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**Retrieval advances of BrO/SO<sub>2</sub> molar ratios from  
NOVAC**

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at the  
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## **(Titel der Masterarbeit - deutsch):**

(Abstract in Deutsch)

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## **Retrieval advances of BrO/SO<sub>2</sub> molar ratios from NOVAC:**

Measurements of magnitude and composition of volcanic gas emissions allow insights in magmatic processes. Within the Network for Observation of Volcanic and Atmospheric Change(NOVAC) automatically scanning UV-spectrometers are monitoring gas emission at volcanoes. The emissions of BrO and SO<sub>2</sub> can be retrieved from the recorded spectra by applying Differential Optical Absorption Spectroscopy(DOAS) and comparing the optical absorption of the volcanic plume to the background. Therefore, the background spectrum must not be affected by volcanic influence. Classically, the background spectrum is taken from the same scan but from a elevation angle which has been identified to be outside of the volcanic plume. However, experience shows those background spectra can still be contaminated by volcanic gases. Alternatively reference spectra can be derived from 1) a theoretical solar atlas spectrum or 2) a volcanic-gas-free reference spectrum recorded by the same instrument. 1) comes with a drawback of reduced precision, as the instrumental effects have to be modeled and added to the retrieval. For 2), the alternative reference spectrum should be recorded at similar conditions with respect to meteorology and radiation. We use the first option to check for contamination and the second to evaluate the spectra to maintain a god fit quality. We present our approach and its results when applied on NOVAC data from Tungurahua and Nevado Del Ruiz.

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# 1 Introduction

Volcanic activities on Earth have always shaped the earth surface and influenced atmospheric processes. Volcanoes are often particularly recognized by their dramatic consequences of a major volcanic eruption. But volcanoes influence our lives in more than this way. Volcanic gases can effect the weather (timescales of days to weeks) or the climate (timescales of months to years) Schmidt and Robock [2015]. Examples are the lake eruption in Iceland (1783-1784) followed by a very hot summer and a cold winter in central Europa Thordarson and Self [2003] and the Tambora eruption, indonesia in 1815 which caused the "year without summer" in 1816.

Considering the plate tectonics of earth most volcanoes are caused by diverging or converging of the continental plates and therefore located at the margins of the continental plates. Another possibility for occurrence of volcanoes is the the interior of continental or oceanic shelves. Schmincke [2000]

The most abundant volatile species released during a volcanic eruption are water vapour ( $H_2O$ ; relative amount of the plume: 50%-90%) and carbon dioxide ( $CO_2$ ; relative amount of the plume: 1%-40%) Platt and Bobrowski [2015]. But the short effects of those two gases are rather low since there effect on atmospheric composition is negligibly due to the high abundance of atmospheric  $H_2O$  and  $CO_2$ . But on timescales of the age of the earth the volcanic emission of  $H_2O$  and  $CO_2$  are the source of our current atmosphere. Schmidt et al. [2015]

A typically volcanic plume consists of many different gases alongside  $H_2O$  and  $CO_2$  sulfur dioxide ( $SO_2$ ) contributes with 1%-25% to the plume, hydrogen sulfide ( $H_2S$ ) with 1%-10% and hydrogen chloride with ( $HCl$ ) 1%-10%. Furthermore there are trace gases for example carbon disulfide ( $CS_2$ ), carbon sulfide ( $COS$ ) carbon monoxide ( $CO$ ) hydrogen fluoride ( $HF$ ) and hydrogen bromide ( $HBr$ ) Platt and Bobrowski [2015]

A decrease of stratospheric ozone ( $O_3$ ) has been observed after the eruption of El Chickon in 1982 and the eruption of mount Pinatubo 1991. A depletion stratospheric  $O_3$  results in ozone holes. The depletion comes from volcanic aerosols which serve anthropogenic chlorine/bromine into more reactive forms Solomon et al. [1998]. Volcanic gases can alter the radiative balance of the earth in timescales relevant for climate change due to scatter and absorption of solar radiation Schmidt et al. [2015]. The gas composition of the volcano plume change with activity and could be a indication for the processes inside the earth.

In this work we are particularly interested in the ratio of  $BrO$  and  $SO_2$ . The halogen sulfur ratio is a proxy for volcanic processes. Therefore we make the assumption that the ratio of  $BrO$  and  $SO_2$  contains informations about its degassing source

depth. A change in BrO/SO<sub>2</sub> prior to eruption was observed at Etna and Nevado del Ruiz.

To gain further knowledge about the volcanoes the Network for Observation of Volcanic and Atmospheric Change (NOVAC) was installed. NOVAC is a Network of DOAS Instruments located next to about 30 volcanoes in America, Africa and Europe. At every Volcano there are two to four DOAS Instruments installed, recording record back-scattered solar radiation spectra at different viewing angles.

NOVAC is a network which produces a large amount of data and we have the chance to evaluate long time periods which is a unique opportunity to study correlations of the trace gases.

Since the conditions at volcanoes are rough, the instruments need to be rather simple to keep the maintenance cheap and to assure a longer lifetime of the instruments. So we need to waive on temperature stabilization even at the expense of the quality of the data.

One possibility to measure the volcanic trace gases is to use Differential Optical Absorption Spectroscopy [Platt and Stutz \[2008\]](#). DOAS exploit the wavelength dependency of the absorption of light. Here the gas emissions can be retrieved from the quotient of the absorption signal of the volcanic plume and a reference region. This will be explained in a further chapter.

The reference region, is usually treated as free of volcanic trace gases. If the reference region is for any reason contaminated by volcanic trace gases, the reference spectrum has to be replaced by a volcanic-gas-free reference. Alternative spectra could be for example a theoretical solar atlas spectrum or a volcanic-gas-free reference spectrum recorded in the temporal proximity(eg. a day before) by the same instrument. The first option comes with the drawback of reduced precision, as the instrumental effects have to be modeled and added to the retrieval. The reduction in precision is acceptable for the SO<sub>2</sub> retrieval, but not suitable for a BrO retrieval because then most data would be below the detection limit. For the second option, the alternative reference spectrum should have been recorded at similar conditions with respect to meteorology and radiation as well as in the temporal proximity due to instrumental changes with time and ambient conditions. We combined both options in order to achieve both, enhanced accuracy but still maximum possible precision of the SO<sub>2</sub> and BrO retrievals. We present an algorithm which finds the optimal reference spectrum automatically. As first step, a possible SO<sub>2</sub> contamination of the standard reference is checked by a comparison with the theoretical solar atlas. If a contamination is detected, as second step, the algorithm picks a volcanic-gas-free reference (beforehand automatically checked for contamination) from another scan.

In this work we are mainly dealing with data from Tungurahua in Ecuador in the timespan of 01.08.2008 to 30.07.2009. Later on, we will also show the results of Nevado del Ruiz a volcano located in Colombia.



# Part I

## Theoretical Background

## 2 Volcanism and volcanic chemistry

### 2.1 Volcanism

The high thermal energy in the deep interior of the earth is mostly well separated from the earth's surface by the earth's crust. A volcano is geological structure that allows magma to reach the earth's surface. Such a phenomenon can occur in various ways. In the following paragraphs the different types of volcanoes are described.

**Mid-ocean ridge volcanism** The mid-ocean ridge volcanism can be traced back to tectonic processes of oceanic plates. The spreading of two plates, that are pulled apart, leads to a thinning of the oceanic earth crust. This way solid material from the upper mantel (lower than 100 km) can ascend to depths of approximately 50 km. As the pressure at this depth is much lower, the mantle material starts to melt to basaltic magma that fills the gap between the two plates.

**Continental rift zone volcanism** Similar to mid-ocean ridge volcanism continental rift zone volcanism results from two continental plate are pulled apart.

**Subduction zone volcanoes** Subduction zone volcanoes occur if an oceanic plate converges under another plate (oceanic or continental). This way the descending plate penetrate into the lower mantle. At a depth of 80-150 km the water of this plate evaporates and rises and causes the mantle material above to melt. The resulting water-rich magma mainly consists of andesite. Subduction zone volcanoes are known for their violent eruptions caused by the low viscosity magma.

**Hot-spot volcanoes** Hot-spot volcanoes occur on continental or oceanic plates. This type of volcanoes arises from a hot spot at the coremantle boundary inside Earth that leads to a plume in the mantle where solid material can rise. This material melts to basaltic magma at a depth of 100-150 km. Through a futher rise also other types of magma (e.g. rhyolitic, more-viscous magma) can arise. **volcano, n.: 1. Physical Geogr.** A hill, mountain, or other feature, typically conical in form, that is built up of solidified lava and rock debris and has a crater or vent through which, in periods of activity, molten rock (lava), rock fragments, steam, and gas are emitted from within the planet's crust Oxford English Dictionary (2013) This chapter starts with a brief introduction to the reasons for volcanism and explains the different types of volcanism. Its purpose is to provide an overview of the complex processes happening during the long journey from the mantle and crust inside the Earth to

the point at which the gases can be measured in the atmosphere. From melting rock and the magma degassing to the chemistry happening in the atmosphere, there are numerous processes influencing the amounts of gas and composition that are ultimately measured. The basics of volcanism described in Section 2.1 mainly follow the textbooks by Schmincke (2003), Francis and Oppenheimer (2004) and Frisch and Meschede (2013). The basic concepts of volatile degassing from the magma and which processes influence the chemical composition of the gases will be explained in Section 2.2. The chemistry of sulphur and bromine after their release into the atmosphere as well as the implications of volcanic degassing on the atmosphere and the Earth's climate will be discussed in Section 2.3. The introductory chapter will conclude in Section 2.4 with examples of the usefulness of volcanic gas emission measurements. An outlook will be given as to how measurements of the SO<sub>2</sub> emission rate and the chemical composition can be used to gain knowledge about volcanic systems and especially how they can help to improve the accuracy of volcanic eruption forecasts. 7

### 2.1.1 Volcanic degassing

Volcanoes emit large quantities of various gases during eruptions but also during phases characterized by quiescent degassing. Emissions of volcanic gases into the atmosphere can influence the climate and serve as a precursor of volcanic activity. Even more, in most cases the exsolution of volatiles from the magma is the driving force behind the volcanic eruption. This demonstrates the importance of studying volcanic gas emissions. When measuring volcanic gas emissions it is crucial to understand the origin of the gas in order to find meaningful interpretations of the results. It is necessary to understand how gases are exsolved from the magma, how they are transported to the surface and which interactions during gas ascent can alter the gas composition. A simple model based on Henry's law can be used to explain degassing of volatiles from magma and the variability in the gas composition. Henry's law describes which equilibrium concentration  $c$  of a gas can be dissolved in a liquid with a Henry's constant  $k$  at a gas pressure  $p$ :  $c = k \cdot p$  (2.1) In this model the melt starts at depth in a single liquid phase. As the magma rises the pressures decreases while  $c$  stays constant. When a volatile reaches saturation (i.e.  $c > k \cdot p$ ) a second gas phase forms in addition to the liquid melt. This process is referred to as first boiling. The Henry's constant and thus the solubility of a volatile in the melt depend on the system's temperature as well as on the chemical composition of the liquid and the volatile. Another process called second boiling is caused by crystallization in magma that cools down. As most crystals contain almost no volatiles, the crystallization process leads to an increased concentration of volatiles in the melt, and can lead to degassing without changes of the system's pressure. This model can help explain the importance of measuring the ratio between different trace gases. Figure 2.2 shows an example of degassing due to Henry's law. Figure 2.2 (a) shows the vesicularity<sup>1</sup> of a melt as a function of depth. The vesicularity is shown for different starting concentrations of CO<sub>2</sub> and for three values of

the CO<sub>2</sub>/H<sub>2</sub>O ratio. Higher CO<sub>2</sub> concentrations lead to exsolution of gas at greater depth, as does a higher CO<sub>2</sub>/H<sub>2</sub>O ratio. A magma with a start concentration of 1000 mg CO<sub>2</sub> per kg melt and a CO<sub>2</sub>/H<sub>2</sub>O ratio of 5 has a vesicularity of 50 all CO<sub>2</sub> and 70 the SO<sub>2</sub> and almost none of the HCl are exsolved. When ascending further the degassing of HCl will start at a depth of 100m while at this depth most of the H<sub>2</sub>O has already exsolved. The composition of gases can therefore evolve, and in this example the SO<sub>2</sub>/HCl ratio would decrease during magma ascent. Using this model gas compositions can give insights into processes at depth and the equilibrium temperatures at which the gas phase was formed as long as the gas phase remains unchanged during ascent (Edmonds, 2008). In reality, however, exsolved gas bubbles need to rise to the surface to be observed. The rise of gas to the surface can alter the chemical composition and lead to patterns in the observed gas emission rates. While the mechanisms and how they can lead to degassing patterns will be described below, it is first necessary to address how the rise of gas can lead to variations in the chemical composition: Temperature changes of the ascending gas can lead to a re-equilibration (i.e., SO<sub>2</sub> reacts to H<sub>2</sub>S at decreasing temperatures) and gases can also interact with crustal rock or groundwater during ascending. According to Giggenbach (1996) the composition of gases due to processes at depth does not vary during “conventional observational periods”. The author claims that most variations observed are not caused by variations of the magma at depth but due to processes during the ascent of the gases. However, these processes and therefore also the gas composition might still vary with volcanic activity. After gas bubbles are formed they need to ascend for degassing at the surface to occur. Two different models are frequently used to describe the behaviour of gas bubbles after their formation: the rise speed dependent (RSD) model and the collapsing foam (CF) model (Parfitt, 2004). In the RSD model bubbles form during magma ascent. As gas bubbles always have a lower density than the magma they are buoyant. Depending on the magma rise speed and the viscosity of the magma, the RSD model can explain two mechanisms for degassing. In a low-viscosity magma that ascends with a low velocity, the gas phase can form bubbles that can rise to the surface separately from the magma. This is called open-system degassing. During their ascent gas bubbles can also coalesce and form larger bubbles that rise faster. If the gas phase can leave the magma, the viscosity of the magma decreases, which in turn slows down the ascent. In magmas with higher viscosity and a relatively high rise speed the bubbles might not be able to coalesce but grow by diffusion and decompression. Gas bubbles cannot separate from the magma, but ascend together with the magma until it is erupted. This process is called closed-system degassing. The formation of a gas phase that rises together with the magma decreases the magmas density and can thus be a trigger for a faster magma ascent. The RSD model can be used to explain periodicities in volcanic activity. A simple model with a one-dimensional volcanic conduit containing rising magma is explained in Sparks (2003a,b). In this system the magma can obtain the two different steady states described above, which can be summarized as:

- Slow-ascending magma, in which bubbles can coalesce and leave the magma and the viscosity increases.
- Fast-ascending magma, in which bubbles

form but cannot coalesce and rise with together the magma. This leads to lower-density magma which accelerates even more. Figure 2.3 shows the magma flow rate as a function of magma chamber pressure. Between A and B we have the steady state where gas can leave the magma (open-system degassing). If the pressure in the conduit increases further, caused by material originating from the magma chamber the flow rate increases. At point B, the magma rises too fast for bubbles to coalesce and the system jumps directly to state C (there is no steady solution between B and D). In this regime the magma rises too fast for bubbles to escape. The gas phase leads to a lower density and this further accelerates the magma, which leads to an eruption of the system. In the eruptive state between point C and D material is transported out of the conduit faster than it is replenished from the magma chamber and the systems pressure decreases. The decreasing pressure and flow rate lead to point D. At point D the magma chamber pressure is too low to keep up the explosive regime, and with a further decreasing magma chamber pressure the system drops back to open-system degassing at point A. In the CF model magma is stored in a magma chamber or a dyke system at some depth (Parfitt, 2004). Bubbles form and rise to the top of the reservoir where they form a closely packed gas foam layer. Once the foam reaches a critical thickness, it collapses and forms a large gas bubble that rises up to the surface driving the volcanic eruption (Vergniolle, 1996). Depending on the viscosity of the magma either an annular flow (low viscosity) or a periodic series of gas slugs resulting from partial collapse of the foam (high viscosity) can be observed. The CF model can also explain periodicities in degassing patterns by the time needed to rebuild the foam layer to a critical thickness after its collapse. Magma does not necessarily need to erupt for degassing to occur. Degassed magma is more dense than volatile rich magma, and convection can lead to degassing, where the degassed magma sinks back into the magma chamber. This process can lead to substantial amounts of degassing without any erupted magma (Kazahaya et al., 1994; Stevenson and Blake, 1998). It is also often the case that more gas is released during an eruption than can be dissolved in the magma that was erupted. For example, during the 1982 eruption of El Chicón, Mexico, 40 times more gas was measured than was estimated from the erupted magma with petrological methods (Shinohara, 2008)

### 2.1.2 Volcanic gases and their impact on the climate

Volcanoes emit large amounts of gases into the atmosphere. In descending magnitude the most important gases are H<sub>2</sub>O, CO<sub>2</sub>, various sulphur species led by SO<sub>2</sub> and H<sub>2</sub>S and halogen compounds (see Table 2.1). While water vapour is the most abundant gas in a volcanic plume, and responsible for the condensation of the plume that can be observed at many quietly degassing volcanoes from large distances, the total abundance is negligible when compared to evaporation from oceans. CO<sub>2</sub> emissions are thought to have played an important role during the formation of Earth's atmosphere. However, today CO<sub>2</sub> emission from volcanoes are several orders of magnitude smaller than anthropogenic CO<sub>2</sub> emissions. While anthropogenic

