# Quantifying the impact of moderate volcanic eruptions on the stratosphere

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It is expected that the aerosols in the stratosphere, are predominantly sulfates resulting from natural or anthropogenic sources of precursor gases mainly: carbonyl sulfide (OCS), sulfur dioxide ($SO_2$). Sulphate aerosols are regarded as the main constituent of the "Junge layer" between the tropopause and about 30 km. This assumption is regularly challenged by detection of solid aerosols with aircraft and balloon measurements. The direct injection of gaseous $SO_2$ into the stratosphere by major volcanic eruptions is likely to generate significant amounts of sulfate aerosols that can stay for several years. Recently, Vernier et al. (2011) have shown from satellite measurements that moderate eruptions modulate the aerosol content during periods not influenced by a major volcanic eruption, called "background" periods. Surprisingly, the radiative impact of the background stratospheric aerosols over the last decade, has been found to be significant with a counterbalance to global warming (Solomon et al., 2011).

Solomon S., et al. (2011), The persistently variable "Background" stratospheric aerosol layer and global climate change, Science 333, 866 DOI: 10.1126/science.1206027.
Vernier J.-P., et al. (2011), Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade Geophys. Res. Lett., 37, doi:10.1029/2010GL044307.

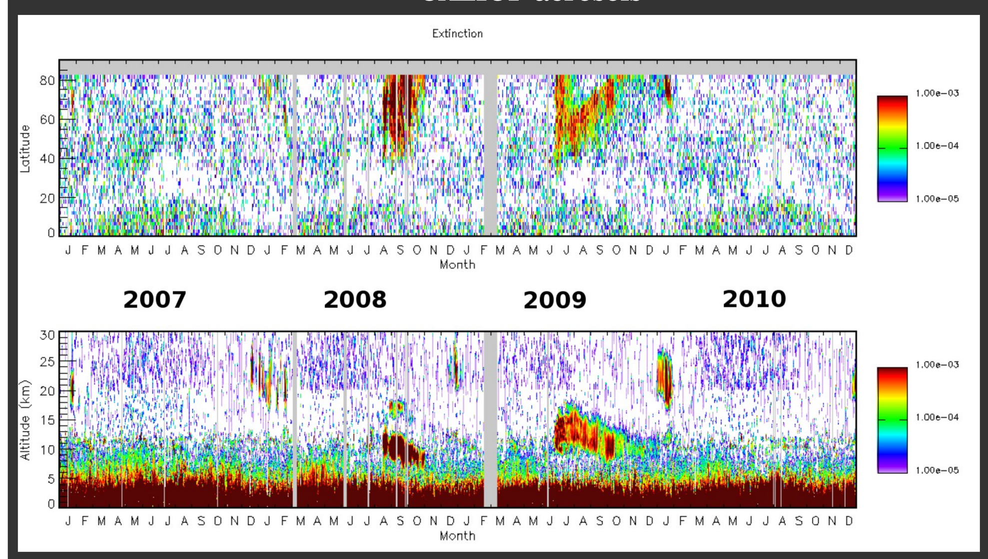
Northern high latitudes

## Sarychev eruption (12 June 2009)

In the framework of the StraPoLÉté project eight stratospheric balloons were launched from the Esrange base (Sweden) in summer 2009. A number of in-situ optical aerosol counters (STAC), a UV-visible remote sensing spectrometer for the aerosol extinction (SALOMON) and a photopolarimeter (microRADIBAL) provided information on the nature and size distribution of the stratospheric aerosols. The observations highlighted high amounts of aerosols in the lower stratosphere. These observations have been explained by the eruption in June 2009 of the Sarychev volcano(48°N, 153°E) located in the Kuril Islands which injected ash and an estimated 1 Tg of sulphur dioxide into the upper troposphere and lower stratosphere.

