space-borne sensors and in the middle/long term we aim at combining volcanic ash satellite retrievals with the application of volcanic ash transport and dispersion models. The ultimate aim is to make this kind of products operational at the Argentinean's National Space Agency's (CONAE) Ground Segment for further use by end users such as the Buenos Aires VAAC.

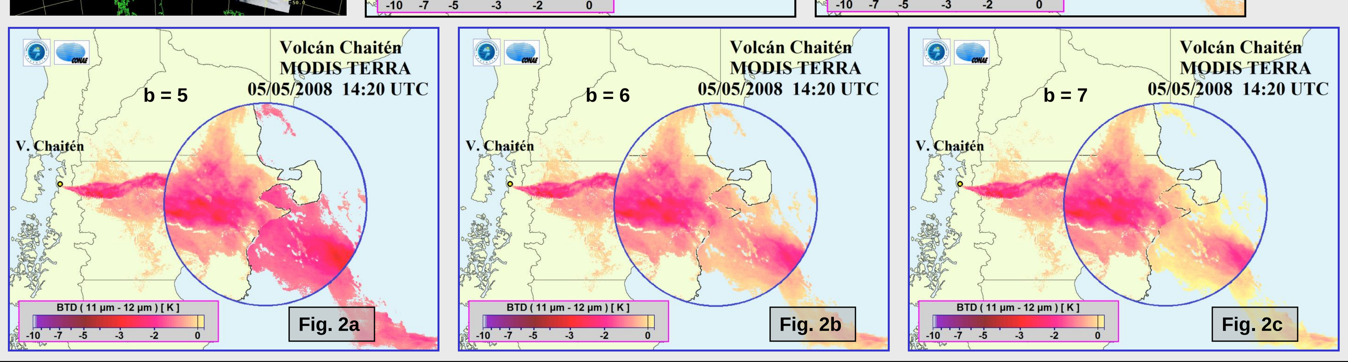


DISCRIMINATION THRESHOLDS – VAPOR WATER CORRECTIONS :

Our main goal is to explore existing approaches for detecting and quantifying volcanic ash within the scope of the VAAC Buenos Aires through the exploitation of the existing remote sensing infrastructure. We started with the operational implementation of the concept of reverse absorption (Prata 1989a,b) at CONAE's Ground Segment by using the BTDs measured by MODIS at 11 & 12 µm, together with an extensive review of the methodologies available (e.g. Prata, 1989; Ellrod, 2003; Pavolonis, 2006, 2010, etc.).

Figure 1.a summarizes our attempts to detect volcanic ash from Volcán Chaitén in May 2008 using the concept of reverse absorption and only one threshold (**Thres_BTD = - 0.3K**). Volcanic ash normally presents a **BTD (11 – 12 µm) < 0**, but since clear land presents similar response in this portion of the spectrum, given the extensive areas of land in Argentina the detection is complicated. Thresholds must be lowered substantially, fact that results in the detection of pixels as not contaminated, where volcanic ash actually exists. On the other hand , **Figure 1.b** , the interface between land and sea requires the application of multiple threshold tests (**Thres_BTDcont = - 0.3K** , **Thres_BTDsea = 0.2K**) in order to reduce the discontinuities of the ash cloud at such interface that result from single threshold tests.These discontinuities are a result of the effects of changes in important factors such as surface emissivity and water vapor content in the atmosphere.





The effect of the precipitable water in an atmospheric column on the **BTD (11−12) µm** (Yu et al., 2002) is estimated as **ΔTwv = EXP [6Tx − b]** where **Tx = T11µm / Tmax** (Tmax is a normalisation constant of 320 K) and **b** determines the value of the water vapour effect on **BTD (11−12) µm** at the maximum value of **T11µm** (it is a free adjust parameter for this semi-empirical approach). The upper bound for this correction is **ΔTwv max = EXP [20Tx − 18]** . On the right , **Figure A** & **B** show the ash distribution without and with atmospheric corrections.

On the left , assuming **Thres_BTDcont = - 0.3K** and **Thres_BTDsea = 0.2K** , the **Figure 2.a**, **2.b** and **2.c** show the water vapor corrections on the BTD (11 – 12 µm) for different values of the **factor b**. This correction results in a reduction of the discontinuity of the ash cloud over the interface between land and sea; in "**2.a**" the presence of ash is overestimated, while in "**2.c**" is underestimated. Statistically, in our area of wok the value of the correction factor is **5 < b < 7** . For this example, we adjust with **b = 6** (**Fig. 2.b**).

