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Space-borne detection of volcanic carbon dioxide anomalies: The importance of ground-based validation networks

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We have investigated the feasibility of space-borne detection of volcanic carbon dioxide (CO_2) anomalies, and their integration with ground-based observations. Three goals provide motivation to their integration: (a) development of new volcano monitoring techniques, with better spatial and temporal coverage, because pre-eruptive volcanic CO_2 emissions are potentially the earliest available indicators of volcanic unrest; (b) improvement the currently very poor global CO_2 source strength inventory for volcanoes, and (c) use of volcanic CO_2 emissions for high altitude strong point source emission and dispersion studies.

(1) Feasibility of space-borne detection of volcanic CO_2 anomalies.

Volcanoes are highly variable but continuous CO_2 emitters, distributed globally, and emissions often occur at high altitudes. To detect strong point sources of CO_2 from space, several hurdles have to be overcome: orographic clouds, unknown dispersion behavior, a high CO_2 background in the troposphere, and sparse data coverage from existing satellite sensors. These obstacles can be overcome by a small field of view, enhanced spectral resolving power, and by employing repeat target mode observation strategies.

The Japanese GOSAT instrument has been operational since January 2009, producing CO_2 total column measurements with a repeat cycle of 3 days and a field of view of 10km. GOSAT thus has the potential to provide spatially integrated data for entire volcanic edifices, especially in target mode. Since summer 2010 we have conducted repeated target mode observations of over 20 persistently active global volcanoes including Etna (Italy), Erta Ale (Ethiopia), and Ambrym (Vanuatu), using L2 GOSAT FTS SWIR data.

One of our best-studied test cases is Mt. Etna on Sicily (Italy), which reawakened in 2011 after a period of quiescence and produced a sequence of eruptive activities including lava fountaining events, coinciding with target-mode GOSAT observations conducted there since 2010. For the 2011 activity we compare GOSAT custom re-processed target mode observation CO_2 data to SO_2 data from the Ozone Monitoring Instrument (OMI), the Moderate-Resolution Imaging Spectroradiometer (MODIS), and ground-based SO_2 measurements obtained by the FLAME ultraviolet scanning DOAS network, as well as ground-based multi-species measurements obtained by FTIR technique. GOSAT CO_2 data show an expected seasonal pattern, because the signal is dominated by ambient atmospheric CO_2. However, some possible significant variations do appear to exist before and during eruptive events. Besides cloud and aerosol effects and volcanic emission pulses, two further factors seem to also strongly affect the signal beyond seasonal variability: different altitudes ranges of sensitivity for OMI and GOSAT appear to cause inverse signal correlations when the presence of clouds allows for multiple scattering effects. The second effect is wintertime high-altitude snow cover, which enhances the reflected light yield in the suspected high-concentration column portions near the ground. The latter two effects may dominate between emission pulses and their inverse correlations stand in contrast to magmatic events, which we suspect to give rise to positive correlations.

(2) Integration of space-borne and ground-based observations of volcanic CO_2 emissions.

Monitoring of remote terrestrial volcanic point sources of CO_2 from space and using ground-based observations have advantages and disadvantages. Advantages of satellite methods include homogenous coverage potential, a single data format, and a largely unbiased, mostly global coverage potential. Advantages of ground-based observations include easier calibration and targeting, validation and spatial resolution capacity. While cost plays a strong role in either approach, ground-based methods are often hampered by available personnel to expand observations to global coverage, by a patchwork of instrumentation types, coverage, availability, quality, and disparity of data formats and frequencies.

The solution to achieving high quality regional or global coverage may lie in the combination of the two methods, and satellite campaigns do already rely on ground-based validation methods for their data products. To optimize a combination of space-borne and ground-based techniques, two aspects need to be addressed: (a) database and data format compatibility, and (b) questions of instrumentation network design and compatibility. For regional spatio-temporal atmospheric variances, no homogenous data formats and databases exist to date. In volcanology, such an approach already exists in the emerging WOVOdat database and its data format convention (http://www.wovodat.org). For ground-based CO_2 network designs in volcanology and in greenhouse gas monitoring in general, no common approach has yet found common use that besides integration of existing networks would also enable nesting, scaling and fractal growth.

In summary, promising first results from the GOSAT instrument indicate that a space-based detection of volcanic CO_2 pulses may indeed be possible. Once newer generations of satellite sensors become operational (e.g., OCO-2, OCO-3, and GOSAT-2), better ground resolution and scanning capabilities might enable detection and imaging of volcanic CO_2 plumes. To derive the best quality product from such measurements, we anticipate an urgent need to design new approaches to ground-based validation networks and their data products. Such networks would ideally become more compatible, with a higher degree of instrumentation compatibility, and a common data exchange format to connect between distributed databases. Community-based efforts will be necessary to progress toward these goals.