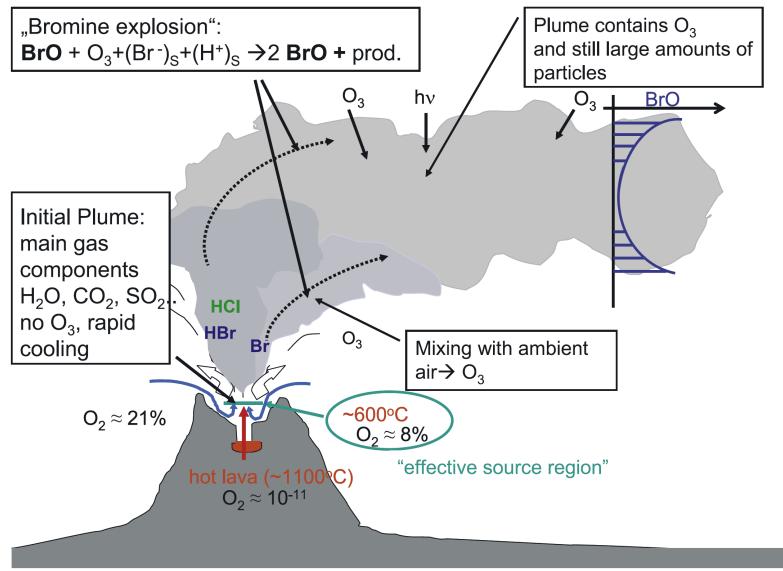


Figure 2.1: schematic sketch of a Bromine Explosion. Release of HBr at the volcanic vent. Mixing with ambient air in the effective source region leads to Br formation. This resulting Bromine species react to BrO with ozone from the plume. Adapted from Bobrowski et al. [2007]

CO<sub>2</sub> emissions were roughly 35 Gt (gigatons) in 2010, volcanic CO<sub>2</sub> emission estimates ranged between 0.13 - 0.44 Gt per year, comparable to the CO<sub>2</sub> emissions from countries as Pakistan (0.18Gt), Kazakhstan (0.25 Gt) or South Africa (0.44 Gt) (Gerlach, 2011, and references therein). However, on time scales of 105 a CO<sub>2</sub> degassing has an important role in the Earth system, since it offsets CO<sub>2</sub> burial in the sediments. SO<sub>2</sub> is the third most abundant gas and can be measured by remote sensing in the UV. It is therefore often measured as a proxy for volcanic activity. The yearly global SO<sub>2</sub> emissions by volcanoes range between 7.5 - 10.5TgSyr<sup>-1</sup> (Halmer et al., 2002) and are therefore of the same magnitude as anthropogenic SO<sub>2</sub> emissions (55TgSyr<sup>-1</sup> for the year 2000 were given in IPCC, 2013). SO<sub>2</sub> and BrO are the two trace gases in volcanic plumes that are the main topic of this thesis. This chapter therefore gives a brief overview over the chemistry of SO<sub>2</sub> and BrO in the atmosphere after emission from the volcanic vent. The impacts of volcanic gas emissions on the environment and especially the influence of SO<sub>2</sub> on the Earth's climate will be discussed following Robock (2000). The part about SO<sub>2</sub> summarizes parts of the review paper by Oppenheimer et al. (2011) and the chemistry of BrO is based on the papers of Bobrowski et al. (2007) and von Glasow (2010). Both parts also contain ideas from von Glasow et al. (2009). Regardless of the path of SO<sub>2</sub> scavenging, dry or wet deposition or oxidation to sulfuric acid, the molecule can influence the environment in several ways. A local effect, especially compared to the influences on the Earth's climate, are direct influences of SO<sub>2</sub> on humans (respiratory problems, asthma) and plants in the areas affected by volcanic gases. Acid rain caused

by volcanic plumes can prevent the growth of plants. Darrall (1989) reviewed the influences of SO<sub>2</sub> on photosynthesis, and found that long-term exposures with SO<sub>2</sub> concentrations between 100 - 250 ppb can inhibit photosynthesis of plants. Delmelle et al. (2002) measured SO<sub>2</sub> concentrations around Masaya volcano, Nicaragua. The authors found concentrations of up to 230 ppb and an area downwind of the volcano with a decreased number of plant communities. Similar studies were done by Longo et al. (2005), who studied SO<sub>2</sub> concentrations and fine aerosol downwind of Kilauea volcano on Hawaii. The authors found high SO<sub>2</sub> concentrations of over 61.9 ppb with atmospheric sampling in the Kau desert south of Kilauea crater. Despite these lower SO<sub>2</sub> concentrations, plant growth is largely diminished in the Kau desert. Fig. 2.4 gives an impression of plants in the Kau desert. It should be noted, though, that while SO<sub>2</sub> certainly has negative effects on plant life other species in the volcanic plume (e.g., HF) are most likely deposited within close proximity of SO<sub>2</sub> on the ground as well. Sulphur influences on the Earth's climate On a global scale, SO<sub>2</sub> and especially its oxidation product sulphuric acid have a large impact on Earth's climate. The total annual SO<sub>2</sub> emissions are low compared with anthropogenic emissions. Halmer et al. (2002) estimated mean annual S emitted as SO<sub>2</sub> by volcanoes between 1972 and 2000 to be in the range between 7.5 - 10.5TgSyr<sup>-1</sup>. The estimates for anthropogenic SO<sub>2</sub> emissions for the year 2000 have a mean value of 55TgSyr<sup>-1</sup> (IPCC, 2013). However, Graf et al. (1997) suggested that the impact of volcanic SO<sub>2</sub> emissions is higher, since they are released into the free troposphere or into the stratosphere during eruptions, whereas most anthropogenic emissions are released into the planetary boundary layer. After emission into the atmosphere SO<sub>2</sub>, is oxidised to sulphuric acid. The lifetime of sulphuric acid in the troposphere is only about 1 week compared with up to one year in the stratosphere (IPCC, 2013). Sulphuric acid directly influences the climate by backscattering radiation from the sun and thus increasing the Earth's albedo. Even more importantly it serves as additional cloud-condensation nuclei (CCN), which results in more and finer condensed particles and therefore in whiter, more-stable clouds and also an increased albedo of Earth (Twomey, 1974, and Fig. 2.5). This leads to more back-scattered radiation (see Fig. 2.5) and more diffusively scattered radiation. The net result of the back-scattered radiation is cooling of the Earth atmosphere, which is the dominating radiative effect of volcanic gases (Robock, 2000). Additionally, aerosol particles can also act as surfaces for heterogeneous reaction cycles that destroy ozone, especially in the stratosphere, which leads to an increased solar flux to the Earth. Larger aerosol particles can backscatter IR radiation emitted from the Earth's surface and the lower atmosphere and thus slightly reduce the net cooling effect in the lower troposphere. Absorption of direct UV and IR radiation from the sun as well as of radiation emitted by the Earth leads to net heating of the stratosphere. The 2013 IPCC report (IPCC, 2013) states that the radiative forcing caused by volcanoes was -0.11 Wm<sup>-2</sup> between the years 2008 and 2011 (for comparison, the radiative forcing of CO<sub>2</sub> was given as 1.68Wm<sup>-2</sup>). Another, counter-intuitive effect is the winter warming in the Northern Hemisphere, which is caused by changes of the stratospheric and tropospheric circulation patterns due to strong temperature gradients

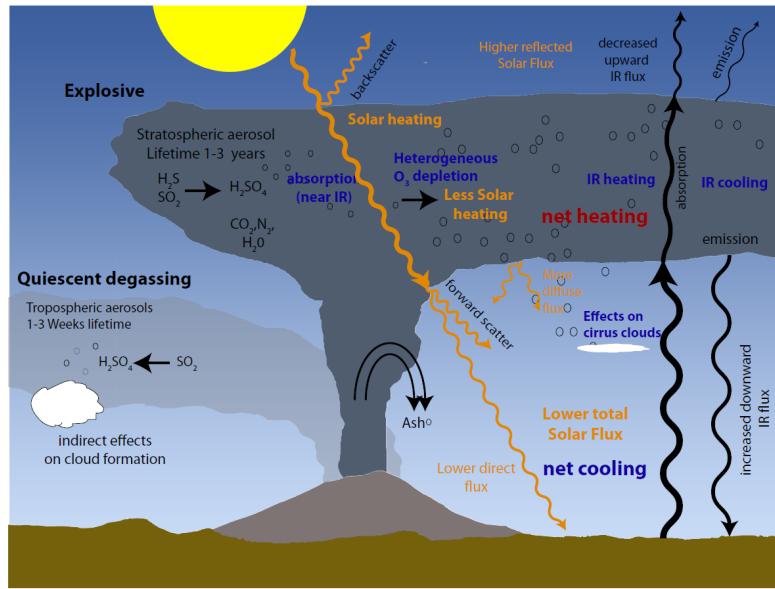


Figure 2.2: Influence of volcanic eruptions and quiet degassing on earth climate.  
Redrawn on the basis of Robock [2000]

between the Arctic and equatorial regions (Robock, 2000).

### 2.1.3 Volcanic plume chemistry

#### 2.1.4 Sulphur species

**2.3.1 Sulphur species** Sulphur species, mainly  $\text{SO}_2$  and  $\text{H}_2\text{S}$  are the third most abundant species in volcanic plumes after  $\text{H}_2\text{O}$  and  $\text{CO}_2$ .  $\text{SO}_2$  contributes up to 25% of the volume of the volcanic plume and  $\text{H}_2\text{S}$  ranges between 1 - 10%. As opposed to the two most dominant species,  $\text{SO}_2$  does not have considerable background levels in the atmosphere. The  $\text{SO}_2$  concentration in the atmosphere is usually below 1 ppb while the concentration in a volcanic plume can easily achieve levels of 1 ppm (Oppenheimer, 2003a). The low background values together with the stability and the relatively strong UV absorption make  $\text{SO}_2$  an easily accessible tracer for volcanic gas emissions (see next Section 2.4). After their release from the reducing conditions in the volcanic vent the gases enter the atmosphere, which is an oxidising environment.  $\text{H}_2\text{S}$  is slowly oxidized to  $\text{SO}_2$  when released into the atmosphere. The first step is the reaction of SH. The SH radical then undergoes a series of reactions in the atmosphere that lead to the formation of  $\text{SO}_2$  (Seinfeld and Pandis, 2006). Theoretically  $\text{H}_2\text{S}$  can react with the halogen radicals Cl and Br to form SH, which results in  $\text{H}_2\text{S}$  lifetimes of only a few seconds (Aiuppa et al., 2007). However, Aiuppa et al. (2007) could not reproduce these low  $\text{H}_2\text{S}$  lifetimes in measurements that showed a constant  $\text{SO}_2/\text{H}_2\text{S}$  ratio at distances up to several kilometres from the vent.  $\text{SO}_2$  is removed from the atmosphere by wet and dry deposition or oxidized to sulphuric

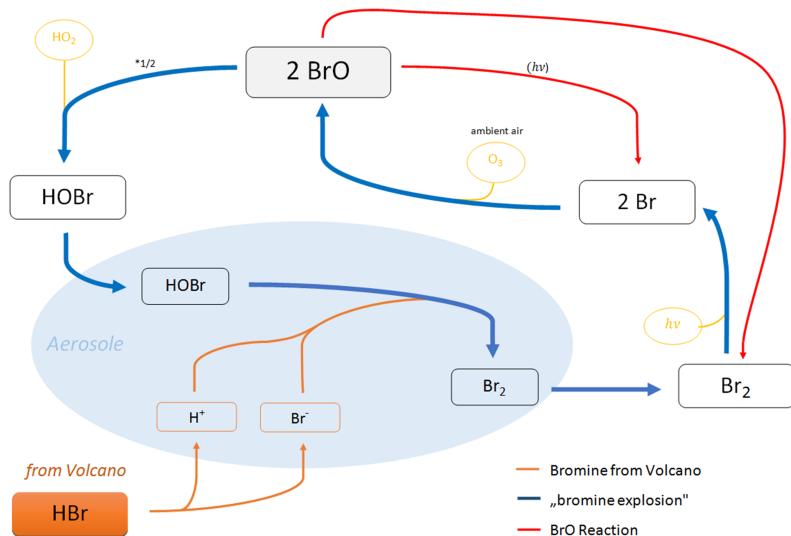


Figure 2.3:

acid. In the gaseous phase the reaction with OH to sulphuric acid is rather slow: The rate constant  $k$  in Eq. C2.4 is given for 50et al. (2004). Möller (1980) calculated an SO<sub>2</sub> loss rate of  $k = 1.2 \cdot 10^{-6} \text{ s}^{-1}$  for homogeneous reactions in the gas phase, or converted to hours a loss of 0.43SO<sub>2</sub> per hour. In heterogeneous reactions, such as reactions of SO<sub>2</sub> on particles or in the liquid phase of particles, the oxidation process is much faster. Möller (1980) gave loss rates of  $k = 0.1 - 1 \cdot 10^{-5} \text{ s}^{-1}$  for reactions of SO<sub>2</sub> on aerosol particles and  $k = 5 \cdot 10^{-5} \text{ s}^{-1}$  for liquid phase oxidation. The equations for the reaction of SO<sub>2</sub> in the liquid phase are (Möller, 1980): 3 can be further oxidized to sulphuric acid or sulphate, e.g. by a reaction with OH (Platt and Stutz, 2008). The oxidation of SO<sub>2</sub> can also take place on aerosol particles by reactions with O<sub>3</sub>, H<sub>2</sub>O<sub>2</sub>, HOCl, HOBr or oxygen if catalysts (iron, manganese) are available (von Glasow et al., 2009). Considering these different pathways and regarding the importance of SO<sub>2</sub> as a tracer for volcanic activity and for the comparison of SO<sub>2</sub> with other trace gases, it is worthwhile to compare measured SO<sub>2</sub> loss rates with the values given above. There are only a few reports of high SO<sub>2</sub> loss rates. Jaeschke et al. and 7  $\cdot 10^{-4} \text{ s}^{-1}$ , which would lead to an e-folding time between only 16 and 23 minutes. However, older data listed in Oppenheimer et al. (1998) showed times between 5 hours and several weeks. McGonigle et al. (2004) studied the depletion rate of SO<sub>2</sub> using the DOAS technique at Masaya volcano, Nicaragua. The authors found that there are negligible variations of up to 500 s - 2000 s after release from the volcano. Furthermore, the authors argue that Jaeschke et al. (1982) had problems with using CO<sub>2</sub> as a tracer to compare the SO<sub>2</sub> concentration. Meanwhile Oppenheimer et al. (1998) based the calculated loss rates on only a few traverse measurements, thus being influenced by variations in the total emission rate from the volcano as well as errors from wind speed and direction. Oppenheimer et al. (1998) measured ash plumes during the wet season at Soufriere Hills, Montserrat.

Repeated measurements at the same volcano with more traverses during the dry season and ash-free volcanic plumes, found an one order of magnitude slower SO<sub>2</sub> loss rate (Rodríguez et al., 2008). Recent studies from satellites by Beirle et al. (2013) investigated the SO<sub>2</sub> loss rates at Kilauea, Hawaii. The authors found mean monthly SO<sub>2</sub> life times between 16 and 57 h, with the longer lifetimes in summer, when the cloud coverage is lower. While satellites are not able to assess potential SO<sub>2</sub> loss close to the volcanic vent due to restrictions of their spatial and time resolution, this study still shows slow SO<sub>2</sub> loss rates with robust observations over a long time-scale. In this work it is assumed that SO<sub>2</sub> is stable during the time frame that usually occurs during ground-based remote sensing measurements (a few up to several tens of minutes during this thesis).

### 2.1.5 Bromine oxide

2.3.2 Bromine oxide Bromine oxide (BrO) was detected for the first time at Soufriere Hills volcano (Montserrat) by Bobrowski et al. (2003). Since then, BrO has been detected at many volcanoes by ground-based measurements (e.g., Bobrowski and Platt, 2007; Bobrowski et al., 2007; Oppenheimer et al., 2006; Vogel, 2011) or from airborne platforms (Heue et al., 2011; Kelly et al., 2013). Theys et al. (2009) were able to detect BrO from satellite after the Kasatochi eruption in 2008, and Hörmann et al. (2013) were able to find BrO in volcanic plumes from 11 erupting volcanoes with data from the GOME-2 instrument. However, it is actually mainly HBr, not BrO, that is emitted from volcanoes. BrO is formed after the volcanic gas mixes with ozone-rich ambient air. Gerlach (2004) and Martin et al. (2006) used thermodynamical equilibrium calculations to assess the source of bromine and found that there is not enough Br or BrO in hot magmatic gases to explain the BrO concentration measured, e.g. at Soufriere Hills by Bobrowski and Platt (2007). Instead, the volcanic gases mix with atmospheric air at high temperatures, in the so-called effective source region (Bobrowski et al., 2007), see Figure 2.6. This can be compared to a chimney, where hot air released from the volcano pulls in atmospheric air through the permeable edifice (Gerlach, 2004). The mixing process at high temperatures changes the gas composition and leads to an increase in bromine species other than HBr such as Br, Br<sub>2</sub> and BrO (Martin et al., 2006; von Glasow, 2010). Further mixing with atmospheric air leads to cooling down to ambient temperatures where the so-called Bromine Explosion starts. The term Bromine Explosion originates from BrO observations in polar regions, where a similar non-linear increase in BrO concentration has been observed (Hönniger and Platt, 2002; Lehrer et al., 1997; Wennberg, 1999). The Bromine Explosion mechanism can be summarized as: C2.8 and C2.9 describe the uptake of HBr and HOBr on the surface of an aerosol particle and subsequent transformation into the liquid phase. At low pH < 6.5 (Fickert et al., 1999) or at cold temperatures H<sup>+</sup>, Br<sup>-</sup> and HOBr react to form Br<sub>2</sub> (C 2.10) that is then released back into the gas phase (C 2.11). Br<sub>2</sub> reacts to Br via photolysis if sunlight is available (C 2.12). The necessity of solar radiation for the Bromine Explosion in volcanic plumes was verified by Kern et al. (2009), who could measure

elevated BrO during daytime, but not at night at Masaya volcano, Nicaragua. In the next step Br that was formed from Br<sub>2</sub> and O<sub>3</sub> reacts to BrO (C 2.13). The role of O<sub>3</sub> in Eq.C2.13 was shown by Bobrowski et al. (2007) and Louban et al. (2009) who measured higher BrO/SO<sub>2</sub> ratios at the edges of the volcanic plume rather than in the middle of the plume, where less ambient (ozone-rich) air is available. Kelly et al. (2013) was able to measure the evolution of ozone depletion in volcanic plumes from an airborne platform. BrO can react with HO<sub>2</sub> to form HOBr again leading back from C2.15 to C2.9. The result of this reaction cycle is the formation of BrO and the destruction of O<sub>3</sub>. BrO can also react with another BrO molecule to form Br<sub>2</sub> or Br (C. 2.15 and 2.16), which in turn would react again to BrO. The Bromine Explosion reaction cycle is schematically shown in Figure 2.7. Considering the multitude of chemical reactions that take part in the formation of BrO and because BrO is a secondary volcanic gas, there is some discussion as to whether BrO/SO<sub>2</sub> ratio can be a useful indicator of volcano activity. If BrO/SO<sub>2</sub> ratios are used as an indicator of volcanic activity, influences from the formation of BrO in the atmosphere have to be ruled out or characterized carefully. SO<sub>2</sub> can be regarded as stable during times that are typically observed in ground-based remote sensing observations (see above). Perspectives on the time scales of BrO formation have changed over the last couple of years. Bobrowski et al. (2007) and Roberts et al. (2009) estimated an increase in the BrO/SO<sub>2</sub> ratio up to several tens of minutes after release from the vent. Newer publications and an improving dataset led Bobrowski and Giuffrida (2012) to the conclusion that the BrO/SO<sub>2</sub> ratio increases in the first minutes after release from the volcano, and then stays constant for some time (see Figure 2.8). Vogel (2011) and Gliß (2013) were able to measure the evolution of the BrO/SO<sub>2</sub> ratio in the young plume of Pacaya volcano and Etna volcano respectively using horizontal DOAS scanning measurements and found a strong increase within the first five minutes after release. Vogel (2011) also measured the BrO/SO<sub>2</sub> ratios in ageing plumes at Mt. Etna and found a constant ratio for plume ages of up to two hours. It has not been sufficiently examined if the BrO/SO<sub>2</sub> ratio depends on the ratio of Br/S exsolved from the magma. Nevertheless, it is import to rule out influences of atmospheric chemistry in order to find a meaningful interpretation of BrO/SO<sub>2</sub> ratios. The influence of the time following the mixing of volcanic gas with the ambient atmosphere will be discussed in Chapter 5.