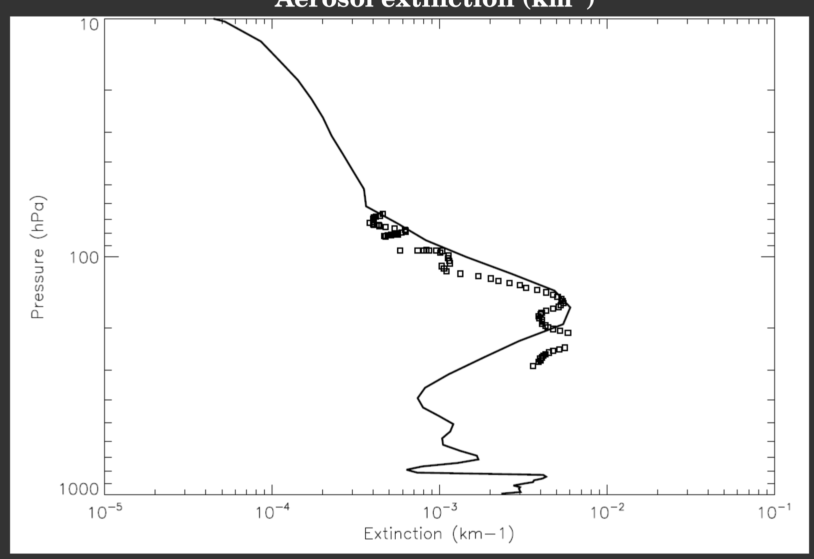
Credit:International Space Station (NASA)

### CALIOP aerosols



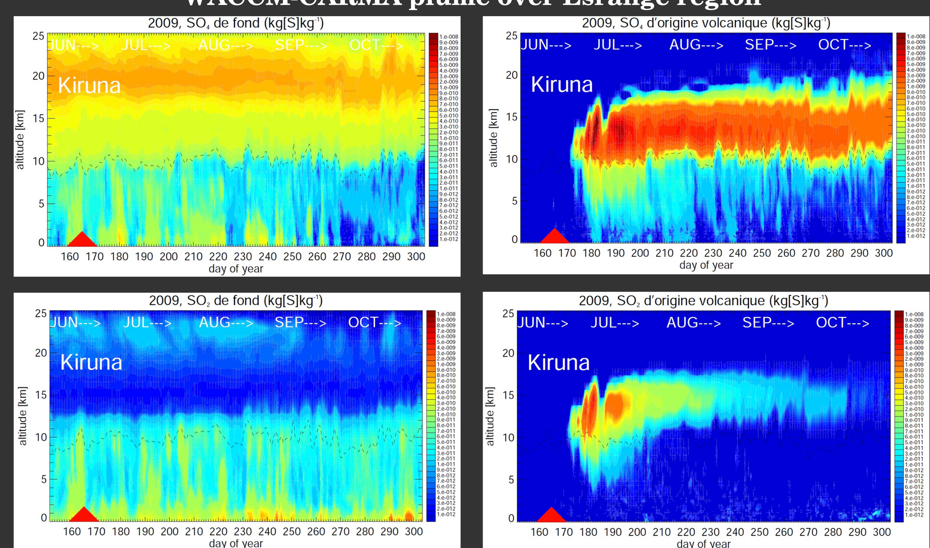

Daily mean aerosol extinction coefficient measured by the CALIOP lidar on board the CALIPSO satellite during the 2007–2010 period. Top: averaged values between 8 and 20 km and for the latitudes between 15W and 45E. Bottom: average profiles over Europe (40-80N, 15 W-45E). Grey bars represent days without data.

