Briefing note on interpreting volcanic gas measurements

Introduction

Volcanic gases are the driving force for an eruption. Different types of gas measurements are used for answering different types of questions. When reviewing information on gas release from an eruption, the terms 'emission rate' (or flux) and 'concentration' commonly appear. These terms have distinct meanings and are not interchangeable.

What is the difference between gas emission rate and concentration?

Emission rate or flux refers to how much gas flows out of the volcano per unit of time and is expressed in units of metric tonnes per day (t/d) or kilograms per second (kg/s). Sulfur dioxide (SO_2) gas emission rates are reported for most eruptions and are generally proportional to the size of the eruption. SO_2 emission rates can be calculated by measuring a cross-section of the plume from the ground, air, or from special analysis of space-based gas mass measurements. These data are used by scientists to forecast eruptions, understand eruption dynamics, and develop more accurate climate change models.

Concentration, by contrast, is a measure of how much gas (or particles) are suspended in a volume of air at a particular place and time, and is usually reported as parts per million (PPM) or micrograms per cubic meter ($\mu g/m^3$). Portable or fixed instruments that sample ambient air are generally used to measure concentrations of volcanic gases and particles. Ambient air measurements are used by public health and environmental scientists for quantifying human exposures, identifying hazardous air quality, and assessing impacts to agricultural crops, livestock, and infrastructure.

How does gas emission rate affect ground-level concentrations?

The relationship between emission rate and concentration can be illustrated by the example of cigarette smokers in a restaurant. The amount of smoke being generated by a table full of smokers can be considered the emission rate. The concentration of second-hand smoke that the adjacent table will experience is dependent on the direction the smoke is blowing, how close the tables are, and if there is some method available for diluting the smoke. If the room is very still, the smoke accumulates, resulting in higher concentrations. If someone suddenly opens a window, the smoke will be diluted by fresh air, and the concentration will decrease, although the amount of smoke being generated is the same.

During an eruption, the concentration of volcanic pollution at a given location generally depends on the distance to the gas emitting vent, the gas emission rate, the wind direction and speed, and atmospheric effects. Pollutant concentrations will be higher closer to the vent where the emissions have not been diluted. The wind direction and speed influence the volcanic plume location and concentration. Atmospheric stability and eruption dynamics will also influence the vertical extent of the plume, and if the plume stays at ground level or is lofted overhead. Emission rates can be used to model downwind concentrations by using detailed wind field and dispersion or flow models. These models can be used to issue forecasts and public advisories of impending volcanic air pollution events. However, the quantitative relationship between emission rate and downwind ground-level concentration is variable and complex (see below).

What do satellite-based instruments measure?

Satellites carry a variety of instruments that measure light absorption by gases or particles, including in volcanic eruption plumes. Examples of instruments that measure SO_2 in the atmosphere include TROPOMI (TROPOspheric Monitoring Instrument) which is carried on the Sentinel-5P satellite, and OMI (Ozone Monitoring Instrument) carried on the Aura satellite. These instruments measure the amount of SO_2 in the vertical column of air between the satellite and the ground surface, as the satellite orbits the Earth. The colorful maps that are generated from the column measurements show the amount of SO_2 integrated over the entire vertical column (known as column amount), but do not provide information on the elevation above ground level at which the SO_2 is located. Therefore, these maps are not useful for assessing ground-based SO_2 concentrations and the associated impact on air quality.

Satellite-derived plume maps (Figure 1) show the color-coded column amount in Dobson units (DU) and the mass in kilotons (kt) for the mapped area (see https://so2.gsfc.nasa.gov/). Additional, careful analysis is required to generate an emission rate from the mapped mass. In this way, satellite-based measurements are intrinsically different from SO_2 emission rate measurements made by volcano observatories, so the numbers reported using these two techniques will likely be different from each other. Observatories may use a variety of ground and airborne platforms, frequently employing spectroscopic techniques for quantifying emissions.