## 2.1.6 Using volcanic gases to study volcanic activity

2.4 Using volcanic gases to study volcanic activity There are many factors influencing the degassing of volatiles and the composition of gases after and during the release from the volcanic vent. Furthermore the plume composition changes when it reacts with the oxidizing atmosphere. Therefore interpreting volcanic degassing data is complex. For example, Oppenheimer et al. (2011) reported in their review paper on SO<sub>2</sub> degassing, that decreasing SO<sub>2</sub> fluxes have been ascribed to:

- depletion of volatiles in a magma body
- decreased permeability of the magma in the conduit

The first process can be regarded as an indicator of decreasing volcanic activity.

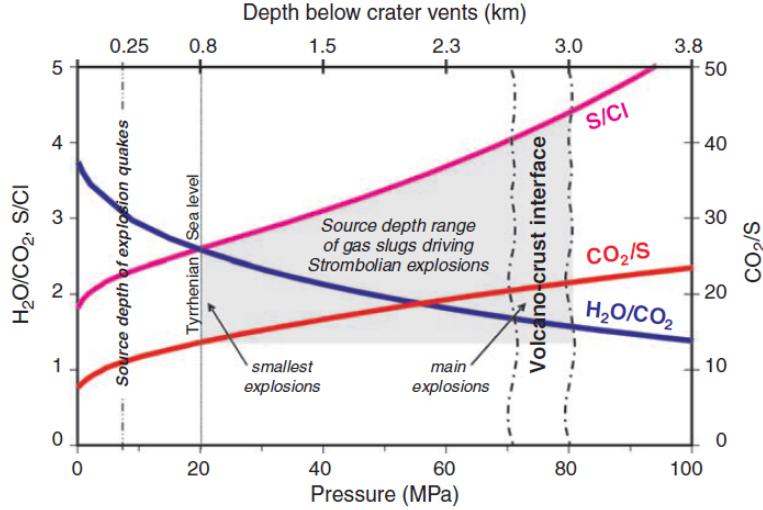


Figure 2.4: Dependency of the ratios of different volcanic trace gases on depth. Data originate from Stromboli volcano. From Lübcke [2014] reproduced from Burton et al. (2007)

The second process can be caused by, for example, the formation of a plug when degassed magma starts crystallization. The plug leads to a build up of gas pressure and ultimately might lead to an eruption (Clarke, 2013). Therefore the observation of decreasing SO<sub>2</sub> emission rates can indicate an increase as well as a decrease of volcanic activity. Despite these complications, measurements of volcanic gases can be an important additional tool for the forecasting of volcanic activity to accompany the classic monitoring techniques like seismicity or deformation measurements. The remote sensing of volcanic gases started with the correlation spectrometer COSPEC (Moffat and Millan, 1971; Stoiber et al., 1983) in the 1970 s. COSPEC measurements together with fumarolic sampling helped, for instance, predict the eruptions of Mount St. Helens, USA, in August 1980 and June 1981 (Casadevall et al., 1983) or Pinatubo, Philippines, in 1991. The remote sensing of volcanic SO<sub>2</sub> experienced further spreading world-wide with the availability of miniature spectrometers (Galle et al., 2003) that measure the SO<sub>2</sub> column density by using Differential Optical Absorption Spectroscopy (DOAS, Platt and Stutz, 2008). Besides being smaller and cheaper, these miniature spectrometers using the DOAS technique have additional advantages for fieldwork in rugged environments, as they are lighter and consume less power. Additionally the availability of more spectral information allows for the correction of radiative transfer problems (Kern, 2009, and also Chapter 3) and to retrieve other trace gases (e.g. O<sub>3</sub>, NO<sub>2</sub> or BrO). An important step towards continuous monitoring of volcanic SO<sub>2</sub> emission rates was made with the Network for Observation of Volcanic and Atmospheric Change (NOVAC, Galle et al., 2010). During this EU-funded project scanning DOAS instruments were installed at several volcanoes world-wide. The spectroscopic data for the BrO/SO<sub>2</sub> ratios evaluated

within this thesis were recorded by the NOVAC network, which will be discussed in more detail in Chapter 5. Besides the monitoring instruments and the network itself, the detection of abnormally high SO<sub>2</sub> emission rates at Santa Ana volcano (El Salvador) before the eruption in 2005 was the first big success of the project (Olmos et al., 2007). These measurements helped to plan the evacuation of thousands of people living in the vicinity of Santa Ana volcano. Scanning DOAS instruments need approximately 5 – 15 minutes for one scan across the complete sky. These techniques are therefore rather suited to measure long-term variations in the SO<sub>2</sub> emission rates. A lot of additional information can be gained when using instruments that allow emission rate measurements with a higher time resolution. Boichu et al. (2010) used two spectrometers with an optical system that led to a wide field-of-view covering the complete volcanic vent at Mount Erebus, Antarctica. This set-up allowed SO<sub>2</sub> emission rate measurements with a time resolution of the order of 1 Hz. Frequency analysis of the data revealed patterns with periods between 11 and 24 minutes that allowed discussion of different models for the degassing at Mt. Erebus. The SO<sub>2</sub> camera, which is also used in large parts of this thesis, makes SO<sub>2</sub> emission rate measurements with a similar time resolution possible. Holland et al. (2011) used SO<sub>2</sub> camera measurements at Santiaguito, Guatemala to identify shear-fracturing as the main process leading to cyclic patterns of explosive eruptions rather than building of a viscous plug. Tamburello et al. (2013) applied SO<sub>2</sub> cameras at Etna, Italy, using a similar approach as Boichu et al. (2010), and suggested that periodic signals with periods between 40 – 250 s and 500 – 1200 s are caused by bursting of rising gas bubbles. First steps in the direction of the analysis of high time resolution SO<sub>2</sub> camera data are presented in Chapter 4 of this thesis. In addition to the SO<sub>2</sub> emission rate, the ratio between different trace gases can be indicative of volcanic activity as well. The solubility of volatiles depends, e.g. on depth and chemical composition of the magma (see Chapter 2.1), therefore the composition of volcanic gases has been studied in depth. A good introduction to gas compositions and their interpretation can be found in Giggenbach (1996). A more recent review article about halogens in volcanic system was published by Aiuppa et al. (2009). Initial studies (e.g. Noguchi and Kamiya, 1963) investigated the Cl/S ratio by direct sampling. The authors found a decrease of the Cl/S ratio before an eruptive period (Noguchi and Kamiya, 1963; Stoiber and Rose, 1970). Later Pennisi and Le Cloarec (1998) found that Cl and F degas in a similar manner, while the Cl/S ratio varied between non-eruptive and eruptive periods. The authors argue that chlorine is exsolved from the magma at deeper levels (Cl/S > 1) while at shallower levels sulphur degassing dominates (Cl/S CO, SO<sub>2</sub> and HCl) by remote sensing using an open-path Fourier transform infrared spectrometer (OP-FTIR) at Stromboli, Italy. The authors found that the ratio of CO<sub>2</sub>/SO<sub>2</sub> and SO<sub>2</sub>/HCl were 3-5 times higher during explosions than during quiescent degassing. These observations paired with higher equilibrium temperatures lead the authors to the conclusion that the explosions are driven by gas slugs that originate from a deeper level than gas observed during quiescent periods. The authors then used melt inclusion data and a chemical model simulating degassing of magma to interpret the data. The

S/Cl and H<sub>2</sub>O/CO<sub>2</sub> ratios show that bigger explosions originate from a depth of approximately 2.7 – 3km while smaller eruptions originate from depths as shallow as 0.8 km below the crater at sea level. The BrO/SO<sub>2</sub> ratio has been measured using DOAS remote sensing measurements by several authors (e.g., Bobrowski and Platt, 2007; Bobrowski et al., 2003, 2007; Hörmann et al., 2013; Kelly et al., 2013; Oppenheimer et al., 2006; Theys et al., 2009; Vogel, 2011). However, despite naming the possibility to use BrO/SO<sub>2</sub> ratios as an additional tracer for volcanic activity, most of these studies focused on the formation of BrO in the atmosphere. First long-time measurements at Etna, Italy, were published by Bobrowski and Giuffrida (2012). The authors measured the BrO/SO<sub>2</sub> ratio covering the years 2005 - 2009 and found higher ratios during non-eruptive periods. During four eruptive periods BrO/SO<sub>2</sub> ratios were higher three months before the eruption compared to the ratios observed one month before the eruption. Studies on the seasonal variability and the influence of humidity did not reveal obvious correlations. The authors suggested a model in which bromine is released earlier than sulphur during the magma's ascent to explain the observed behaviour.

## **Tungurahua**

Tungurahua is a subduction zone volcano located in the Ecuadorian Andes (Lat: 01°,28'S; Long:78°,27'W). 2014 Tungurahua was one of the most active volcanoes in southern America, since then the activity was decreasing. Tungurahua is 5023m high and is one of the defining volcanoes of the eastern volcanic rows in Ecuador. Hall et al. [1999]

## **Nevado Del Ruiz**

Nevado Del Ruiz is also a subduction zone volcano. Nevado Del Ruiz is located in the Central Cordillera of Colombia, 140 km west of Bogota. (Lat: 04°,53'S; Long:75°,19'W) The hight of Nevado Del Ruiz is 5389 m.

### 3 Remote sensing of volcanic gases

In this thesis we are interested in the volcanic trace gases SO<sub>2</sub> and BrO, both measured with the Differential Optical Absorption Spectroscopy (DOAS) a remote sensing technique proposed by [Platt and Stutz \[2008\]](#)

#### Beer-Lambert Law

The Lambert-Beer law describes the attenuation of light when traveling through a material.

This section will give an overview about the reasons for decreasing light intensity when going through a medium.

Atoms and Molecules exists in several energy states, depending on the different electron configuration. Moreover Molecules have additionally rotation and vibration states, also enclose to the energy states. If a photon matches the energy gap between two possible energy states, this includes, that the lower energy state is occupied and the selection rules are fulfilled the molecule could absorb the photon, remaining in a higher energy state.

The additional photon energy could be loosed by collision with another molecule or by emission. But since the direction of the emitted photon is mostly not the same direction of the absorbed photon the intensity I<sub>0</sub> of the light before passing the medium is higher than the intensity I after traveling the distance L through the medium.

This can be described as:

$$I(L, \lambda) = I_0(\lambda) \cdot \exp \left( - \int_0^L \sigma(\lambda, p, T) \cdot c(l) dl \right) \quad (3.1)$$

where  $c(l)$  is the location-dependent concentration of the trace gas of interest.  $\sigma(\lambda, p, T)$  is the absorption cross section,  $\sigma(\lambda, p, T)$  is unique for each molecule and depends on pressure p and on the temperature T.

An important quantity used in many optical remote sensing techniques is the optical density  $\tau$ . The optical density is a measure for the weakening of radiation when going through a material.  $\tau$  can be calculated using the lambert beer law:

$$\tau = -\ln \left( \frac{I(\lambda)}{I_0(\lambda)} \right) = \sigma \cdot S \quad (3.2)$$

Hereby is  $S$  the column density. The column density is the concentration of the trace when integrating along the light path, the dimension of  $S$  is therefore the number of molecules divided by an area:  $\frac{\text{molec}}{\text{cm}^2}$ .

$$S = \int_0^L c(l) dl \quad (3.3)$$

When measuring at a volcano, that means measuring in the atmosphere the situations gets more complex, since we need to deal with several absorbers and scattering processes have to be taken into account. One possibility is to treat scattering effects as pseudo absorbers with the respective extinction coefficients for Rayleigh ( $\epsilon_R$ ) and Mie ( $\epsilon_M$ ) scattering

$$I(L, \lambda) = I_0(\lambda) \cdot \exp \left( - \int_0^L \sum_j \sigma_j(\lambda, p, T) \cdot c_j(l) + \epsilon_R(\lambda, l) + \epsilon_M(\lambda, l) dl \right) \quad (3.4)$$

The first term of eq. (3.4) in the exponential function, multiple absorbers  $j$  are considered, the corresponding concentration depends on the position  $l$  of the light path. The last two terms in describe the extinction due to Rayleigh and Mie scattering in the atmosphere.

Inelastic scattering (for example the Ring effect) and effects due to turbulences in the atmosphere are neglected here.

### 3.1 Differential Optical Absorption Spectroscopy(DOAS)

It is impossible to distinguish between various broad-band effects, like scattering in the atmosphere or instrument effects which influence the measured spectra [Lübcke \[2014\]](#). Therefore eq. (3.4) cannot be applied to real measurements.

Differential Optical Absorption Spectroscopy (DOAS) was invented in the late 1970s by [Perner and Platt \[1979\]](#). This section will give an overview about the DOAS technique. More detailed information can be found in the work of [Platt and Stutz \[2008\]](#)

Differential Optical Absorption Spectroscopy uses the fact, that absorption can be divided into broad-band parts and narrow-band parts. Broad band parts are effects that only changes weakly with the wavelength, i.e. scattering and instruments effects have a broad-band structure. The narrow band part includes effects that strongly depends on the wavelength. Within the DOAS-Method only narrow-band absorption features of molecules are used to obtain their column densities. The absorption cross section of trace gases  $j$  have broad-band ( $\sigma_b(\lambda)$ ) and narrow band ( $\sigma'(\lambda)$ ) features, only the narrow-band structures are used in DOAS.

$$\sigma(\lambda) = \sigma_b(\lambda) + \sigma'(\lambda) \quad (3.5)$$

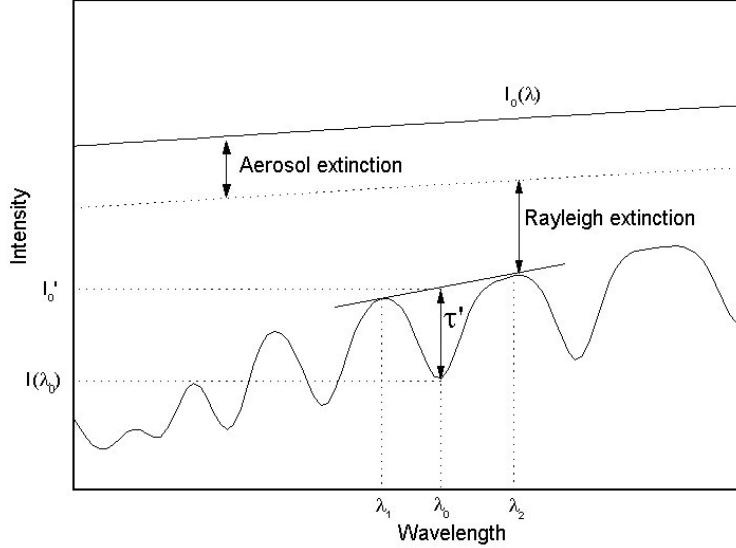


Figure 3.1: Basic idea of the DOAS principle: Light attenuate due to broad band and narrow band effects. The broad band extinction is caused by aerosols and Raylight scattering ( $I_0 \rightarrow I'$ ). The measured intensity  $I$  is formed by narrow band effects due to differential absorption structures by trace gases with the optical density  $\tau'$ . Adapted from Kern [2009]

With this considerations the Lambert-Beer law eq. (3.4) can be rewritten dividing the exponential part into a narrow-band part and a broad-band part:

$$I(\lambda, L) = \overbrace{I_0(\lambda) \cdot \exp \left( - \int_0^L \sum_j \sigma_{b,j}(\lambda, p, T) \cdot c_j(l) + \epsilon_R(\lambda, l) + \epsilon_M(\lambda, l) dl \right)}^{=I'_0(\lambda)} \cdot \exp \left( - \int_0^L \sum_j \sigma'_j(\lambda, p, T) \cdot c_j(l) dl \right) \quad (3.6)$$

The so defined  $I'_0(\lambda)$  differs from  $I_0(\lambda)$  only by broad band effects. With  $I'_0(\lambda)$  a differential optical density  $\tau'$  can be defined:

$$\tau' = \ln \left( \frac{I'_0(\lambda)}{I(\lambda)} \right) = \int_0^L \sum_j \sigma'_j(\lambda) \cdot c_j(l) dl = \sum_j \sigma'_j(\lambda) \cdot S_j \quad (3.7)$$

The optical density can now be calculated by using the difference of the column density  $S_M$  in the measurement spectrum to the column density  $S_R$  of a reference spectrum. From Equation (3.6) we know:

$$I_{P,R} = I'_0 \cdot \exp(-S_{P,R} \cdot \sigma(\lambda)) \quad (3.8)$$

In general the obtained column density  $S_M$  is called differential slant column density: "dSCD". If the reference spectrum does not contain the trace gas of interest (is not contaminated with trace gases) that means  $S_R = 0$ ,  $S_M$  is called the slant column density (SCD). With Equation (3.8) the optical density can be derived by:

$$\tau(\lambda) = -\ln\left(\frac{I_M}{I_R}\right) = \sigma(\lambda) \cdot (S_M - S_R) \quad (3.9)$$

### 3.1.1 Technical Implementation of the DOAS Approach

The theory explained above only describes the ideally situation. In real measurements more problems occur due to instrument limitations inelastic scattering causing the Ring effect and due to impacts of external parameters like temperature. In the following a short overview about these problems and their consequences for our retrieval is given. Further information can be found in Lübecke [2014].