### Aerosol extinction (km⁻¹)



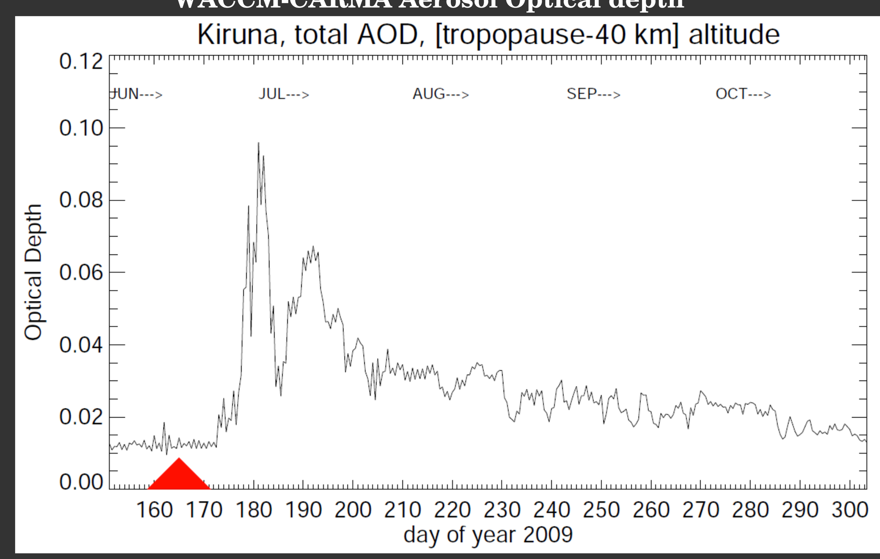

Aerosol extinction ($km^{-1}$) observed by the STAC counter on 7 July 2009 (squares) and calculated by the WACCM-CARMA model (full line).

### WACCM-CARMA plume over Esrange region




$SO_4$ (top) and $SO_2$ (bottom) daily evolution over Esrange region during June-October 2009 period calculated by the WACCM-CARMA model for the background (left) and volcanic (right) situations. The Sarychev eruption is symbolized by the red triangle. The black dotted lines are tropopause.

### WACCM-CARMA Aerosol Optical depth




AOD daily evolution over Kiruna during June-October 2009 period calculated by the WACCM-CARMA climate model. The Sarychev eruption is symbolized by the red triangle.

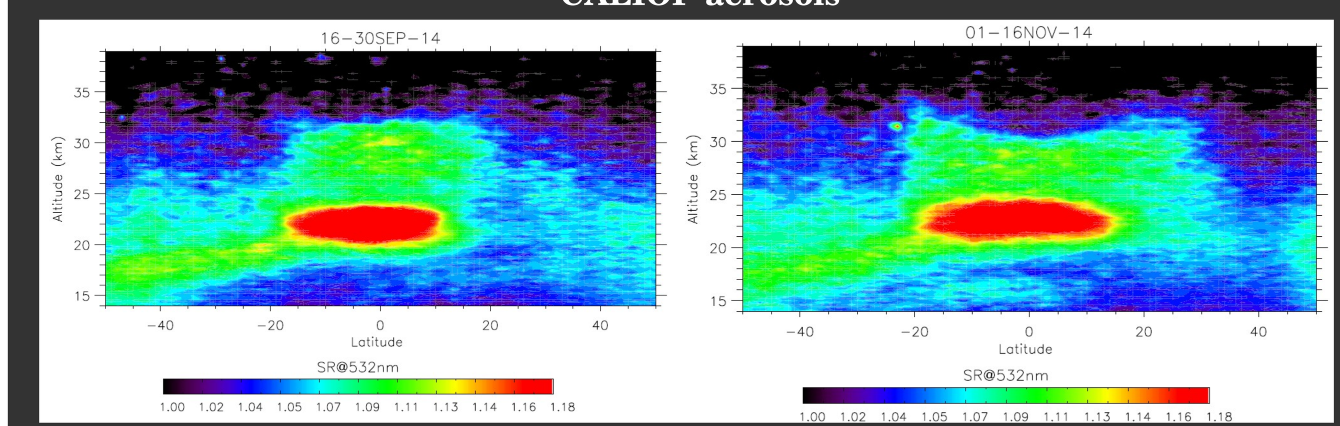
The good agreement between the WACCM-CARMA model and the observations gives evidence that moderate stratospheric eruptions control the variability of the Junge Layer. Moderate eruptions like the Sarychev eruption have the potential to increase the background aerosol loading by a factor 5 to 10.