STATISTICAL ANALYSIS AND IMAGE CLASSIFICATION :

Given the problematic posed by the extensive areas of land and by the interface between land and sea, we are currently working on statistically-based algorithms using standard approaches for the analysis and processing of satellite images. This analysis is based on descriptive statistics and on scatter plots of brightness temperatures (BTs) and spectral indices (i.e. differences of BTs) for regions of interest defined to cover volcanic ash and meteorological clouds both on land and on the sea and clear land and sea surfaces (Figures 2-3). We started using the portions of the infrared spectrum most sensitive to the presence of volcanic ash and SO2, namely the BTs measured at the bands centered at 3.9, 6.7, 7.3, 8.5, 11 and 12 µm by MODIS. Figure 4 shows the results of applying statistically based thresholds based on the analysis above by using a series of three tests that rely on the BTD(11 – 12 µm), the BTD(11 – 8.5 µm), the BTD(11 – 8.5 µm) – BTD(11-12 µm), the BTD (11-6.7 µm) and the BT(11 µm). T1 aims at separating volcanic ash from clear land, T2 recovers pixels contaminated by ash on the sea and T3 aims at mapping the ash pixels close to the source that are cold and present high levels of water vapor (Figure 3d.). The plan is to replicate this analysis in time using the whole MODIS dataset of the eruption of Cordón Caulle in order search for patterns in space and time that would facilitate the standardization of the type of algorithm presented. Standard image classification schemes will also be tested and finally, we expect to include data from other eruptions (e.g. Chaitén, Lascar) and data captured by sensors on board geostationary satellites (e.g. GOES-12/13-Imager, Meteosat-SEVIRI).

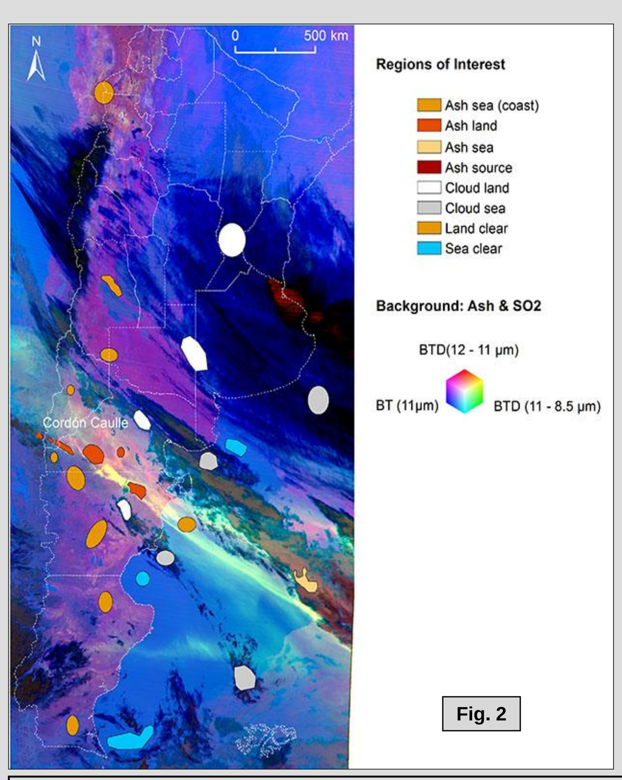
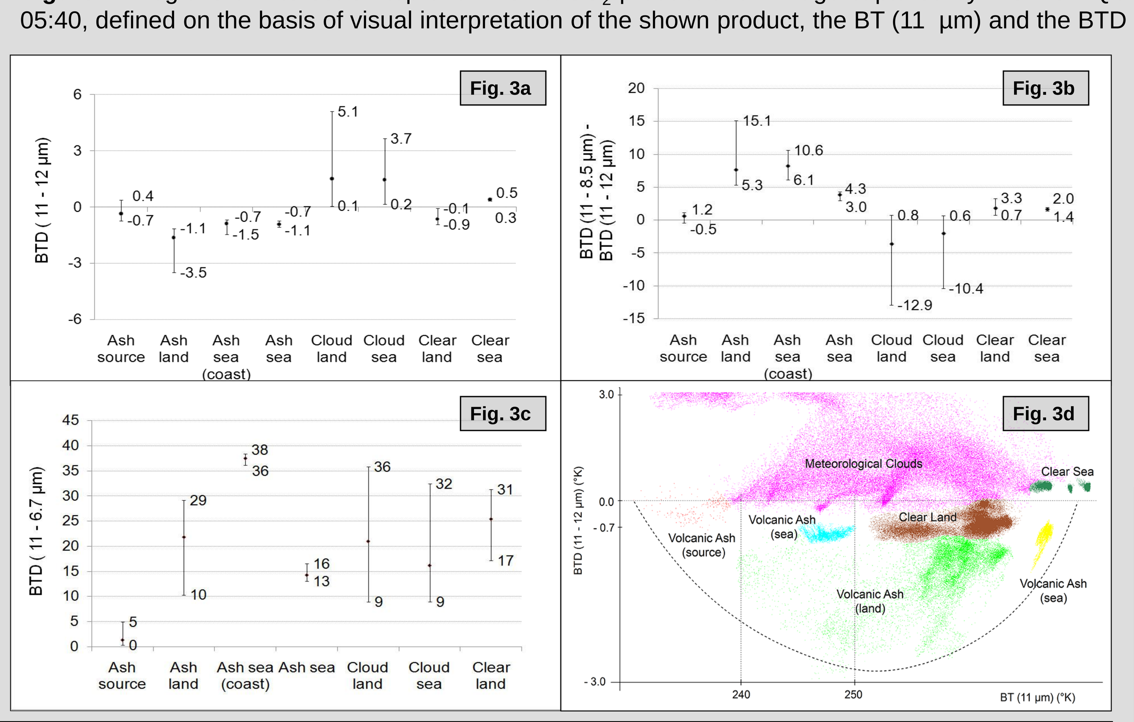