#### Optical and spectral resolution of the spectrometer

The resolution of the spectrometer is finite, thus, the detector receives a spectrum  $I^*(\lambda)$  which can be retrieved with a convolution of the incident spectrum  $I(\lambda)$  with the instrument function  $H(\lambda)$ :

$$I^*(\lambda) = I(\lambda) * H(\lambda) = \int I(\lambda - \lambda') \cdot H(\lambda - \lambda') d\lambda' \quad (3.10)$$

For the evaluation all  $\sigma_j$  of the trace gases of interest need to have the same spectral resolution as the instrument used for recording the spectra. In this work we will use high resolution cross sections and convolute them with the instrument function  $H$ :

$$\sigma*(\lambda) = \sigma(\lambda) * H(\lambda) \quad (3.11)$$

The instrument function  $H$  can be approximated by using the spectral lines of a mercury lamp since the width of those lines is only a few pm, they could be treated as delta peaks when comparing it to the resolution of the spectrometers.

#### Effects of the detector

The detector only has discrete pixels, therefore a wavelength interval is mapped to a pixel  $i$ .

$$I'(i) = \int_{\lambda(i)}^{\lambda(i+1)} I^*(\lambda'd) d\lambda' \quad (3.12)$$

For the retrieval the relationship between the detector channels and the wavelength of the spectrum need to be known. The wavelength to pixel mapping (WMP) for a detector with  $q$  channels can be calculated as:

$$\lambda(i) = \sum_{k=0}^{q-1} \gamma_k \cdot i^k \quad (3.13)$$

Hereby, is  $\gamma_0$  a shift of the spectrum and  $\gamma_1$  is a squeeze (respectively stretch) of the spectrum. The wavelength to pixel mapping can be discovered by using a mercury lamp again and compare pixel-position with the well known wavelength of the individual HG-lines of the mercury lamp.

The wavelength to pixel mapping depends on the instrument temperature as well as on the ambient pressure Lübcke et al. [2014].

### Ring effect

As mentioned above inelastic scattering causes the Ring effect (named after Grainger and Ring, 1962). The Ring effect is observable through a filling of the Fraunhofer lines in spectra of scattered solar radiation, (e.g. if the sunlight travels through the earth atmosphere). When compared to direct sunlight measurements (e.g. outside of the earth atmosphere). (Bussemer [1993], Solomon et al. [1987]) proposes that the Ring effect is a result of rotational Raman scattering mainly of  $O_2$  and  $N_2$  in the atmosphere. Solomon et al. [1987] suggested to treat the Ring effect as a pseudo-absorber.

## **Part II**

### **Evaluation of the Data of Tungurahua and Nevado Del Ruiz**

## 4 Network for Observation of Volcanic and Atmospheric Change

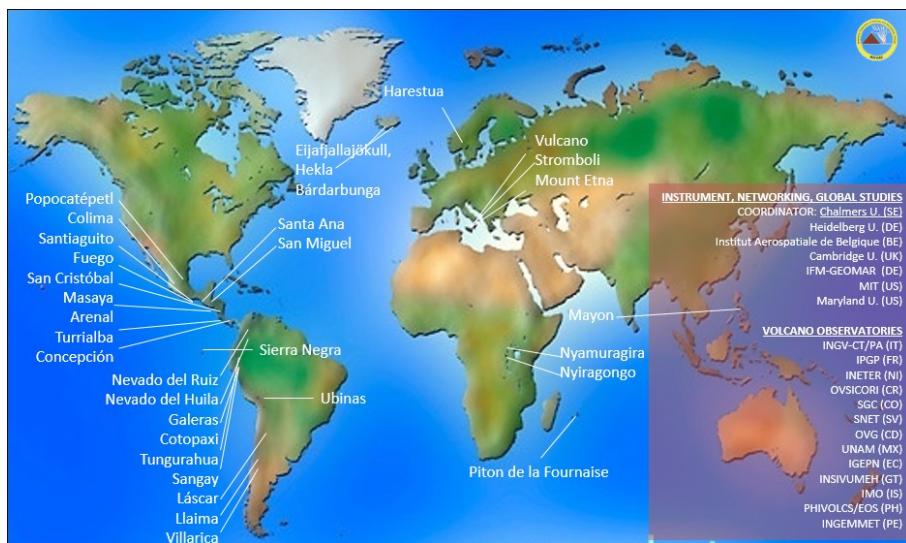


Figure 4.1: Global map of the volcanoes monitored by NOVAC. Used with friendly permission of Santiago Arellano.

Network for Observation of Volcanic and Atmospheric Change (NOVAC) is a network of instruments monitoring volcanoes over the whole world. NOVAC was installed to gain another tool for risk assessment, for gas emissions and geophysical researches.

NOVAC was originally funded by the European Union on the first October in 2005. The aim of NOVAC is to establish a global network of stations for the quantitative measurement of volcanic gas emissions. At the beginning, NOVAC encompassed observatories of 15 volcanoes in Africa America and Europe, including some of the most active and strongest degassing volcanoes in the world. Although the EU-funding has stopped, the network has been constantly growing since it was founded. In 2017 more than 80 instruments are installed at over 30 volcanoes in more than 13 countries. Figure 4.1 shows a map, with all volcanoes of the Network for Observation of Volcanic and Atmospheric Change.

The great advantage of the data monitored in NOVAC is the fact that NOVAC provides continuous gas emission data over many years. This ensures statistically meaningful results for the data evaluation.

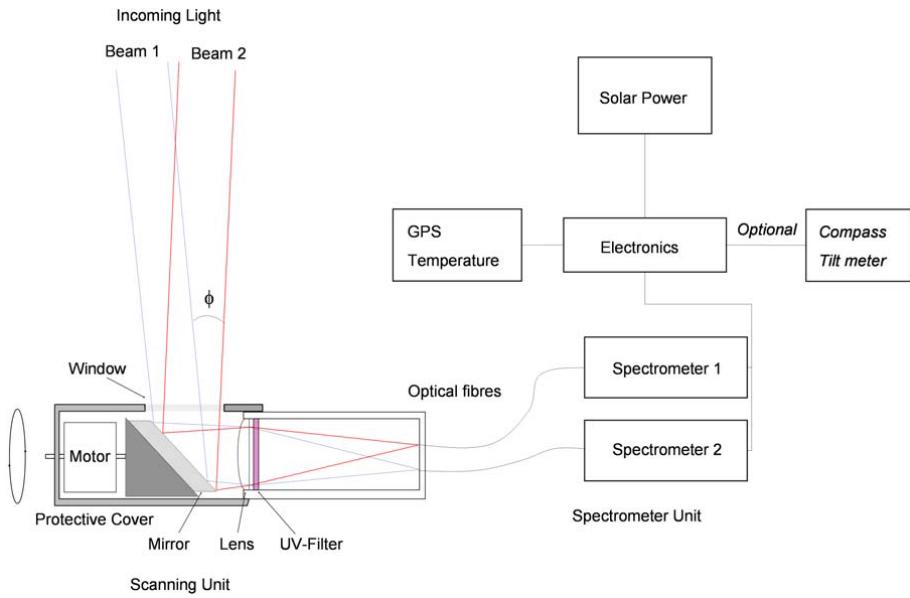


Figure 4.2: shematic sketch of a NOVAC instrument. From Galle et al. [2010]

The instruments used in NOVAC are scanning UV-spectrometer named Mini Doas instruments.

The Mini DOAS instrument represents a major breakthrough in volcanic gas monitoring as it is capable of real-time semi-continuous unattended measurement of the total emission fluxes of SO<sub>2</sub> and BrO from a volcano. Semi-continues in this case means that the measurement is only possible during daytime and if the Sunlight is sufficient.

The basic Mini DOAS system consists of a pointing telescope fiber-coupled to a spectrograph. Ultraviolet light from the sun, scattered from aerosols and molecules in the atmosphere, is collected by means of a telescope with a quartz lens defining a field-of-view of 12 mrad. NOV

The spectrometers measure in the UV region in a wavelength range of 280 to 420 nm. In this range the differential structures of SO<sub>2</sub> and BrO are dominant.

The NOVAC-instruments need to be very robust to stand the conditions around volcanoes. Therefore the design of the instruments is rather simple, this means the instruments do not have internal stabilisation features like temperature stabilization to keep the measurement independent of external parameters.

This comes with a reduced precision of the data, but the huge amount of data produced by NOVAC compensates for this limitation.

## 4.1 Measurement Routine

The instruments are set up five to ten km downwind of the volcano. To cover most of the occurring wind directions two to five instruments are installed at each vol-

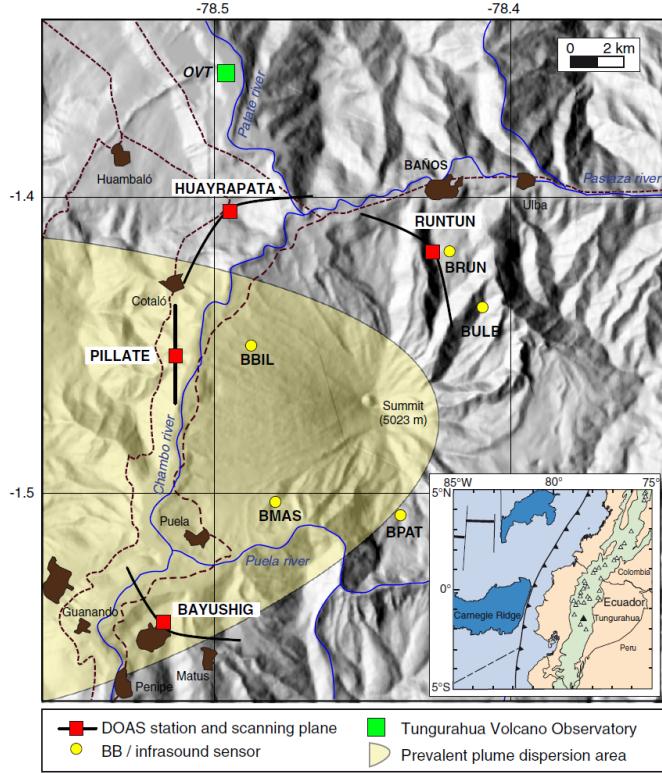


Figure 4.3: Topographic Map of the Tungurahua Volcano. The predominant plume direction is shaded in yellow. Four NOVAC stations are shown as red squares, the corresponding scanning geometry is sketched with black lines.

cano. Ideally, the measurement plane is orthogonal to the plume, to get the best measurement results. In reality, the measurement plane might be rotated.

For the calculations of gas data from the DOAS retrieval a scan of the Plume and a scan without any volcanic trace gases (reference spectrum) is needed. This is done without any knowledge of the plume location by scanning the whole sky. The measurement routine starts with a spectrum in zenith direction: the pre-reference. The exposure time of the pre-reference will be used for the whole scan. Afterwards, the dark current spectrum is recorded for the correction of the dark current and offset.

Then the instrument turns automatically to the side, recording spectra at the elevation angle from  $-90^\circ$  to  $90^\circ$  with steps of  $3.6^\circ$ .

The instruments records 53 spectra per Scan. One hole measurement takes 6 to 15 minutes.

## 5 Evaluation Routine

Section 3.1 gives an overview about the theory of the DOAS Method. This chapter will go through the algorithm which is used for the evaluation of the spectroscopic data recorded in NOVAC. The occurring problem of contamination of the reference will be explained and possible solutions will be presented.

### 5.1 NOVAC-Evaluation

The fitting routine used for this work is based on the DOASIS software [Kraus \[2006\]](#). The equations of the DOAS retrieval of this work are slightly different from eq. (3.7). Equation (3.4) can be rewritten to:

$$\begin{aligned} \ln(I(\lambda, L)) &= \ln(I_0) + P(\lambda) - \int_0^L \sum_j \sigma_j(\lambda, p, T) \cdot c_j(l) dl \\ &= \ln(I_0) + P(\lambda) - \sum_j \sigma_j(\lambda, p, T) \cdot S_j \end{aligned} \quad (5.1)$$

The term  $P(\lambda)$  is a polynomial that accounts for all broad-band effects that differ between the background spectrum  $I_0(\lambda)$  and the measurement spectrum  $I(\lambda)$ . All Gases  $j$  with relevant structures in the wavelength range used for the evaluation of SO<sub>2</sub> (BrO) and the additional pseudo absorbers are listed in section 5.1. The remaining task of the DOAS routing is to find a model function  $F(\lambda)$  that minimizes  $\chi^2$ :

$$\chi^2 = \sum_{i=\lambda_1}^{\lambda_2} (\ln(I(i)) - F(i))^2 \quad (5.2)$$

While  $F(\lambda)$  can be expressed on the basis of eq. (5.1):

$$F(\lambda) = \ln(I_0) + P(\lambda) - \sum_j \sigma_j(\lambda) \cdot S_j \quad (5.3)$$

The DOAS fitting routine uses a combination of a standard least-squares fit and a Levenberg-Marquardt algorithm to minimize  $\chi^2$

The Network for Observation of Volcanic and Atmospheric Change provides Spectral Data for 50 different elevation angles. For the DOAS evaluation we need a

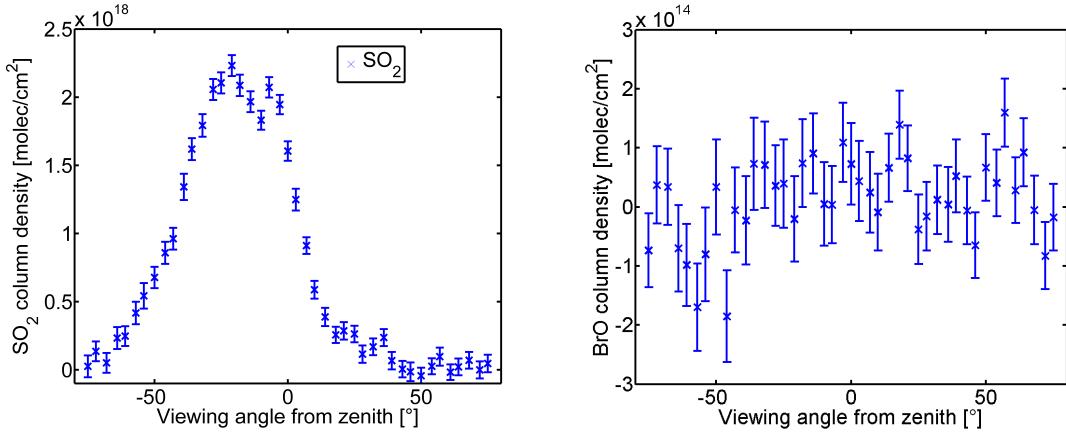
## BrO Evaluation    SO<sub>2</sub> Evaluation

---

|                 |
|-----------------|
| SO <sub>2</sub> |
| O <sub>2</sub>  |
| O <sub>3</sub>  |
| O <sub>4</sub>  |

---

Table 5.1: All Gases used in NOVAC- Evaluation when retrieving the column densities of BrO and SO<sub>2</sub>



(a) SO<sub>2</sub> SCD as a function of the elevation angle with error bars resulting from the DOAS fitting routine  
(b) BrO SCD as a function of the elevation angle with error bars resulting from the DOAS fitting routine

Figure 5.1: SCD's as a function of viewing angles. Adapted from [Warnach \[2015\]](#)

reference and a measurement spectrum. To get the SCD's we need to get references without any amount of the volcanic trace gas of interest (This will be discussed more detailed in section 5.2). With the so found  $F(\lambda)$  the column density of BrO and SO<sub>2</sub> from the measurement spectrum relatively to the reference spectrum can be calculated using the calculations made above.