Jégou, F. et al. (2013), Stratospheric aerosols from the Sarychev volcano eruption in the 2009 Arctic summer, Atmos. Chem. Phys. Discuss., 13, 3613-3662.

Southern tropical latitudes

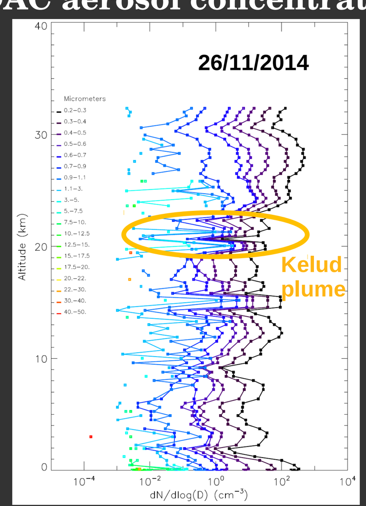
## Kelud eruption (13 February 2014)

### CALIOP aerosols

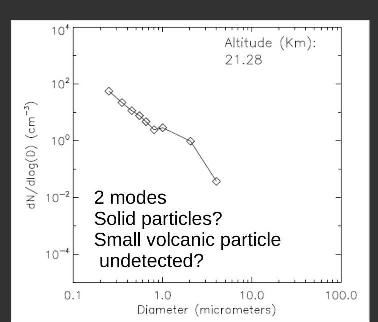



Zonally average scattering ratio observed by the CALIOP lidar on board the CALIPSO satellite during 16-30 September (left) and 01-16 November (right) 2014 period (courtesy of J.P. Vernier).

### LOAC aerosol concentrations

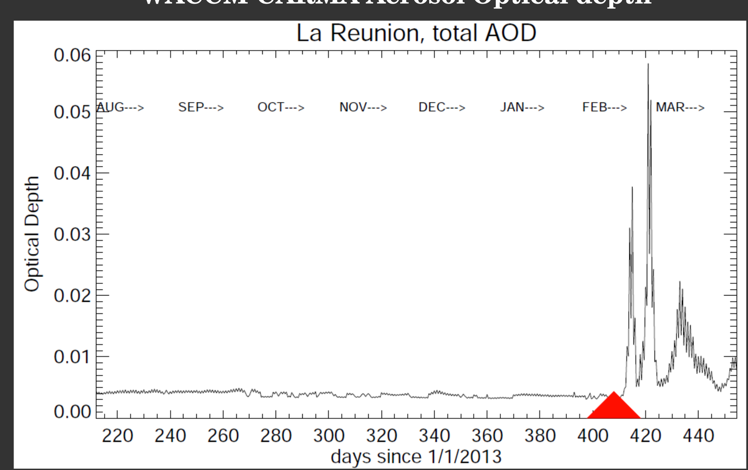



Aerosol profiles observed by the LOAC counter over the Reunion Island (20.5°S, 55.2E) on 26 November 2014. The different colours represent the 19 size ranges from 0.2µm to 50µm. The location of the Kelud plume is highlighted in orange.




Size distribution of the total number of aerosols observed by the LOAC counter over the Reunion Island (20.5°S, 55.2E) on 26 November 2014 at 21 km.

### WACCM-CARMA Aerosol Optical depth

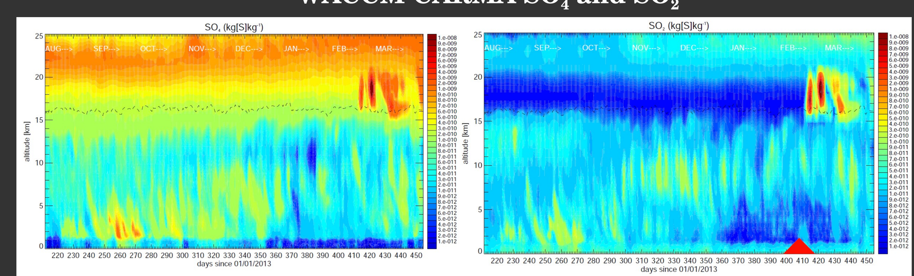



AOD daily evolution over Reunion Island between August 2013 and March 2014 calculated by the WACCM-CARMA climate model. The Kelud eruption is symbolized by the red triangle.