Figure 2 Regions of interest on top of an Ash & SO_2 product of an image captured by MODIS-AQUA on 16th June 2011, 05:40, defined on the basis of visual interpretation of the shown product, the BT (11 µm) and the BTD (11 – 12 µm).



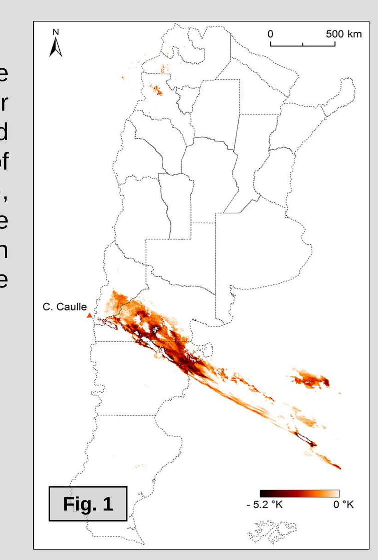


Figure 1

BTD (11 – 12 µm)

Figure 3

5th, 50th (Median) and 95th percentiles of the BTD (11 – 12 µm), the BTD(11 – 8.5 µm) – BTD (11-12 µm) and the BTD (11-6.7 µm) for the regions of interest defined on the image of 16th June 2011 at 05:40 in a, b and c, respectively. The last plot (d) shows the scatter of pixels along the BTD (11-12 µm) vs. the BT(11 µm) with the classes (ROIs) to which the pixels belong in different colors.

The dotted line constitutes the typical U-shaped curve of volcanic ash across the minimum values of the BTD (11- 12 µm) as a function of the BT (11 µm).

The volcanic ash cloud of Cordón Caulle on 16th June 2011, 05:40 constrained on the basis of the application of statistically based thresholds :

Fig. 4

	T_1 (°K)	T_2 (°K)	T_3 (°K)
BTD(11 – 12 µm) <	- 0.7	- 0.7	0.0
BTD(11 – 8.5 µm) >	4.0	2.0	-
TBTD*(11, 12 & 8.5 µm) >	5.0	3.0	-
BT(11 µm) <	-	250.0	240
BTD(11 – 6.72 µm) <	-		5.0

* TBTD = BTD (11 – 8.5 µm) – BTD (11 – 12 µm)

False alarms still occur, especially in the northwest of the country, probably due to the presence of atmospheric dust. Southwards from the cloud, there are also isolated pixels identified by this classification as ash.