In the following we describe the technical implementation of the DOAS approach using the data of NOVAC instruments:

The first important task is to locate the measurement spectrum in the volcano plume and the reference region which need to be outside of the plume. To do so we use the pre-reference (the spectra recorded at an elevation angle of 0°) to evaluate spectra for SO<sub>2</sub> at every elevation angle as described in chapter 3.1, that means we divide each recorded spectra by the pre-reference and take the logarithm to get rid of the Fraunhofer structures and to be able to just look at the important structures of the plume. The result is SO<sub>2</sub> dSCD's as a function of the elevation angle. So we can localize the maximum and the minimum of SO<sub>2</sub> amount, but not the SCD's. To get the gas dSCD's of the evaluated spectra, one fits the absorption cross section of

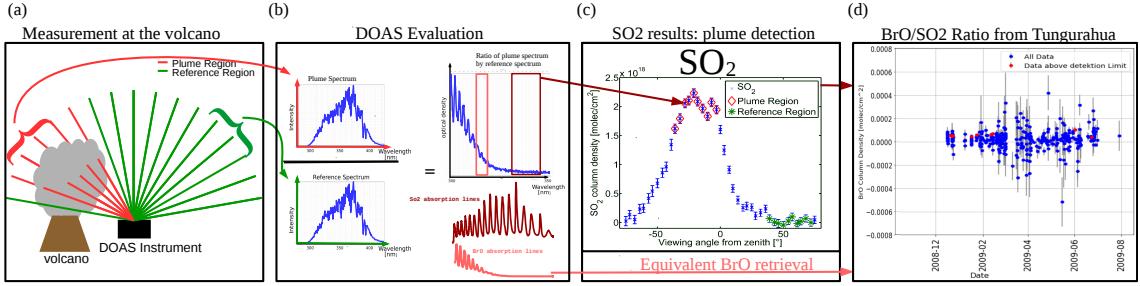


Figure 5.2: NOVAC Evaluation: (a) Measurement at the volcanoe (b) Evaluation of the spectral data with the DOAS routine using the absorption cross sections of BrO and SO<sub>2</sub>. (c) finding the location of the plume and reference (d) the ratios BrO/SO<sub>2</sub> at Tungurahua

all important gases on the recorded spectrum. In our case we take all gases written in tab. ?? into account. Inside the plume the SO<sub>2</sub> amount is much higher than outside the plume. The location of the SO<sub>2</sub> maximum match with the location of the plume. We assume that the minimum of the SO<sub>2</sub> curve refers to a region outside of the plume which is in most times the case. The SO<sub>2</sub> amount in the earths atmosphere is negligible so we take it as a region of zero SO<sub>2</sub>. Now it is possible to locate the plume region as the SO<sub>2</sub> maximum, whereas the minimum of the SO<sub>2</sub> curve the reference region is.

To technically detect the plume region we use a gauss fit of the SO<sub>2</sub> curve. To increase the quality and to get a more robust result the sum over several plume spectra is taken. If the gauss curve is too wide we use only the 10 spectra with the highest SO<sub>2</sub> amount. For the reference we use the sum of 10 spectra with the lowest SO<sub>2</sub> amount.

The so found reference spectrum is used to fit it on the SO<sub>2</sub> absorption lines of Gases to get the absolute column densities of SO<sub>2</sub> and BrO in the plume spectrum. In fig. 5.1 (a) the SO<sub>2</sub> SCD as a function of the elevation angle is shown. The SO<sub>2</sub> curve show a clear maximum at the position of the plume at an elevation angle of approximately  $-30^\circ$  to  $0^\circ$  and a reference region at an elevation angle of  $40^\circ$  to  $70^\circ$ . (b): The extrema of the BrO curve are not as distinct as at the SO<sub>2</sub> curve.

Since the BrO column density is much lower than the SO<sub>2</sub> column density and lies just slightly above the detection limit the plume is hard to detect using the BrO column density as it is shown in fig. 5.1 (b). Therefore we use plume location we found by using SO<sub>2</sub> to evaluate the BrO column density.

For the evaluation we use the data of more than one measurement, to increase the fit quality.

We are mainly interested in the BrO/SO<sub>2</sub> ratio, with the calculations described above it is now possible the get this ratio. In ?? is the NOVAC Evaluation visualized.

Taking the BrO/SO<sub>2</sub> ratio if the column densities are close to zero yields unpre-

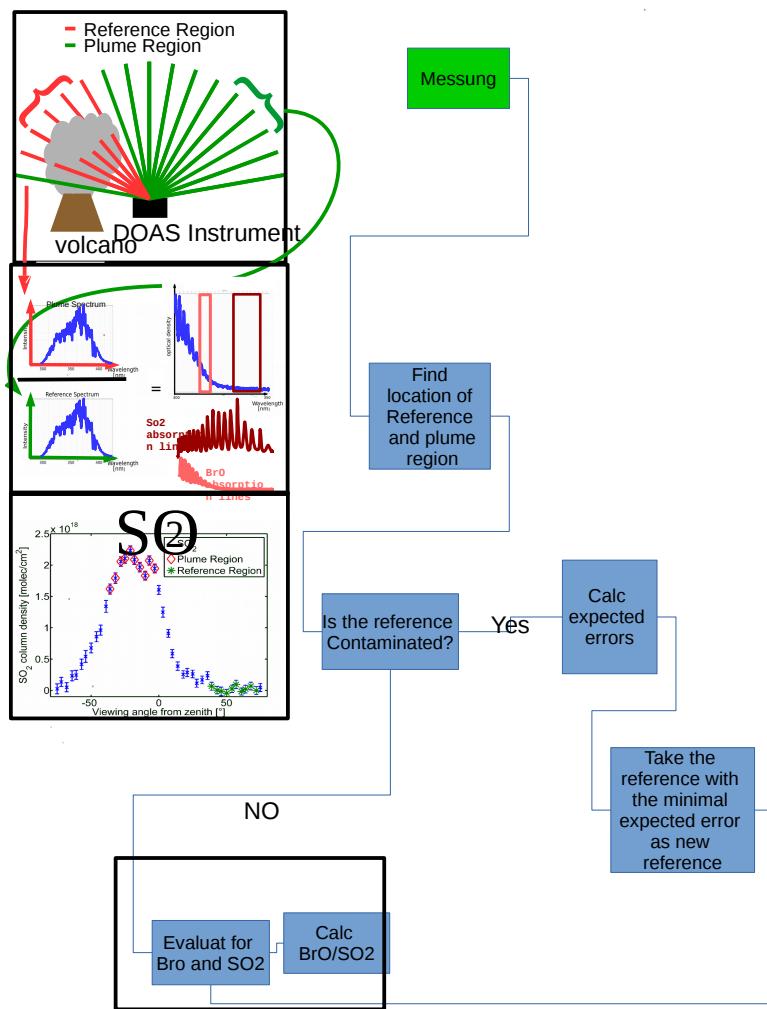


Figure 5.3: Sketch of the DOAS Routine

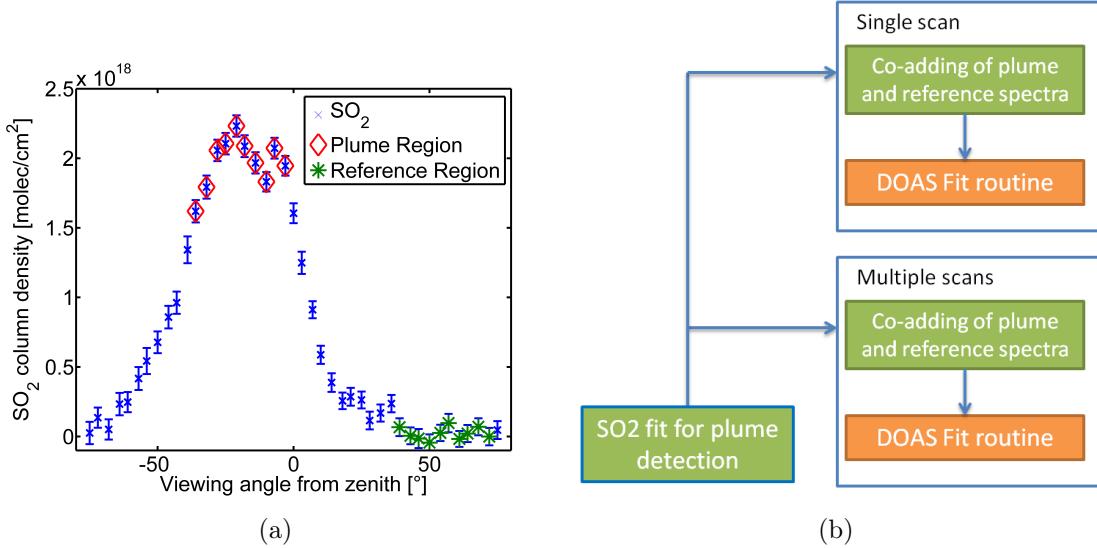


Figure 5.4: (a) SO<sub>2</sub> SCD as a function of the elevation angle. The co-added Plume region is marked with red diamonds, and the co added reference region with green stars. From Warnach [2015]. (b) Flow chart of the BrO and SO<sub>2</sub> evaluation. From Lübcke [2014].

dictable and unrealistic results. Thus spectra measured outside of the volcano plume need to be excluded. This could be achieved by setting a BrO or/and a SO<sub>2</sub> threshold. A reasonable BrO threshold need to be at least in the order of the DOAS fit error. But this could lead to elevated BrO/SO<sub>2</sub> ratios, since the BrO error is often close to the detection limit, and thus exclude all low BrO column densities from the evaluation. The other possibility is to set a SO<sub>2</sub> threshold. In this thesis an SO<sub>2</sub> threshold of  $7 \cdot 10^{17} \frac{\text{molec}}{\text{cm}^2}$  was used for the selection of spectra for the evaluation of the BrO/SO<sub>2</sub> ratio.  $7 \cdot 10^{17} \frac{\text{molec}}{\text{cm}^2}$  is relatively high column density. However this approach assures that no significant amount of gases will be filtered out, therefore the BrO/So2 will not be significantly influenced Lübcke et al., 2014 and that all accepted measurement spectra will be inside of the volcano plume.

## 5.2 Contamination Problem

It might occur that in rare (ca. 10% of the data) scenarios, the volcanic plume covers the whole scan region. This could happen if for example the volcanic plume of the day before still extend over the hole scan area as a consequence of windless conditions. In consequence, the reference is contaminated with volcanic trace gases. Thus the gas amount is underestimated by the NOVAC-Evaluation: In fig. 5.5 we see an example from April 2011 (Tungurahua) where the reference region is contaminated by volcanic trace gases. The blue SO<sub>2</sub> curve shows our calculations with the NOVAC-Evaluation, but since there is still SO<sub>2</sub> in the reference region, therefore

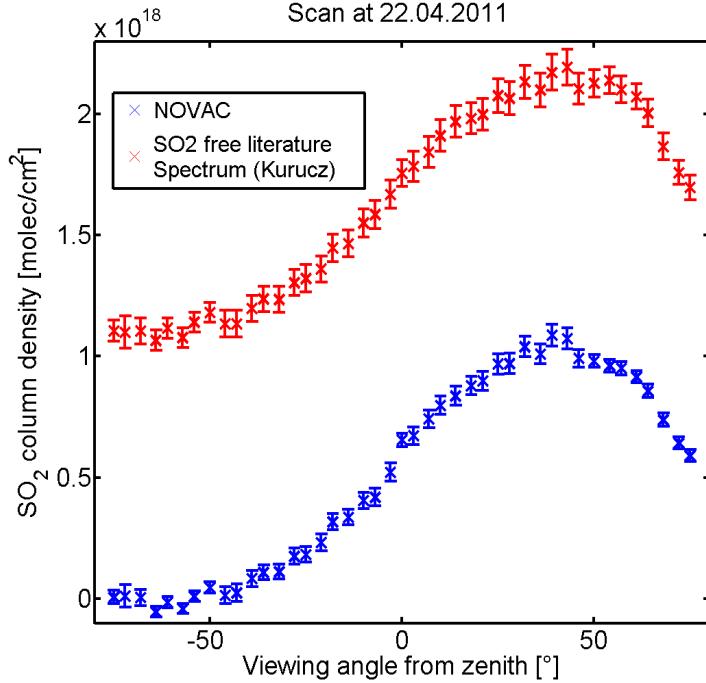


Figure 5.5: Scan with a contaminated reference spectrum from April 2011. From Warnach [2015]

the assumption, that the  $\text{SO}_2$  amount could be set to zero in the reference region is wrong. The red curve shows the real  $\text{SO}_2$  curve, and we will underestimate the total  $\text{SO}_2$  amount of the plume. Contamination occur in approximately 10% of the data.

If the reference region is for any reason contaminated by volcanic trace gases, the reference spectrum has to be replaced by a volcanic-gas-free reference. Alternative spectra are a theoretical solar atlas spectrum (the use of a solar atlas spectrum will be described in section 5.2) ore a a volcanic-gas-free reference spectrum recorded by the same instrument.

In the following we will discuss both of these options:

## Evaluation using a Solar Atlas Spectrum

An alternative to choose the region with the lowest column density as reference region is to use a theoretical high resolution solar atlas spectrum as reference Chance and Kurucz [2010]. The use of a theoretical solar atlas spectrum as a reference which is completely volcanic-trace-gases-free was first proposed by Lübcke et al. [2014]. The advantage of using a solar atlas spectrum as reference is, that we know

Figure 5.6:

Figure 5.7:

that there are no volcanic trace gases, we do not need to assume, that the minimum SO<sub>2</sub> amount is zero. The disadvantage is, that using a solar atlas spectrum comes along with a drawback of precision: A theoretical solar atlas spectrum is far more precise than the spectra of the NOVAC instruments therefore the instrument functions need to be modeled and added to the retrieval.

The reduction of precision is acceptable for the SO<sub>2</sub> retrieval but not suitable for a BrO retrieval because then most data would be below the detection limit.

Possible contaminations can be checked by a theoretical solar atlas spectrum to evaluate the SO<sub>2</sub> amount in the reference.

## Evaluation using a Spectrum of the same Instrument

An alternative reference spectrum could be a volcanic-gas-free reference spectrum recorded by the same instrument. When using such a reference several problems occur:

As described in chapter 4 the instruments used in NOVAC do not include features like temperature stabilisation due to that the measurements are not independent from external parameters. So we need to choose a reference recorded at similar conditions with respect to meteorology and radiation as well as in the temporal proximity due to instrumental changes with time and ambient conditions. Ideally the external conditions should be equal to the conditions when the plume was recorded.

In this work we will combine both options in order to achieve both, enhanced accuracy but still maximum possible precision of the SO<sub>2</sub> and BrO retrievals. So we use the solar atlas spectrum to check for contamination and a reference spectrum recorded in temporal proximity by the same instrument as reference.

In the following we will discuss how to find the an optimal reference from another scan automatically.

Figure 5.8:

# 6 Limitations for the evaluation of BrO

Since the SO<sub>2</sub> amount in a volcano plume is rather high (magnitude of SO<sub>2</sub> at Tungurahua  $\approx 1e^{18}$ , Warnach [2015]) , the evaluation of SO<sub>2</sub> is unproblematic compared to BrO.

Evaluating BrO is more difficult since the amount is much smaller and the measurement error relative to the column density much larger. Since we want to get the BrO/SO<sub>2</sub> we need to maximize the accuracy of BrO. Therefore the aim is to choose the reference with respect to the BrO error, to minimize the BrO Error and to increase the amount of reliable BrO/SO<sub>2</sub> ratio data.

We figured out, that the BrO Error depends strongly on the surrounding conditions when recording the plume and the reference. In the following, we will take a closer look at the dependence of the BrO error on external parameters.

## 6.1 BrO Error dependence on external parameters

The measurement and evaluation depends on the surrounding conditions like temperature or cloudiness Lübcke [2014]

If choosing a new reference we need to take the surrounding conditions into account. The better the surrounding conditions of the time where the reference is measured coincide with the conditions of the time when the plume is measured, the lower is the BrO error

The surrounding conditions we take into account are temperature, colorindex, exposure time, elevation-angle, daytime and the temporal difference.

In almost all cases (99%) the absolute BrO Error is minimal when using the reference recorded at the same time as the plume spectrum. So we won't be able to get an BrO Error which is smaller than the "Same Time Error".

### 6.1.1 Time

Due to instrument drifts the fit quality decreases with the time difference between recording the plume and the reference. Therefore it is better to use a reference in temporal proximity.

Figure 6.1 shows the instrumental drift as a function of time, to create fig. 6.1 we used Tungurahua data, 2008 from June to November. We can observe that the drift changes with time. If we use the reference and plume spectra of the same time, we do not need to care about these effects, since the shift is equal for the plume and reference spectrum, but if the recording time is not the same the quality of the fit changes with the differences in wavelength shift which increases with the time

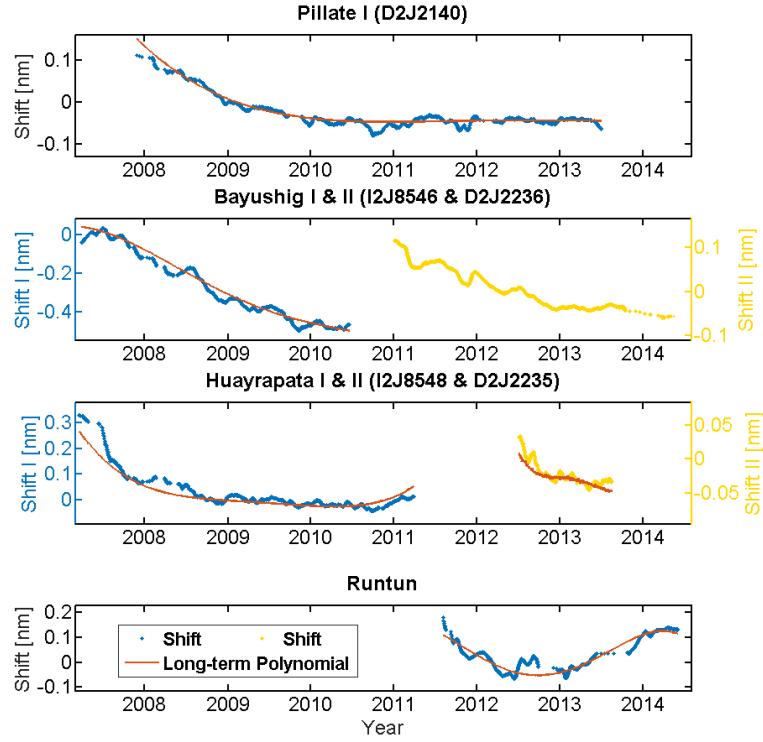


Figure 6.1:

difference.

In fig. 6.3 the BrO Error as a function of the time difference between recording the plume and the reference is shown. The running mean is drawn with a black line. The BrO Error increases with time difference.

