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Volcanic Sulfur Dioxide estimates through Machine Learning using MSG-SEVIRI and Sentinel-5P TROPOMI

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Sulfur dioxide (SO₂) represents the third most abundant volcanic gas released by magma degassing in the shallow crust. Its monitoring provides information on magma ascent rates, conduit dynamics, and eruption style and intensity, thereby supporting volcano monitoring and hazard assessment.

The TROPOMI instrument onboard Sentinel-5 Precursor, launched in 2017, is the most recent sensor delivering daily measurements of atmospheric SO₂ column densities at an unprecedented spatial resolution of 5.5 km x 3.5 km at nadir.

The aim of the present study is to improve the current SO₂ detection capabilities by combining TROPOMI products with data from the MSG-SEVIRI radiometer, which offers higher spatial resolution (about 3 km x 3 km at nadir) and revisit times of 15 minutes, or 5 minutes in Rapid Scan mode.

To enhance SO₂ retrieval capabilities, a data-driven AI model was implemented to estimate SO₂ vertical column densities at SEVIRI spatial and temporal resolution, using TROPOMI observations as reference. A multilayer perceptron was designed and trained based on the SO₂ Vertical Column Density measured by TROPOMI. The model was optimized by minimizing the Mean Squared Error, with an early-stopping strategy applied to prevent overfitting.

This approach allows SEVIRI data to inherit the sensitivity of TROPOMI while preserving its native high-frequency coverage. The method substantially increases measurement density and improves spatial detail, enabling more refined and continuous monitoring of volcanic degassing.

Mount Etna (Italy), with its open-vent persistent degassing activity sustaining SO₂ fluxes of 500 to more than 5000 t/day, was taken as a study case. Results were quantitatively validated against measurements from ground-based monitoring networks and satellite data from literature, finding an optimal agreement with the latter and managing to capture the SO₂ plume where ground-based instruments fail.

Model performance was evaluated on the held-out test set using several statistical indicators, including the coefficient of determination (R^2), the mean squared error (MSE), the root mean squared error (RMSE), and the mean absolute error (MAE). The model achieved an R^2 of 0.845 on test data, indicating that approximately 84% of the variance in the observed SO₂ VCD is captured by the model predictions. The MSE was estimated at 0.000002 mol²/m⁴, corresponding to an RMSE of 0.0014 mol/m², while the MAE was 0.0016 mol/m². Overall, these low error magnitudes demonstrate the model's capability to reproduce the observed SO₂ VCD with high accuracy.

This integrated technique offers a promising tool for rapid and robust volcanic hazard assessment, introducing improvements to current retrieval methods, and enhancing early warning capabilities for aviation safety, as well as studies of climate impacts from volcanic emissions.