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THE ASH RESUSPENSION EVENT :

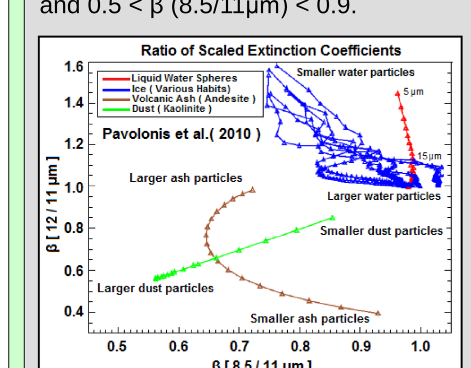
During the period 14th-18th October 2011 important remobilization of volcanic ash from Cordón Caulle took place in Argentina leading to air traffic disruption such as the closure of Córdoba Airport .

The preliminary products below show on the left top-down, the ash/dust cloud based on the concept of reverse absorption (Prata, 1989) and 3.9 /11 /12 µm bands empirical algorithm (Ellrod et. al , 2003).

On the right, the fine particles in purple overlain onto the ash/dust cloud and mapped on the basis of the microphysics captured by the parameters β(12/11 µm) and β(8.5/11µm), which are given by the ratio of the extintion coefficients at the two corresponding wavelengths (Pavolonis & Sieglaff, 2010), for the 14th, 15th and 16th October from top to bottom, respectively.

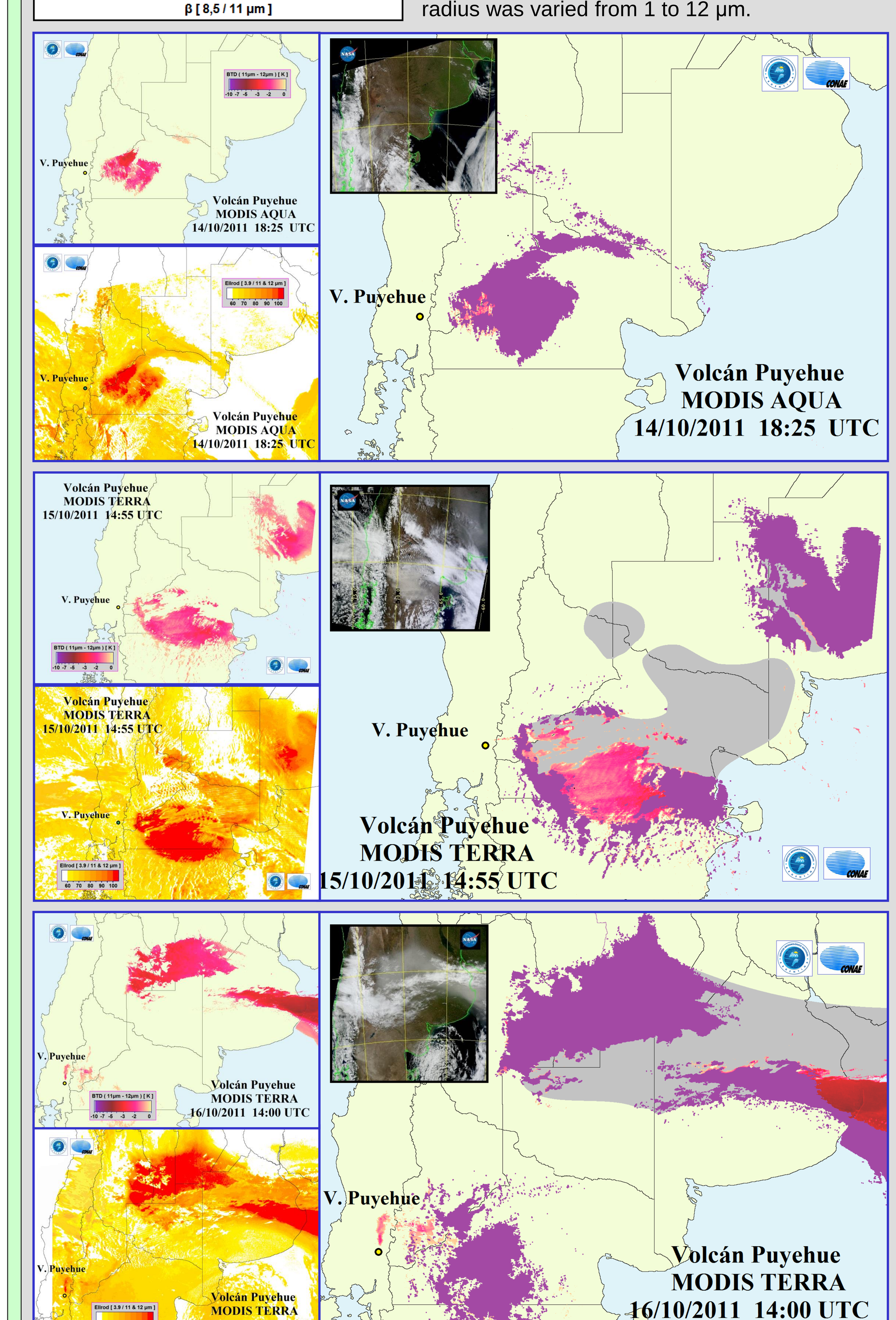
The discontinuities indicated by the grey zones are due to the presence of meteorological clouds on the top of the ash/dust cloud.