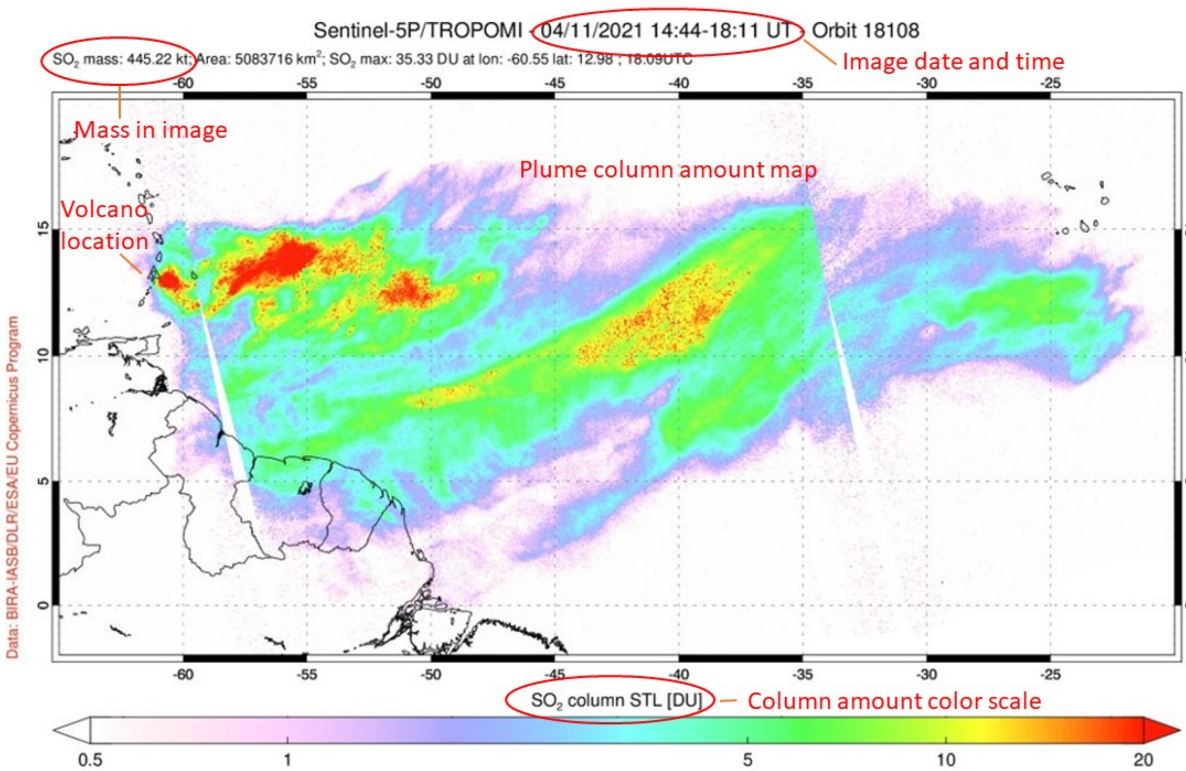

Figure 1: Column amount map for 11 April 2021 from the TROPOMI instrument aboard the Sentinel-5P satellite. Key information such as date, volcano location, column amount, and calculated mass are circled in red. Image from [NASA Global Sulfur Dioxide Monitoring Home Page.](https://so2.gsfc.nasa.gov/)

How do satellite SO_2 measurements (e.g. TROPOMI, OMI) and observatory measured SO_2 emission rates relate to ground level concentrations?

Complex computer modelling is required to forecast downwind concentrations from ground- or space-based emission rate (flux) or mass measurements. Modelled ground-level concentrations may realistically be considered as qualitative or semi-quantitative. The models use detailed information on plume source characteristics and dispersion, local and regional terrain, wind, and atmospheric conditions. High emission rates will generally correlate with high ground-level concentrations close to the volcano, but the downwind ground-level concentrations will depend on many factors, including the height above ground level at which the plume was erupted and transported. Even under the best circumstances, studies suggest that models can be expected to predict ground-level volcanic pollution events with about 50-80% accuracy. Therefore, forecasts of ground-level volcanic air pollution based on models, are best used in combination with ambient air quality concentration measurements, which confirm the accuracy of the model.

How will an SO_2 cloud impact near and distant locations?

During eruptions, plumes of volcanic emissions can travel for hundreds to thousands of kilometres (miles) downwind, creating volcanic air pollution locally and in distant locations. As SO_2 travels in the atmosphere, it reacts with oxygen, moisture, dust, and sunlight over a period of minutes to days, to produce acidic sulfate aerosol. Communities close to an eruption (tens of kilometres) may be exposed to volcanic pollution (mainly sulfate aerosol and unreacted SO_2 gas) depending on how close they are to the erupting vent, how much gas is emitted, and wind and atmospheric conditions. Communities that are further downwind (hundreds to thousands of kilometres) or that are exposed to an aged plume, will mainly be exposed to sulfate aerosols, with any unreacted SO_2 gas unlikely to exceed air quality guidelines. There are some exceptions, where very large eruptions (i.e. emitting more than 100 kt/d SO_2) may cause noticeable SO_2 gas pollution at hundreds of kilometres distance (e.g. Holuhraun, Iceland, 2014-2015). The height at which the plume is injected into the atmosphere, along with the atmospheric stability, will influence the vertical extent of the plume, and if it descends to ground level. Plumes generated in explosive eruptions which are carried high into the atmosphere, may disperse well above ground level. Plumes generated near ground level, in mildly explosive or effusive eruptions, may disperse close to the ground, depending on local atmospheric conditions. Asthmatics are particularly sensitive to both SO_2 and sulfate aerosol, so comprehensive ground-based monitoring of gas and particle concentrations will help protect populations near and far downwind of volcanic eruptions.

Further resources:

IVHHN Air quality monitoring for volcanic emissions

IVHHN General information of volcanic gases and international air quality standards and guidelines

IVHHN The health hazards of volcanic and geothermal gases: a guide for the public

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