To evaluate the maximal time difference, where we still get reliable results we calculated for all possible reference-plume pairs the corresponding BrO Error. With this data we are able to find for all plume spectra the associated reference where the BrO Error is minimal. In ?? a histogram is plotted with the probability of picking the best reference as a function of the time difference. Obviously the best results are if the day of measuring the reference is the same day as measuring the reference that means, if the time difference is smaller than one day. We allow all time difference which are in one sigma area.

We found out that the time interval where it is still reasonable to use references is about 14 days. Therefore we only use references where the recording time difference between plume and reference is smaller than two weeks. When using a references with a temporal difference to the plume of more than 14 days the probability, that the fit quality and thus the BrO error increases to much for our purposes.

### 6.1.2 Temperature

The instrument design of the NOVAC instruments compromise between accuracy and longevity as explained in chapter 4. In particular there are no internal thermal stabilizations installed as an attempt to reduce the need for power. This can influence the recorded spectra.

Each pixel of the spectrometer, which is used for the DOAS experiment, collects photons of a certain wavelength range.

The calibration for the wavelength to pixel mapping (WMP) is commonly done with a Mercury lamp or by the comparison with the high defined Kuruz spectrum. As the WMP depends on the optical alignment of the spectrometer, which itself depends on the temperature, it is not constant. Changes in the spectrometers temperature can cause changes in the instrument line function and shifts in the WMP (Pinardi et al. [2007]). Moreover, Warnach [2015] show that, short term shifts are related to the instrument temperature (see Figure 6.4).

The above discussed temperature dependence of the WMP causes a reduction of the fitquality with increasing instrument temperature between plume and reference. Thus the BrO Error increases as well with the temperature difference. To quantify the BrO error dependency on the temperature all plume spectra of Tungurahua from August 2008 to August 2009 (Nevado del Ruiz from .... to ....) where evaluated with all plume spectra of the same time. In this time span 1647 "multi-add" spectra from tree different instruments where recorded, so we get approximately  $1646^2$  plume reference pairs and their corresponding BrO error and temperature. The BrO error as function of the temperature difference can be seen in fig. 6.5. The blue dots shows the mean BrO error at the specific temperature difference, the standard deviation is illustrated with gray bars.

When compare the data of Tungurahua and Nevado Del Ruiz it is noteworthy that the BrO error on temperature dependence of the Data of Nevado Del Ruiz is stronger and the deviation is weaker than at Tungurahua, this may occur due to the larger temperature fluctuation at Nevado Del Ruiz. ?????????? quellen bitte!

When looking at all discussed external parameters, temperature has the strongest impact on the BrO error due to the strong impact on the WMP. [h!]

- The BrO error has the strongest dependence on the temperature difference. At Tungurahua (Nevado Del Ruiz) the BrO error increases by factor of  $3.53 \cdot 10^{12}$  per degree.

$$\begin{aligned} \rightarrow BrO_{Error} &= f(ext.P) + 3.53 \cdot 10^{12} \cdot \frac{\Delta T}{1C^\circ} + \mathcal{O}() && Tungurahua \\ \rightarrow BrO_{Error} &= f(ext.P) + 7.56 \cdot 10^{12} \cdot \frac{\Delta T}{1C^\circ} + \mathcal{O}() && NevadoDelRuiz \end{aligned}$$

between monitoring the plume  
and reference region

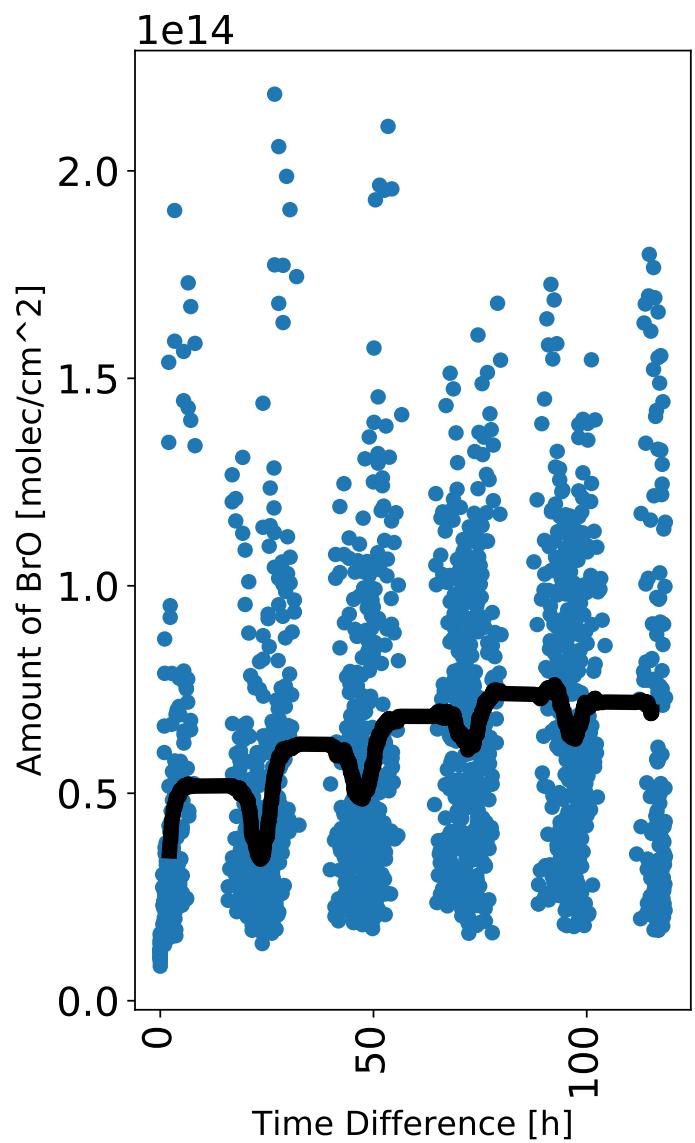


Figure 6.2:

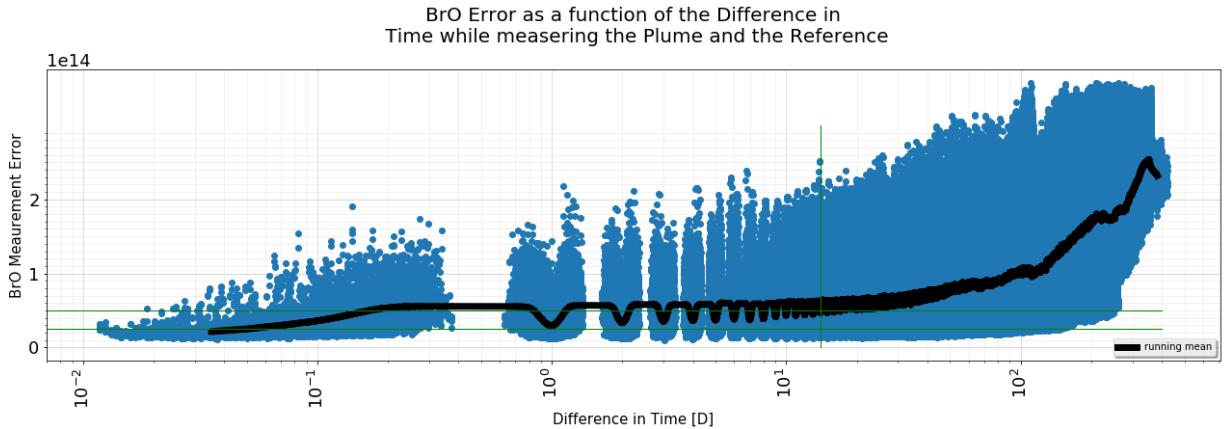


Figure 6.3:

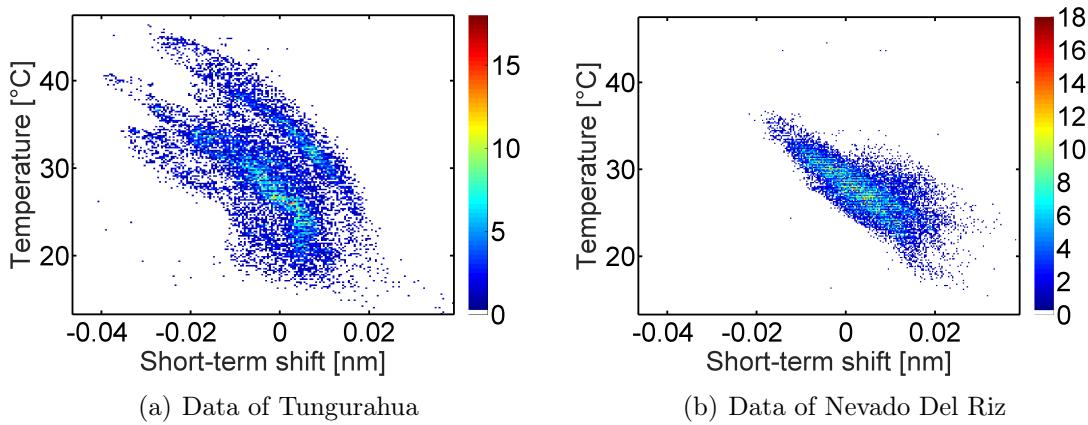


Figure 6.4: Titel unterm gesamten Bild

### 6.1.3 Daytime

During the day a lot of external parameters like temperature, solar altitude etc. change. In particular the solar altitude could have an impact on the fit quality since the light path of the sun is much longer at the evening than at noon. Figure 6.6 shows the dependency of the BrO error on the daytime. The data are calculated as described for the temperature. As for the temperature the dependence of Nevado Del Ruiz is much larger than of Tungurahua, this might occur during the larger distance from the equator of Nevado Del Ruiz -> besser beschreiben

- We found a dependency of the BrO error on the daytime. We assume, that this dependency comes from other external parameters which change during the day.
- The BrO Error increases with the daytime differences like:

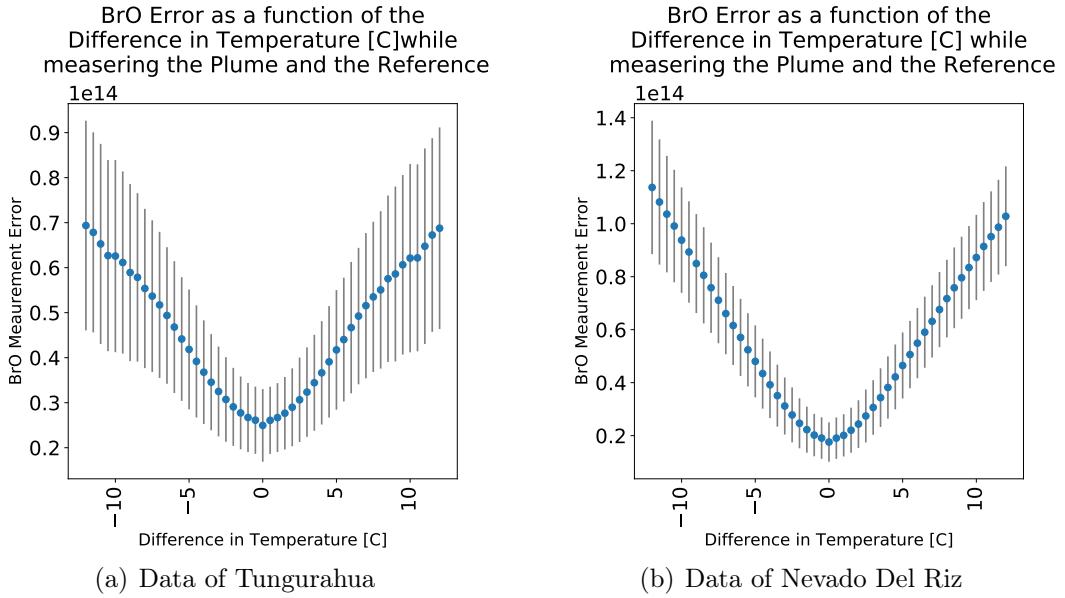


Figure 6.5: The BrO Measurement Error as a function of the difference of temperature between measuring the reference and the plume are shown. To evaluate the plume spectra all reference spectra with a temporal distance of no longer than two weeks are used. A increase of the BrO Error with the distance in temperature is observable.

$$\rightarrow BrO_{Error} = f(ext.P) + 1.33 \cdot 10^{12} \cdot \frac{\Delta DT}{1h} + \mathcal{O}() \quad \text{Tungurahua}$$

$$\rightarrow BrO_{Error} = f(ext.P) + 1.58 \cdot 10^{13} \cdot \frac{\Delta DT}{1h} + \mathcal{O}() \quad \text{NevadoDelRuiz}$$

### 6.1.4 Colorindex

Clouds have a strong influence on the atmospheric radiative transfer and thus affect the interpretation and analysis of DOAS - observations Wagner et al. [2014].

Clouds can be identified by several measurement quantities that they influence. As Mie scattering is dominant in clouds the wavelength of the light that is scattered is different than the Rayleigh sky. Thus, clouds can be easily identified by their white color. Therefore, the cloudiness of the sky can be quantified in a scalar measure defined by the ratio of the measured intensity at two wavelengths, the so-called colour index. Wagner et al. [2014] showed that for a zenith-looking instrument the measured radiation intensity is enhanced by clouds. Thus, clouds can cause large errors for the retrieved gas column density and the corresponding uncertainties. Cloud effects are especially severe if the cloudiness for the recorded plume and

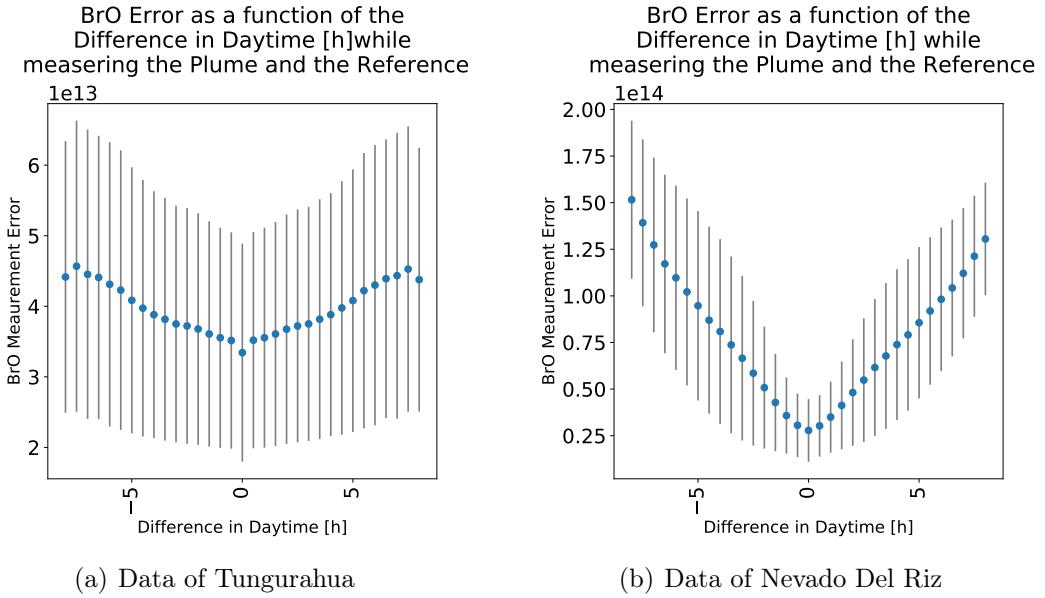


Figure 6.6: The BrO Measurement Error as a function of the difference of the day time between measuring the reference and the plume are shown. To evaluate the plume spectra all reference spectra with a temporal distance of no longer than two weeks are used. A increase of the BrO Error with the distance in day time is observable.

reference spectra strongly defer. Also for broken clouds the described effect can be observed as measurements at some elevation angles might be influenced by clouds while others are not. In this work the Colour Index (CI) is the ratio between the intensities at 320nm and 360 nm. These two wavelengths are as far apart as the filter used for stray-light prevention in the spectrometers allows. On the other hand, the lower wavelength avoids the deep UV range where SO<sub>2</sub> and O<sub>3</sub> absorption plays a dominant role. The Mie scattering in the clouds is responsible for the higher amount of radiation from larger wavelengths. This results in a decrease of the CI ([Lübcke \[2014\]](#)).

We evaluated the CI at the zenith, to increase the stability of the fit we added in each cases 10 intensities. Using always the zenith to evaluate the colour index makes the colour index more comparable, but if broken clouds occur, the CI of the reference and the plume could differ from the calculated CI of the zenith. This could be a reason for the large deviations of the mean BrO error as function of the colour index (see fig. 6.7)

- The BrO Error increases with the Colorindex differences as

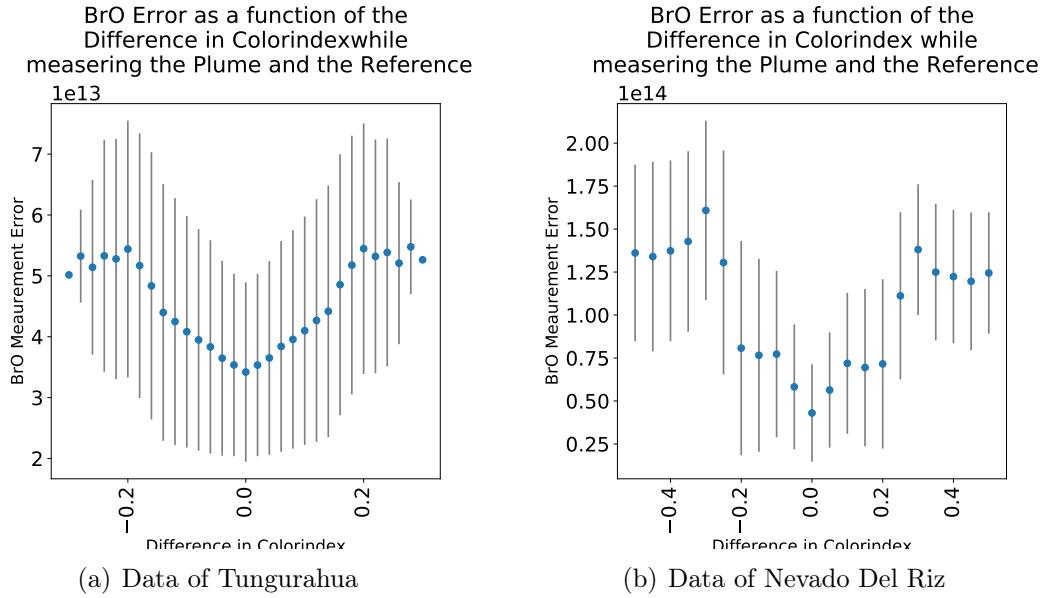


Figure 6.7: The BrO Measurement Error as a function of the difference of colorindex between measuring the reference and the plume are shown. To evaluate the plume spectra all reference spectra with a temporal distance of no longer than two weeks are used. A increase of the BrO Error with the distance in colorindex is observably.

$$\rightarrow BrO_{Error} = f(ext.P) + 1.01 \cdot 10^{13} \cdot \frac{\Delta Cidx}{0.1} + \mathcal{O}() \quad \text{Tungurahua}$$

$$\rightarrow BrO_{Error} = f(ext.P) + 4 \cdot 10^{13} \cdot \frac{\Delta Cidx}{0.1} + \mathcal{O}() \quad \text{NevadoDelRuiz}$$

### 6.1.5 Elevation Angle

The elevation angle describes the angle between the horizon and the zenith. When using the plume spectrum and the reference spectrum of the same time, the difference in elevation angle cannot be zero, since the plume is always somewhere else than the reference located.