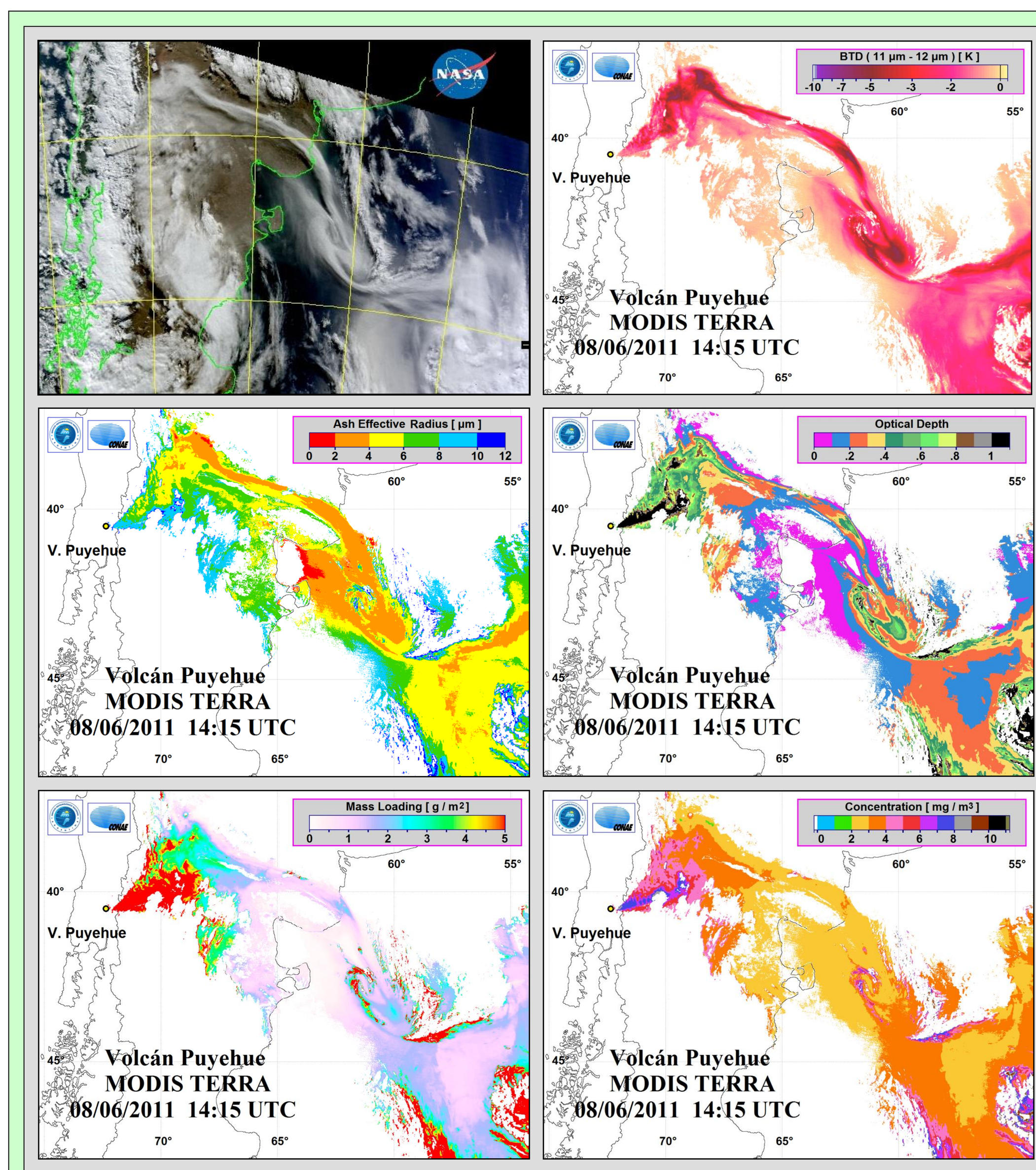
The ash/dust cloud limits are based on a discrimination threshold of -0.2 K applied to the BTD (11 - 12 µm) and the pixels with fine particles are those with 0 < β (12/11 µm) < 1 and 0.5 < β (8.5/11µm) < 0.9.