### Kelud eruption on 13 February 2014, Java Island (8°S-112°E)

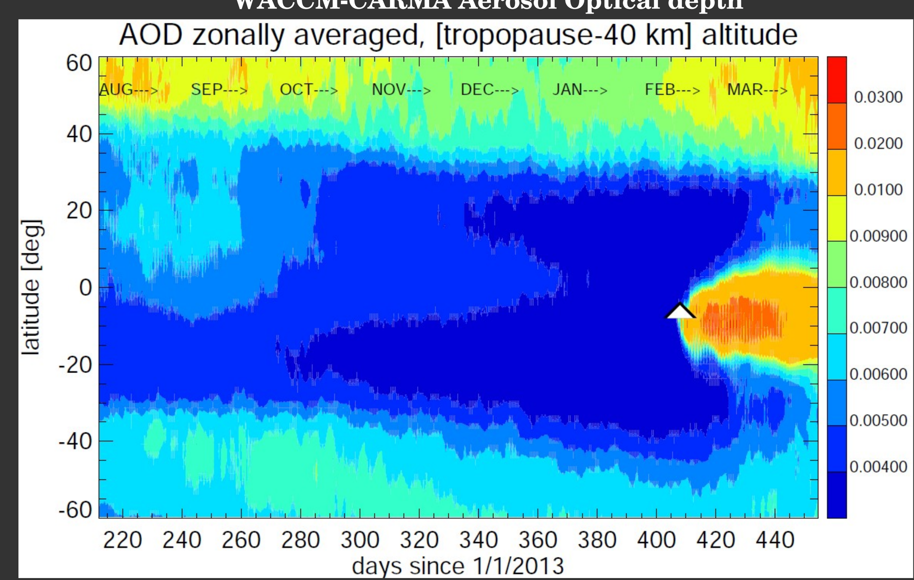
**Satellite estimation of the $SO_2$ injected: 200 kt ( IASI), 250 kt (OMI), 290 ± 30 kt (OMPS)**

### WACCM-CARMA $SO_4$ and $SO_2$



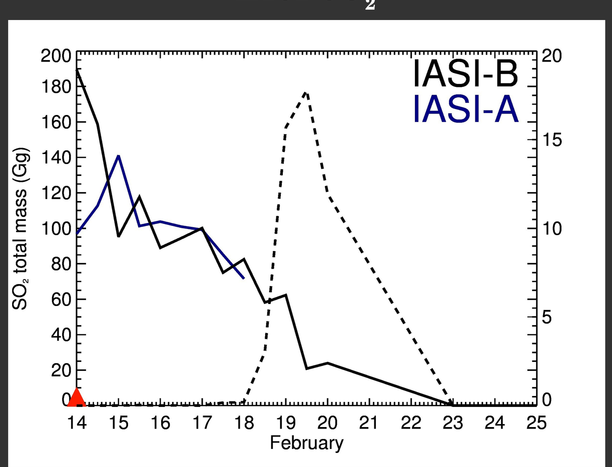
$SO_4$ (left) and $SO_2$ (right) daily evolution over Reunion Island region between August 2013 and March 2014 calculated by the WACCM-CARMA model. The Kelud eruption is symbolized by the red triangle. The black dotted lines are tropopause.