The BrO error doesn't depend significantly on the difference between the Elevation Angles. This could have several reasons. One problem is, that the Elevation Angle of Plume and Reference spectrum is not the same. This could also be a reason of uncertainty of the evaluations of the plume spectrum.

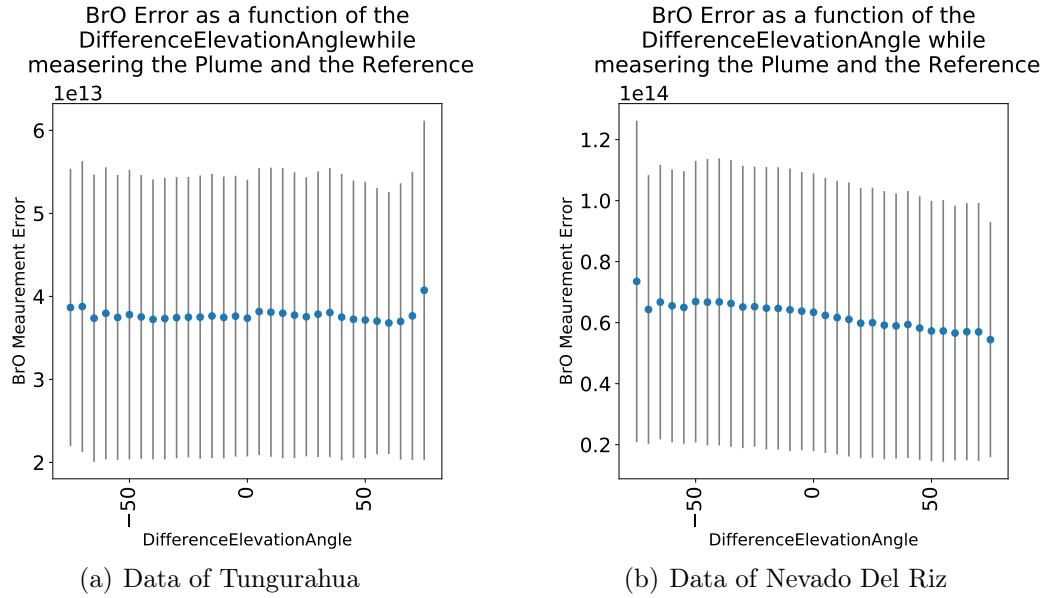


Figure 6.8: The BrO Measurement Error as a function of the Elevation Angle. To evaluate the plume spectra all reference spectra with a temporal distance of no longer than two weeks are used. We can't see any significant correlation.

## 6.1.6 Exposure Time

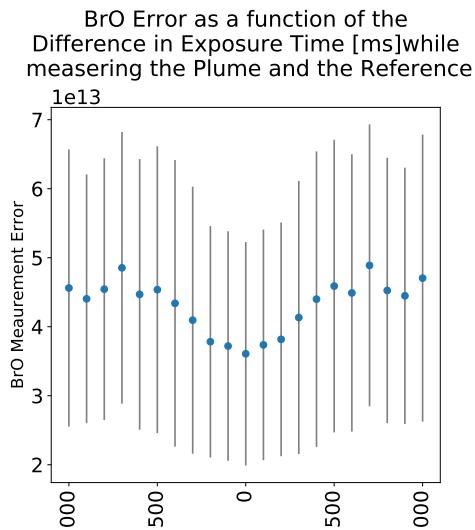
The Exposure Time is a degree of sky lightness. The exposure time is the length of time the sensor of the NOVAC instrument is exposed to light. The amount of light that reaches the film or image sensor is proportional to the exposure time. The exposure time is adjusted in the way that the maximum intensity does not overly the capacity of the sensor.

We can observe a small dependency of the BrO error on the Exposure time at Tungurahua and Nevado Del Ruiz as it is shown in fig. 6.9

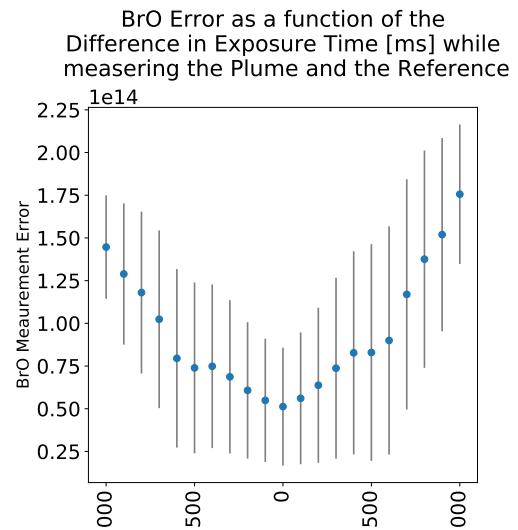
- The BrO Error increases with the exposure time differences as

$$\rightarrow BrO_{Error} = f(ext.P) + 1.92 \cdot 10^{12} \cdot \frac{\Delta ET}{10^{-2}s} + \mathcal{O}() \quad Tungurahua$$

$$\rightarrow BrO_{Error} = f(ext.P) + 1.0 \cdot 10^{13} \cdot \frac{\Delta T}{10^{-2}s} + \mathcal{O}() \quad NevadoDelRuiz$$



(a) Data of Tungurahua



(b) Data of Nevado Del Riz

Figure 6.9: The BrO Measurement Error as a function of the difference of exposure time between measuring the reference and the plume are shown. To evaluate the plume spectra all reference spectra with a temporal distance of no longer than two weeks are used. A increase of the BrO Error with the distance in exposure time is observably.

## 7 Method

Based on the findings about the influence of external parameters on the BrO error we developed an algorithm which is able to pick an appropriate volcanic-trace-gas free reference.

The first step is, to evaluate every reference with solar atlas spectrum, to check for contamination. A Spectrum is treated as contaminated if the SO<sub>2</sub> column density of the reference (evaluated with a solar atlas spectrum) is larger as  $2 \cdot 10^{17} \frac{\text{molec}}{\text{cm}^2}$ .

If the reference is contaminated:

- We have a list of possible references where all references are not contaminated and the temporal distance to the plume date is no longer than 14 days.
- we calculate of all possible references the differences in the external parameters
- We use the analysis of external parameters described above to estimate the BrO error of all references
- We choose the reference with the smallest estimated BrO error as new reference
- We evaluate the plume spectra with the new reference.

The assumption is, that the BrO error  $\epsilon_{BrO}$  can be described as the sum of  $\epsilon_0$  and the deviation of  $\epsilon_{BrO}$  with respect to all external parameters.  $\epsilon_0$  is the BrO error when evalute the plume spectrum with the "same-time-reference", it is determined due to the accurateness of the NOVAC-instruments.

$$\epsilon_{BrO} = \epsilon_0 + \frac{d\epsilon}{dt} + \frac{d\epsilon}{d^\circ} + \frac{d\epsilon}{dT} + \frac{d\epsilon}{ddt} + \frac{d\epsilon}{dc} + \mathcal{O}(OE) \quad (7.1)$$

$$\rightarrow \Delta\epsilon_{BrO} = \epsilon_{BrO} - \epsilon_0 = \frac{d\epsilon}{dt} + \frac{d\epsilon}{d^\circ} + \frac{d\epsilon}{dT} + \frac{d\epsilon}{ddt} + \frac{d\epsilon}{dc} + \mathcal{O}(OP) \quad (7.2)$$

With  $\epsilon_{BrO}$  describes the BrO Error, t: time between plume time and referencetime, T, temperaure; dt: daytime, c: colorindex, OP: other excluded external parameters  
The task occurring at this stage is to find the best representation for the deviations.  
An then find the reference which minimize  $\Delta\epsilon_{BrO}$

The easiest way is to just calculate the BrO error of all possible references for every plume. Using this method we would be able to just choose the reference where the BrO error is minimal. But this takes to much time since the evaluation would be proportional to the number of possible references because the evaluation need to be

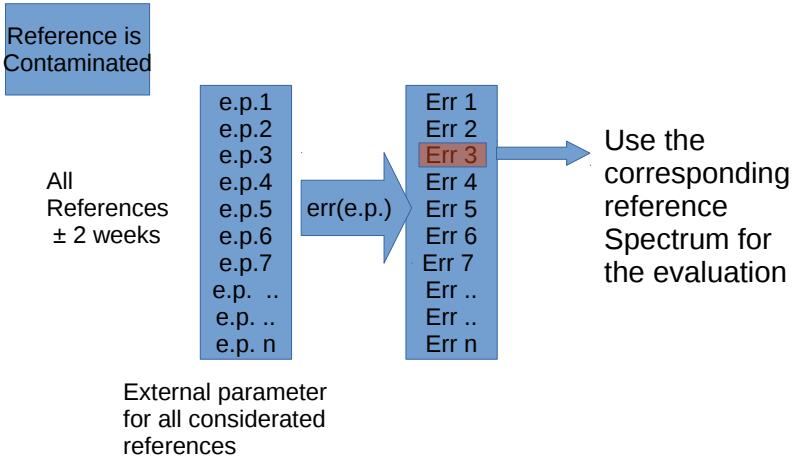


Figure 7.1:

done for every plume-reference pair. Doing the evaluation for every plume-reference pair would make it impossible to do the evaluation in real, or near real time. But we use this optimal evaluation to rate our model and compare them among each other. The optimal evaluation always choose the reference with the smallest absolute error. We don't use the relative error due to his vulnerability. Using the relative error could lead to a less preciseness.

Hier ein Bild, das eine Plume gegen viele referencen auswertet und hier die Abweichungen zeigt

The results of the algorithm which chooses the reference automatically are described relative to an optimal evaluation. If the relative error is larger than 5 we don't use the data.

We tried several methods for choosing the best reference based on the analysis of external parameters. Fitting the data with a first order polynomial brought the best results.

## 7.1 Fit data

When looking at the analysis of the external parameters (see fig. 6.5-6.9) we can observe curves which are symmetric to the zero position. Therefore we conclude that it makes no difference whether the difference of a specific external parameter is positiv or negativ. Thus we take the absolute values for our calculations.

| (a) Data of Nevado Del Riz D2J2201_0 |           |            |
|--------------------------------------|-----------|------------|
| Constant                             | value     | importance |
| $a_T$                                | 7.338e+12 | 0.840      |
| $a_{ET}$                             | 1.545e+10 | 0.045      |
| $a_t$                                | -2.6e+09  | 0.0        |
| $a_{dt}$                             | 1.805e+12 | 0.091      |
| $a_c$                                | 2.301e+13 | 0.031      |

| (b) Data of Nevado Del Riz D2J2200_0 |           |            |
|--------------------------------------|-----------|------------|
| Constant                             | value     | importance |
| $a_T$                                | 1.162e+13 | 0.908      |
| $a_{ET}$                             | 2.811e+10 | 0.046      |
| $a_t$                                | -1.7e+09  | 0.0        |
| $a_{dt}$                             | 1.076e+12 | 0.034      |
| $a_c$                                | 3.587e+13 | 0.016      |

| (c) Data of Nevado Del Both Instruments |            |            |
|---|------------|------------|
| Constant                                | value      | importance |
| $a_T$                                   | 1.073e+13  | 0.973      |
| $a_{ET}$                                | 3.478e+10  | 0.070      |
| $a_t$                                   | -9.1e+08   | 0.0        |
| $a_{dt}$                                | 1.523e+11  | 0.006      |
| $a_c$                                   | -6.811e+13 | -0.047     |

Table 7.1: (a)Data from Nevado Del Ruiz from the D2J2201\_0 instrument. All external parameter where taken into account.  $\epsilon_0 = 5.404e+12$  (b)Data from Nevado Del Ruiz from the D2J2200\_0 instrument. All external parameter where taken into account.  $\epsilon_0 = 1.105e+13$  (c) Data from Nevado Del Ruiz from both instrument. All external parameter where taken into account.  $\epsilon_0 = 1.260e+13$

If we assume that all differentiations are linear, than we can write eq. (7.2) as:

$$\Delta\epsilon_{BrO} = a_t \cdot \Delta t + a^\circ \cdot \Delta^\circ + a_T \cdot \Delta T + a_{dt} \cdot \Delta dt + a_c \cdot \Delta c + \mathcal{O}(OP) \quad (7.3)$$

We used the same data as in fig. 6.5-6.9 to get the coefficients  $a_x$  of eq. (7.3). We used on ordinary least square linear regression to get the coefficients  $a_x$ . In particular we used the python function LinearRegression from the library sklearn [SKl](#).

The constants for Tungurahua and Nevado Del Ruiz are:

- Plume data are reliable if the SO<sub>2</sub> column density is larger as  $7 \cdot 10^{17} \frac{\text{molec}}{\text{cm}^2}$
- Data are above the detection limit if the column density as two times larger than the fit error.
- If the reference is contaminated:

Figure 7.2:

Figure 7.3:

## 7.2 Other approaches

- In the optimal results are 15% valid data
  - We also tried other possibilities than fitting to find the reference where the BrO error is minimal. In the following we present two additional possibilities but compared to fitting the results are not as good.

### 7.2.1 Nearest neighbours

- Description of the Nearest Neighbours Method

Nearest neighbor search (NNS), as a form of proximity search, is the optimization problem of finding the point in a given set that is closest (or most similar) to a given point. Closeness is typically expressed in terms of a dissimilarity function: the less similar the objects, the larger the function values. Formally, the nearest-neighbor (NN) search problem is defined as follows: given a set  $S$  of points in a space  $M$  and a query point  $q \in M$ , find the closest point in  $S$  to  $q$ . Donald Knuth in vol. 3 of *The Art of Computer Programming* (1973) called it the post-office problem, referring to an application of assigning to a residence the nearest post office. A direct generalization of this problem is a  $k$ -NN search, where we need to find the  $k$  closest points. Most commonly  $M$  is a metric space and dissimilarity is expressed as a distance metric, which is symmetric and satisfies the triangle inequality. Even more common,  $M$  is taken to be the  $d$ -dimensional vector space where dissimilarity is measured using the Euclidean distance, Manhattan distance or other distance metric. However, the dissimilarity function can be arbitrary. One example are asymmetric Bregman divergences, for which the triangle inequality does not hold.

### 7.2.2 Iterative

- Description of the iterative Method

The idea of the iterative method was, that the importance of the individual external parameters are very different, that means if we have the list of possible references, we took all references where the temperature difference is minimal, so we get a new, much smaller list of possible references. From this list we choose all references where the next external parameter for example the daytime is minimal and get again a new list. We proceed this way with the following external parameters. We experiment

|                        |             | Error | Amount<br>of Data | valid<br>data |
|------------------------|-------------|-------|-------------------|---------------|
| All<br>Variables       | independent | 1.51  | 95%               | 10,5%         |
|                        | dependent   | 1.40  | 98%               | 8%            |
| Exposure<br>Time       | independent | 1.47  | 97%               | 10%           |
|                        | All         | 1.39  | 98%               | 7%            |
| Exp.Time<br>u Coloridx | independent | 1.40  | 98%               | 11            |
|                        | All         | 1.35  | 98%               | 7%            |

Evaluation of all contaminated data from Nevado Del Ruiz

| Instrument | Dev from opt eval.<br>(mean/median) | valid data        |
|------------|-------------------------------------|-------------------|
| D2J2201_0  | 1.14 / 0.82293                      | 128/283 = 45.2%   |
| D2J2200_0  | 1.5 / 0.89965                       | 954/1109 = 86.0%  |
| Both       | 1.26/0.847                          | 1073/1392 = 77.1% |

Table 7.2: Data from Nevado Del Ruiz from the D2J2201\_0 instrument. All external parameter where taken into account.  $\epsilon_0 == 5.404e + 12$

with the sequence of the parameters, to increase the success of the method. The final sequence was:

*Temperature* • .....

## 8 Comparison with NOVAC Evaluation

This chapter shows and discuss the difference of the BrO, SO<sub>2</sub> and BrO/SO<sub>2</sub> ratio data when evaluating with the NOVAC-Method, or with the contamination based method. The aim is to discover the systematic differences between the different retrievals and to discuss the reliability of the data.