Ongoing research includes statistical analysis of these parameters and of infrared spectra and comparison with modeling schemes such as FALL-3D (Folch et al., 2013).

On the left, the figure shows the relationship between β (12/11 µm) and β (8.5/11µm) as given by the single scatter properties for various cloud compositions with a varying effective particle radius.
The Andesite and Kaolinite effective particle radius was varied from 1 to 12 µm.





QUANTITATIVE ASH RETRIEVALS :

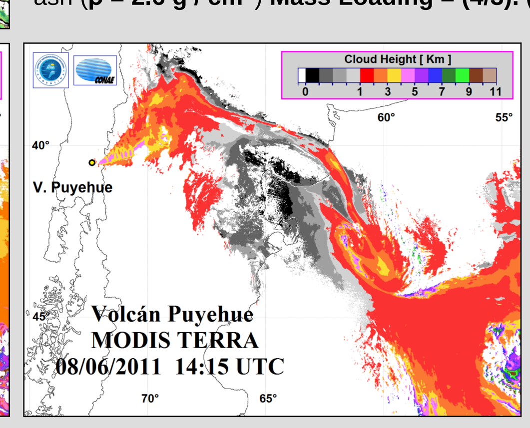
On the left, a series of products is shown, based on the simplified model of A. Prata (Quantitative Remote Sensing of Volcanic Ash, Prata - 2011).

The eruption of the Puyehue volcano, in June 2011, was characterized by the huge amount of ash dumped into the atmosphere spreading throughout the south-central region of Argentina, and the subsequent remobilization caused by the strong west winds, affecting cities, rivers, roads, animals, and serious inconveniences on air navigation.
Since the characteristics of the Patagonian soil (steppe) presents similar response to the volcanic ash, the use of the reverse absorption method BTD (11µm –12 µm) < 0 (Reverse Absorption Technique. A. Prata – 1989) is difficult, so for removing most of false positives, the images were filtered using a series of test (Complement to the Reverse Absorption Technique; M.Pavolonis et al. - 2006) adjusted for the studied area.

We have carried out preliminary tests on the quantification of mass loadings and concentration by using a simplified approach based on the brightness temperatures measured at 11 and 12 µm and a radiative transfer model that solves the infrared absorption/scattering processing of the volcanic ash clouds (Prata & Grant, 2001; Prata, 2011).

The emissivity of the bands of 11 microns and 12 microns were calculated based on the radiance and then applied to obtain the ratio of Extinction Coefficient (**β 12/11 = ln [1- *E*12] / ln [1 – *E*11]**) , the Effective Radius of the particles was obtained in a fourth order polynomial adapted MODIS (**reff = EXP (C4 (β12/11) ^ 4 + C3 (β12/11) ^ 3 + C2 (β12/11) ^ 2 + C1 (β12/11) + C0))** , and the optical depth of the distribution as a function of the emissivity of the band of 11 microns (***T* = (-) ln [1 – *E*11]**). (Algorithm Theoretical Basis / Volcanic Ash, M. & J. Sieglaff Pavolonis - 2010).