### WACCM-CARMA Aerosol Optical depth



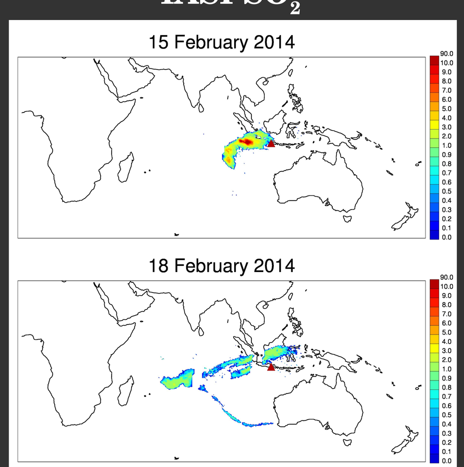

AOD daily evolution calculated by the WACCM-CARMA model over the [-60°;-60°] latitude band, from the tropopause to 40 km, and between August 2013 and March 2014. The Kelud eruption is symbolized by the white triangle.

### IASI $SO_2$




$SO_2$ total mass (Gg) over the southern hemisphere (full lines, left scale) and the Reunion Island (dashed line, right scale) observed by the IASI-A (blue) and IASI-B (black) (courtesy of L. Clarisse).

### IASI $SO_2$




$SO_2$ total column (Du) over the Indian ocean on 15 and 18 February 2014, observed by the IASI-A (courtesy of L. Clarisse).

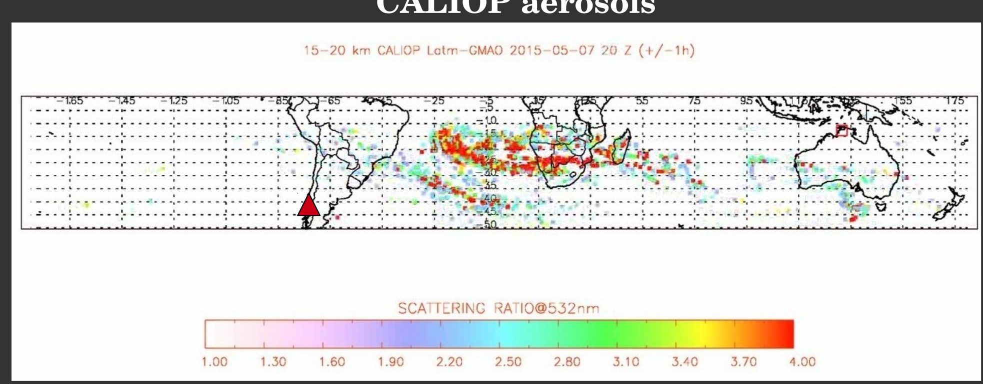
Southern sub-tropical latitudes

## Calbuco eruption (22 April 2015)

### Calbuco eruption on 22 April 2015, Chili (41.2°S-72.4°W)

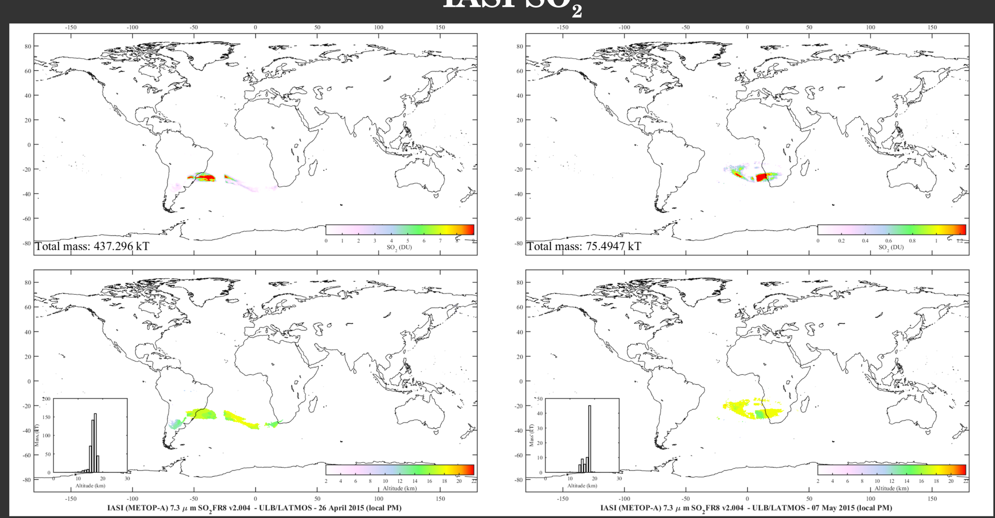
**Satellite estimation of the $SO_2$ injected : 440 kt (IASI)**

