

SO₂ advection height from Forest Fires Using Satellite Imagery

*Nanami Ohshima¹, Hiroyasu Tokue^{2,8}, Sasara Jouko⁸, Kinuka Matsuzaki⁸, Asahi Hashimoto^{3,8}, Mako Shibata^{4,8}, Hiroshi Kawamata^{5,8}, Nobuyasu Naruse⁶, Yukihiro Takahashi^{7,8}

1. Sapporo Kaisei Secondary School, 2. Institute for Space-Earth Environmental Research, Nagoya University, 3. Forestry Research Institute, Hokkaido Research Organization, 4. The University of Edinburgh, 5. Institute of the Advancement of Graduate Education, Hokkaido University, 6. School of Medicine, Shiga University of Medical Science, 7. Department of Cosmosciences, Graduate School of Science, Hokkaido University, 8. Non-profit Organisation Super Scientist Programme Plus

The area burned by forest fires has been increasing year by year, and Alexandra Tyukavina et al. (2022) estimated that it increased globally at an average rate of 302,400 ha yr⁻¹ from 2001 to 2019. With the rise in large-scale forest fires, the long-range transport of sulfur dioxide (SO₂) released into the atmosphere and its climate impacts have drawn attention. Through oxidation processes, SO₂ forms sulfate aerosols that contribute to the radiative balance and influence cloud microphysical properties. Furthermore, when accompanied by strong convective activity, fire-derived components are transported into the upper troposphere and lower stratosphere, thereby influencing atmospheric processes at higher altitudes. Therefore, understanding the three-dimensional spatiotemporal behavior of SO₂, including its vertical distribution, is fundamentally important for assessing the atmospheric impacts of forest fires. Gautam et al. (2023) estimated SO₂ transport trajectories by combining ground-level SO₂ concentration measurements near fire locations during forest fires, back-trajectory analysis, and satellite imagery. However, this method relies on assumptions regarding representative altitudes and does not explicitly resolve the actual vertical distribution of SO₂. Furthermore, Mike Burton et al. (2024) estimated the temporal variations in the transport altitude of SO₂ after volcanic eruptions by utilizing back-trajectory analysis and satellite observations of SO₂ concentrations. However, SO₂ emissions from forest fires are lower compared to volcanic eruptions. Due to detection sensitivity constraints, the assessment of altitude-dependent transport remains unclear.

This study aimed to clarify the transport altitude of SO₂ emitted from forest fires. Results from trajectory analysis at each altitude were compared with the SO₂ distribution derived from satellite observations. Forward trajectory analysis was employed to compare the SO₂ distribution with the position of the air mass 48 hours later. Satellite imagery was used from Sentinel-5P, covering images (six total, Sentinel-5 Precursor Level 2 Sulphur Dioxide) acquired from September 9 to 11, 2020, near California, USA. While the lower limit of detection for SO₂ in Sentinel-5P is 1.0×10^{-4} mol/m², this forest fire showed maximum observed values of approximately 2.0×10^{-3} mol/m², which was judged sufficient for analysis. For the trajectory analysis, horizontal winds from the reanalysis data (ERA5) estimated by the European Centre for Medium-Range Weather Forecasts (ECMWF) were used. Starting from 20 hotspots within the SO₂ distribution, air mass trajectories were calculated for each of 16 pressure levels from 100 hPa to 900 hPa. If a high SO₂ concentration area was located within a 30 km radius of the trajectory endpoint, the endpoint was considered consistent with that area.

Satellite observations show that the primary areas of high SO₂ concentration on September 11 were located southeast of the ignition point. The results of the 48-hour forward trajectory analysis showed that the endpoints at 450-550 hPa primarily reached the northwestern to southwestern portions of the high SO₂ concentration area, and the 400 hPa endpoints reached the central part of the high concentration area. This suggests that the high SO₂ concentration distribution observed by satellite was primarily formed by advection across a continuous range of pressure surfaces between 400 and 550 hPa. Furthermore,

since the trajectories calculated from the same starting point reached the high SO₂ concentration area at these multiple pressure levels, this implies that advection occurred across continuous pressure levels from the same location. These results, combining satellite image SO₂ distributions with trajectory analysis at each pressure level, demonstrate that high SO₂ concentration areas from forest fires are advected through a vertically continuous pressure layer.

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