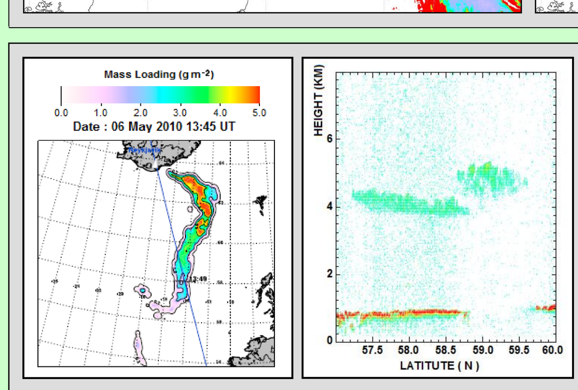
Mass Loading was calculated in function of the Effective Radius, the Optical depth, the Extinction Efficiency and density of the volcanic ash (**ρ = 2.6 g / cm³**) **Mass Loading = (4/3). (ρ. *T* . Reff) / Qext** (Infrared Imager Measurements, A. Prata - 2012)



The Extinction Efficiency (Qext) is function of the Effective Radius, the refractive index and the size distribution (Mie Algorithm). That are on tables for different radius and volcanic cloud Effective Constituents(Algorithm Theoretical Basis Document, Prata- 2013).

The concentration was estimated/plotted as a function of **BTD(11-12µm) vs. Temp.11µm** , depending on the surface temperatures and cloud top. Also it can be calculated, assuming uniform particle size distribution in a homogeneous cloud of thickness **L** as :
C = Mass Loading / L (Infrared Imager Measurements, A.Prata – 2012).

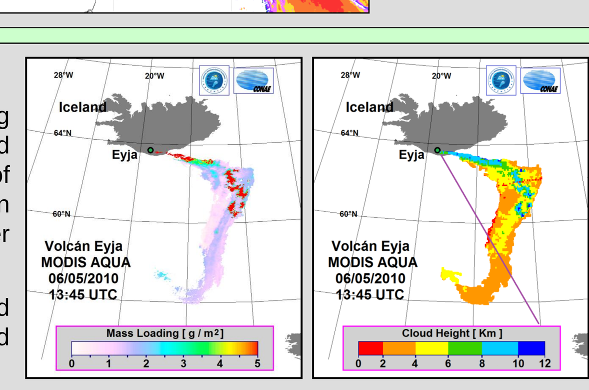
Cloud height was calculated on cloud mask and top pressure (products MOD06 & MOD35 by NASA).



EYJA ERUPTION / CONTRAST RETRIEVALS

On the left, Standard SEVIRI ash Mass Loading retrieval product for 6 May, 2010 at 13:45 UT and CALIOP backscatter corresponding to a segment of the CALIPSO overpass on 6 May, 2010 between 13:48 and 13:50 UT (Eyja Infrared Imager Measurements, A. J. Prata & A.T. Prata – 2012)

On the right, ash Mass Loading using the simplified method (Prata 2011), and ash Cloud Height derived from the Cloud Top Pressure .



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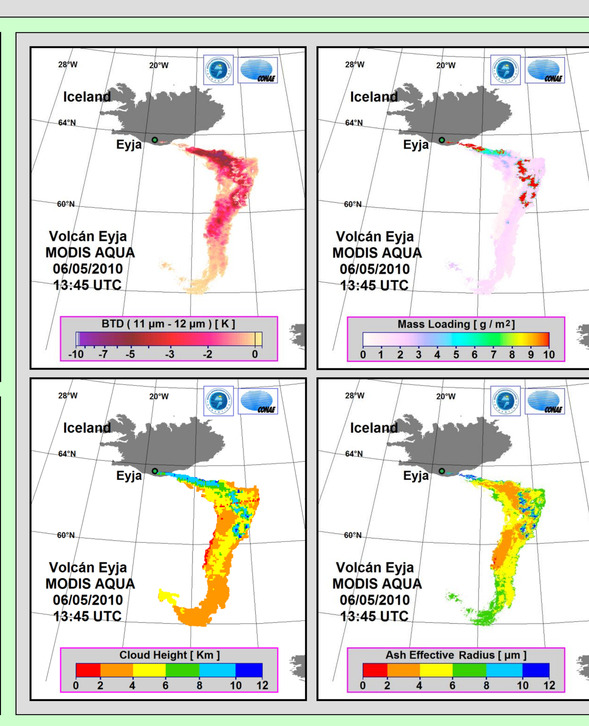

EYJA ERUPTION / CONTRAST RETRIEVALS

On the left and below, a series of products obtained through the simplified method (Prata 2011), using MODIS/ AQUA (1Km) data captured on May 06, at 13:45 UTC.

On the right, the ABI volcanic Ash products generated for the Eyja eruption captured by SEVIRI on May 06, at 12:00 UTC (Pavolonis M. & Sieglaff J., Algorithm Theoretical Basis Document for Volcanic Ash, 2010)