### CALIOP aerosols



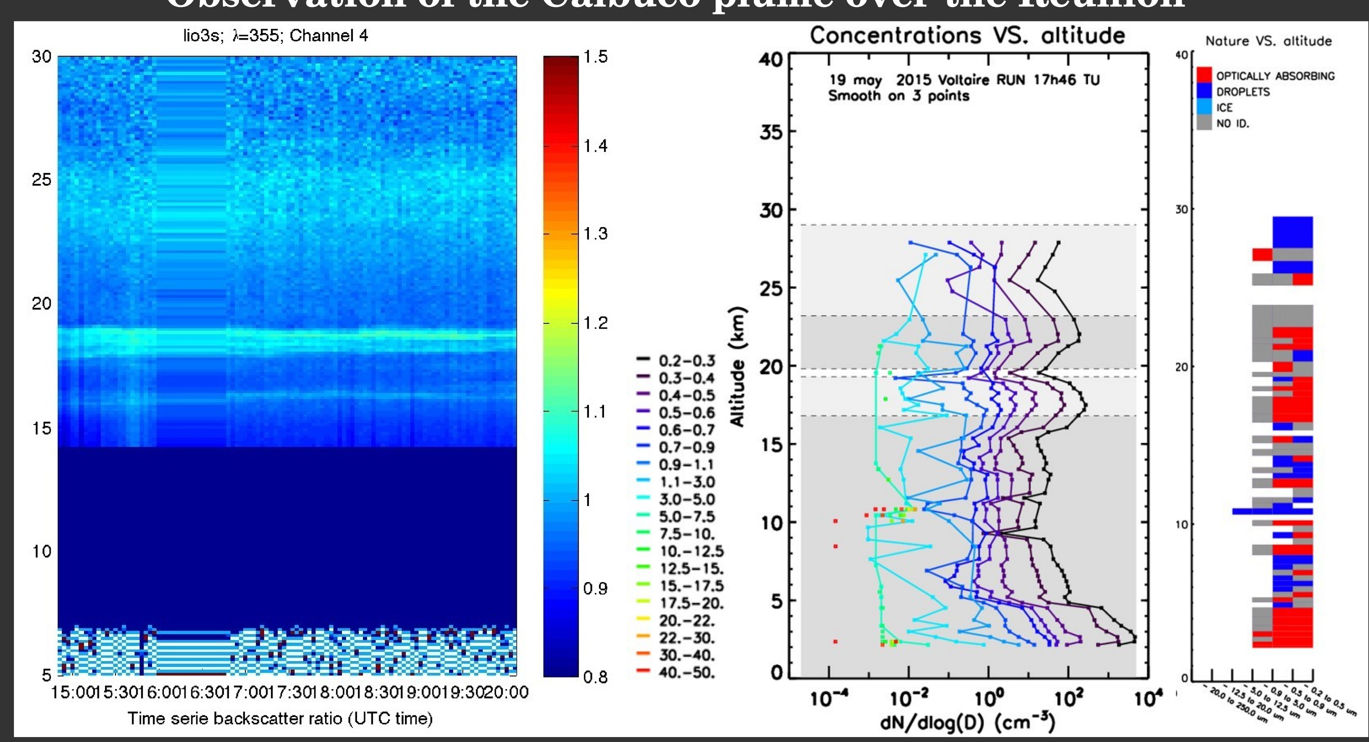

Scattering ration observed by the CALIOP lidar on board the CALIPSO satellite on 07 April 2015 over the southern hemisphere. The Calbuco volcano is symbolized by the red triangle (courtesy of J.P. Vernier)

### IASI $SO_2$




$SO_2$ total column (DU, top figures) and altitude (km, bottom figures) of the Calbuco plume observed by the IASI-B (blue) on board the METOP-B satellite (courtesy of L. Clarisse). The total mass in kT is shown in the top figures and histogram of the plume altitudes in the bottom figures.