The following external parameter where used for the evaluation:

- Temperature
- Daytime
- Colorindex
- check das noch mal

To obtain the reference with minimal expected BrO error the calculation of eq. (7.3) and the corresponding coefficients from table 7.1 were used. The maximal temporal difference between measuring the reference and the plume is two weeks. Figure 8.1 shows a comparison of the data when evaluating with the NOVAC-method and the contamination based method. The x axis shows the column density calculated with NOVAC-method, the y axis shows the column density calculated the the contamination based method. Only data are used where the corresponding SO<sub>2</sub> column density lies above the plume limit ( $SO_2\_SCD > 7 \cdot 10^{17}$ ). Meaning the column densities evaluated with the contamination based method. The corresponding SO<sub>2</sub> SCD's evaluated with NOVAC could be below  $7 \cdot 10^{17}$ . The plots at the left side show the results from the Tungurahua volcano while the plots at the right side show the results from Nevado Del Ruiz volcano. The BrO data are visualized in the plots at the top of fig. 8.1.

Beschreibung

In the middle of fig. 8.1 are the results of SO<sub>2</sub> visualized:

Beschreibung

The BrO/SO<sub>2</sub> ratio is visualized at the bottom of fig. 8.1:

Beschreibung

Another interesting question is, whether the change in the gas column density respectively the ratio depends on the amount evaluated with the NOVAC-method. To

check this dependency fig. 8.2 was plotted. The data used for this figure are the same as for fig. 8.1

- Results only for contaminated data
  - Difference in SO<sub>2</sub> data evaluated with NOVAC-method and contamination-based evaluation
  - Difference in BrO data evaluated with NOVAC-method and contamination-based evaluation
  - Difference in BrO/SO<sub>2</sub> Ratio data evaluated with NOVAC-method and contamination-based evaluation
- Amount of BrO data more than before (valid and not valid and above detection limit)
- Amount of SO<sub>2</sub> data more than before (valid and not valid and above detection limit)
- Amount of BrO/SO<sub>2</sub> data more than before (valid and not valid and above detection limit)
- More BrO data: 51%
- More valid BrO data: 38%
- Compare the daily means: how many more data? due to higher S02 values
-

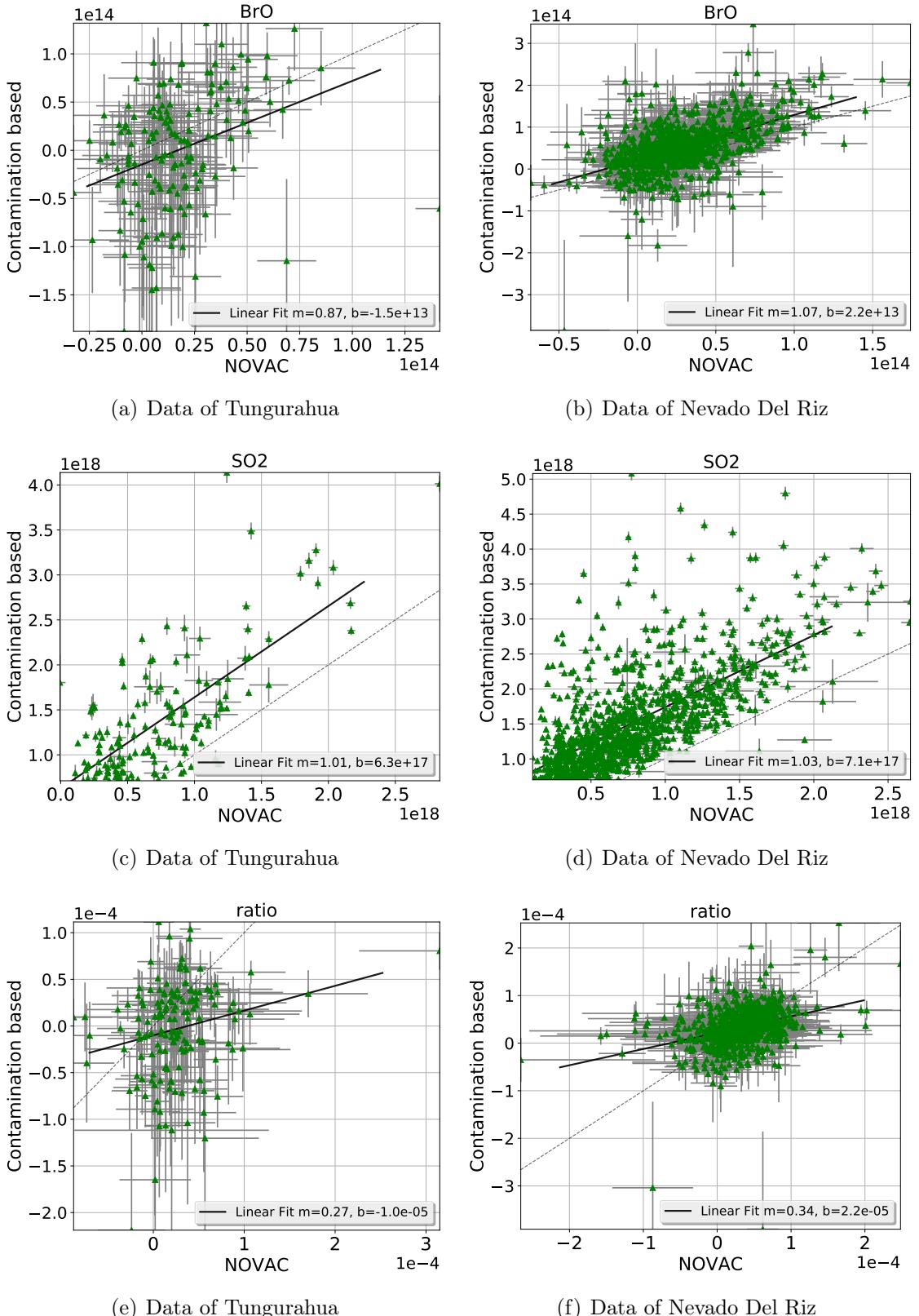


Figure 8.1: The dependency of the Difference between contamination based data and NOVAC to the data evaluated with the NOVAC data

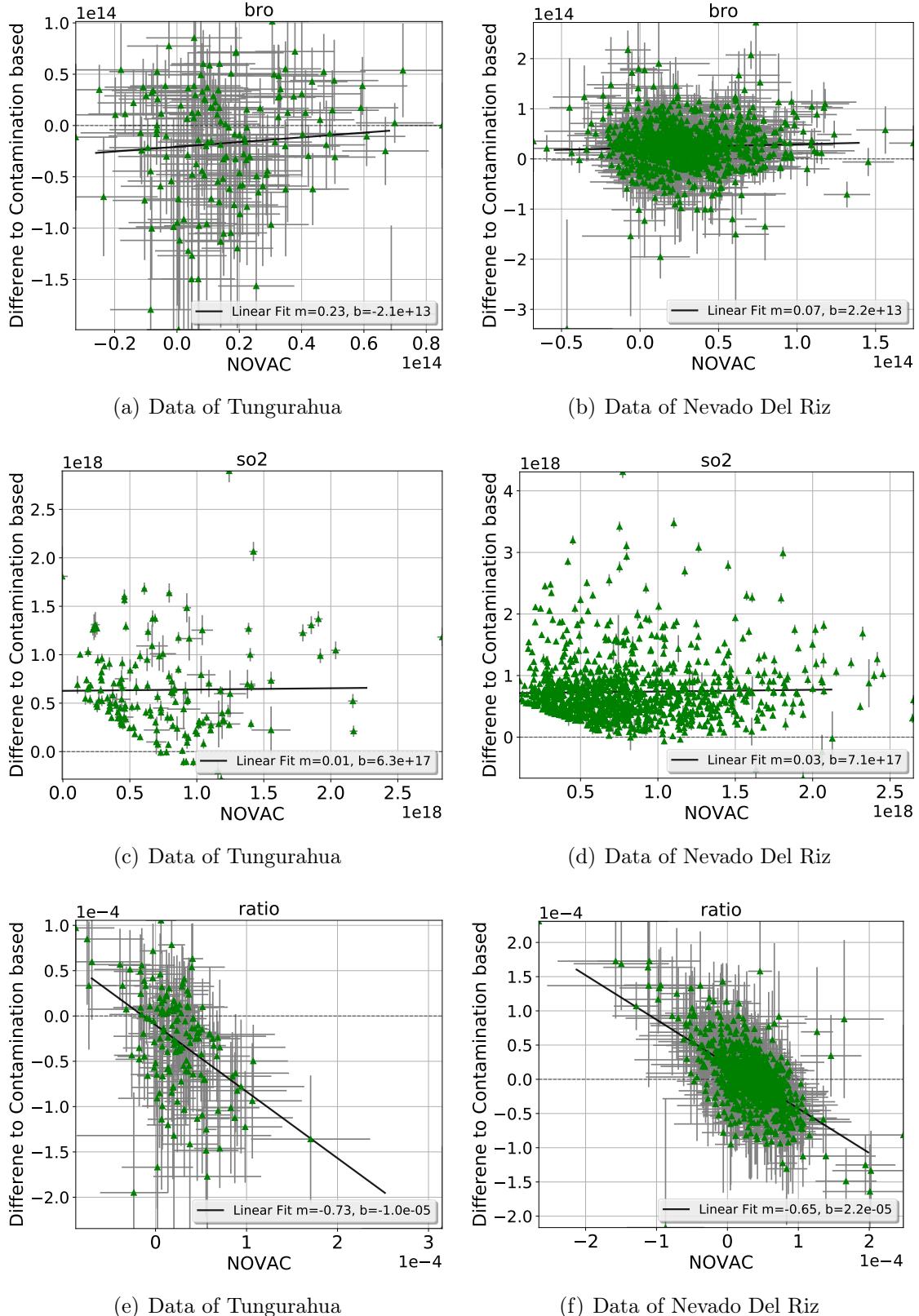


Figure 8.2: The dependency of the Difference between contamination based data and NOVAC to the data evaluated with the NOVAC data

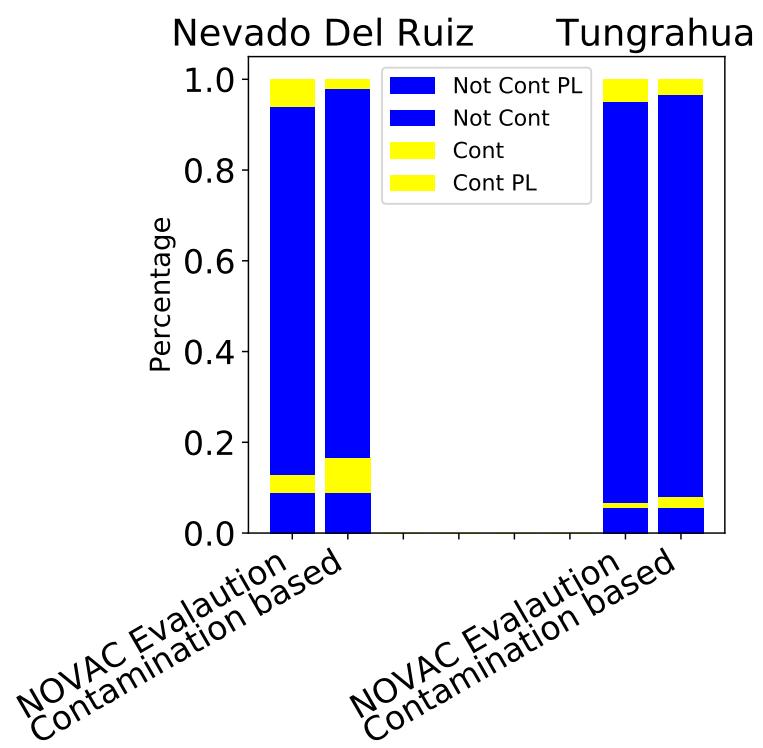


Figure 8.3:

# 9 Results

Interpretation of the BrO/SO<sub>2</sub> ratio time-series

## 9.1 Tungurahua

|   |      |   |       |
|---|------|---|-------|
| <i>MengeanDateninsgesamt :</i>                          | 5883 | ≡ | 1     |
| <i>Davon : (NOVACAuswertung)berplumelimit</i>           | 712  | ≡ | 0.121 |
| <i>Davon : MengeanDaten, dienichtKontaminiertsind :</i> | 5504 | ≡ | 0.936 |
| <i>DavonimPlume – limit :</i>                           | 599  | ≡ | 0.102 |
| <i>DavonberdemDetectionLimit :</i>                      | 36   | ≡ | 0.006 |
| <i>Davonsindkontaminiert :</i>                          | 379  | ≡ | 0.064 |
| <i>Davon(mitNOVacaausgewertet)berplumelimit :</i>       | 114  | ≡ | 0.301 |
| <i>Davon(NeueAuswertung)berplumelimit</i>               | 185  | ≡ | 0.488 |

Dh in den kontaminierten daten sind mit NOVAC ausgewerteten daten 2.485 häufiger über dem plume limit

## 9.2 Nevado Del Ruiz

|   |      |   |       |
|---|------|---|-------|
| <i>MengeanDateninsgesamt :</i>                    | 8962 | ≡ | 1     |
| <i>Davon : (NOVACAuswertung)berplumelimit</i>     | 142  | ≡ | 0.016 |
| <i>Davon : nichtkontaminiertedaten :</i>          | 8596 | ≡ | 0.959 |
| <i>DavonimPlume – limit :</i>                     | 123  | ≡ | 0.014 |
| <i>DavonberdemDetectionLimit :</i>                | 53   | ≡ | 0.006 |
| <i>Davonsindkontaminiert :</i>                    | 366  | ≡ | 0.041 |
| <i>Davon(mitNOVacaausgewertet)berplumelimit :</i> | 20   | ≡ | 0.055 |
| <i>Davon(NeueAuswertung)berplumelimit</i>         | 179  | ≡ | 0.489 |

Dh in den kontaminierten daten sind mit NOVAC ausgewerteten daten 3.449 häufiger über dem plume limit

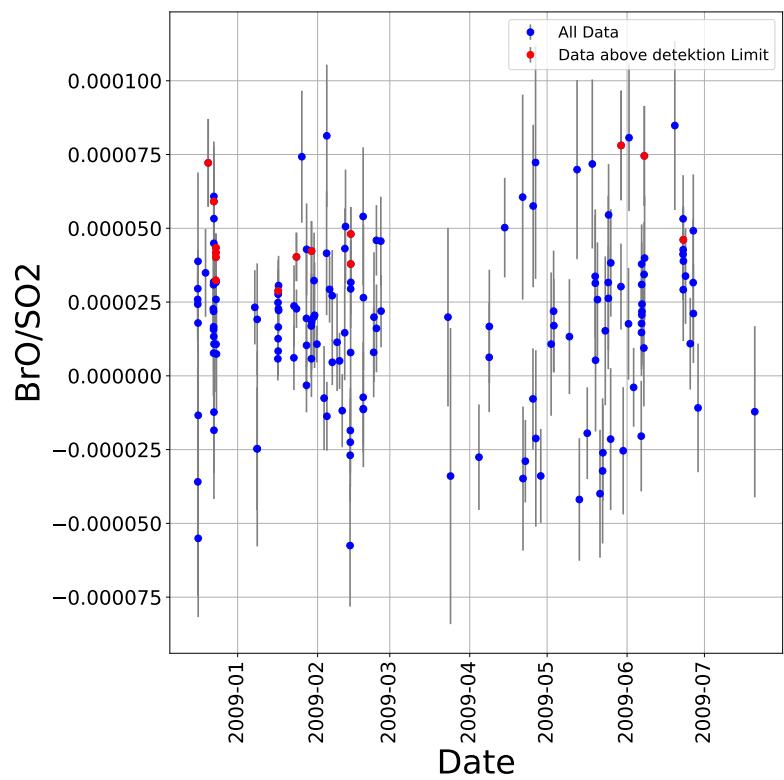


Figure 9.1:

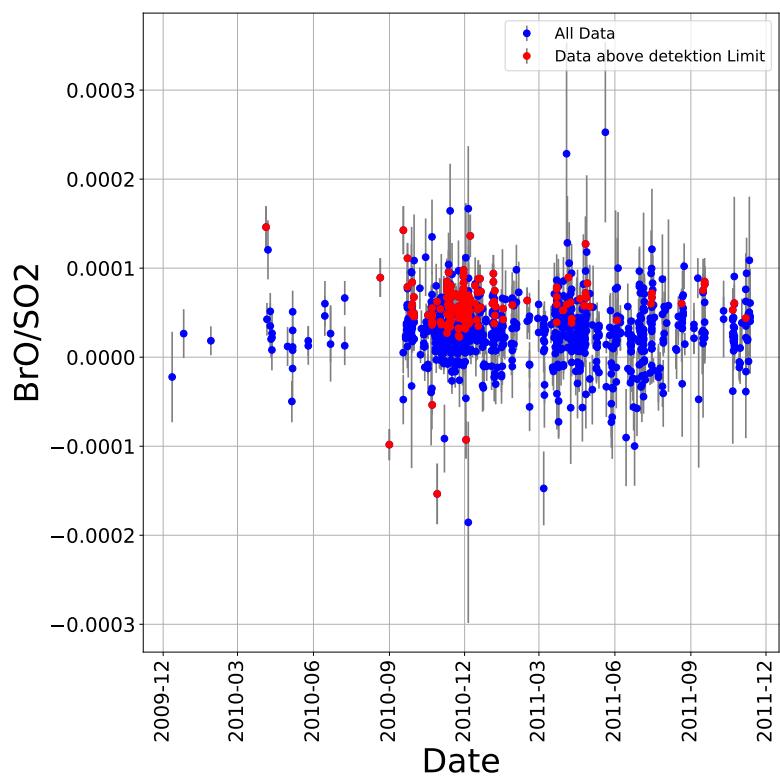


Figure 9.2:

## 10 Issues of our method

### 10.1 Contamination of the plume

- As discussed above it might occur, that, that the reference is contaminated for example by the plume of the day before. If that happens, we underestimate the gas amount by using a contaminated reference. But another possibility is, that the plume is also contaminated. This might be the case if the volcanic gas of the volcano is not taken away by the wind, but accumulates in the plume. If this is the case, using an other reference would lead to an overestimation of the column density of gases.

## 11 Conclusion

....

# Part III

## Appendix

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Erklärung:

Ich versichere, dass ich diese Arbeit selbstständig verfasst habe und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Heidelberg, den (Datum) ..... .