### Observation of the Calbuco plume over the Reunion




Left figure: evolution of the backscatter ratio at 355nm observed at the MAIDO observatory (Reunion Island, France) with an ozone stratospheric lidar. right figures: concentration ans topology (optical informations on the nature) of the aerosols from 2 to 29 km obtained with the LOAC aerosol counter over the Reunion Island on 19 May 2015 in the framework of the MORGANE campaign.

The two instruments show an aerosol layer in the lower stratosphere between 18 and 21 km from the Calbuco eruption.

WACCM simulations are planned to understand the role of the dynamical barriers on the distribution of the aerosols from the Calbuco eruption.

## Perspectives

The climate effects of volcanic eruptions are well acknowledged. These effects are due to the production of a layer of sulphate aerosols in the lower stratosphere, which efficiently backscatters solar radiation, increases the planetary albedo, and causes cooling at the surface. For these radiative effects to accumulate, the aerosols must remain in the atmosphere for an extended period of time. The stratospheric aerosol e-folding lifetime is strongly dependent on the altitude of injection. The residence time of aerosols is about 1 week when the injection occurs only in the troposphere and varies from a few months for moderate eruptions to more than 1 year for major eruptions (volcanic explosive index >6).

The recurrent moderate eruptions have resulted in a net negative radiative forcing in the period subsequent to 2000, offsetting the positive radiative forcing owing to increased concentrations of well-mixed greenhouse gases and hence global warming. It is therefore important to monitor the volcanic emissions to be able to forecast the physical properties of stratospheric aerosols and to quantify their radiative and chemical impact in using Climate Chemistry Model. The LPC2E team with the new particle counter (LOAC) developed by J.-B. Renard, the Environnement S.A. and MeteoModem companies will participate to this monitoring effort.

In the last years an effort have been made to archive all the volcanic $SO_2$ emissions in an unique database. This work was achieved in the framework of the AeroCom hindcast project. All the volcanic emissions of $SO_2$ listed in the Global volcanism Program's database provided by the Smithonian Institution were put together. This new database contains the amounts and altitudes of the $SO_2$ injected from explosive and effusive eruptions from 1 January 1979 to 31 December 2010. The GES_DISC_MSVOLSO2L4_V1 Multi-Satellite Volcanic Sulfur Dioxide database has been recently developed in the framework the MEaSUREs 2012 projects. The particular project, "Multi-Decadal Sulfur Dioxide Climatology from Satellite Instruments", is expected to produce $SO_2$ data by means of combining measurements from backscatter Ultraviolet (BUV), thermal infrared (IR) and microwave (MLS) instruments on multiple satellites. Such climatologies could be used to calculate with the WACCM-CARMA model the climatic impact of all the eruptions whatever their emissions or localisations.

Future campaigns to quantify the variability of the stratospheric aerosols in the tropics are envisaged in the Reunion Island. LOAC flights with coincident lidar observations are expected. These observations could reveal the importance of the dynamical barriers on the variability of the stratospheric aerosols. These observations are also the opportunity to verify the presence of solid aerosols up to the middle stratosphere. The WACCM-CARMA model could be used to investigate the origin of these solid aerosols and the inter-annual efficiency of the dynamical barriers.

Future campaigns are also in discussion to better estimate the Asian Tropopause Aerosol Layer (ATAL) observed by the CALIOP instrument on board the CALIPSO satellite. This aerosol layer is formed each year into the monsoon anticyclone. The presence of this layer is not really understood and could be the result of the convective transport over the Indian sub-continent of the Asian pollutions and made by secondary aerosols. WACCAM-CARMA simulations with Asian regional emissions are planned to improve our understanding of the ATAL. The BATAL campaign in August 2015 was performed in this way with different instruments like the backscatter sonde COBALD or the LOAC counter.