Advances in forecasting volcanic plume evolution

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Laser satellite measurements within a dedicated model can accurately predict volcanic plume positions.

Explosive volcanic eruptions inject gas and ash particle loads into the atmosphere at high altitudes. These particles can impact both climate and air traffic because of their long range transport by horizontal wind motion. This is particularly true when volcanic plumes reach the tropopause level, i.e., the atmospheric layer ranging from approximately 8–12km (14–18km in the tropics) that separates the troposphere and stratosphere. Like other natural events, plumes resulting from volcanic eruptions often highlight weaknesses in our ability to accurately predict their evolution. Thus, it is imperative to develop modeling capabilities that are reactive and accurate to foretell plume effects and minimize disruption. However, horizontal wind motion that induces small scale transport of those plumes is often difficult to forecast. Additionally, the exact altitude of volcanic plumes, which is a fundamental parameter for modeling, is not easily available because of a lack of accurate vertical observations. We herein report our recent progress in assimilating atmospheric observations.

Figure 1. Total attenuated backscatter (top) and depolarization ratio (bottom) at 532nm at 17:15 Coordinated Universal Time, 9 November 2010 between 10–30°S. Low depolarization values of 0.1–0.2 associated with the layers (circled) are an indication that the layer is not made of ice crystals, which are usually associated with higher depolarization, but of volcanic aerosols. (Inset) Map showing orbit track of the Cloud-Aerosol and Lidar Infrared Pathfinder Observations satellite on 9 November 2010, which passed close to Mount Merapi (in red).
laser satellite measurements in quasi-real time for improved volcanic plume forecasting.

Our investigation is based upon observations from the volcanic aerosols injected at the tropopause level after the eruption of Mount Merapi (Java Island, Indonesia), on 3 November 2010. We used an aerosol-dedicated version of the high resolution transport modélisation isentrope du transport méso-échelle de l’ozone stratosphérique par advection (MIMOSA)\textsuperscript{1,2} model. To ensure better model predictions, we assimilated the latest lidar (light detection and ranging) aerosol data from the Cloud Aerosol Light Detection and Ranging with Orthogonal Polarization (CALIOP) instrument onboard the Cloud-Aerosol and Lidar Infrared Pathfinder Observations (CALIPSO) satellite.\textsuperscript{3} We obtained the data from NASA\textsuperscript{4} and, in France, from the Cloud-Aerosol-Water-Radiation Interactions (ICARE) data center.\textsuperscript{5}

First, we used CALIPSO observations to determine the position of the plume. The CALIPSO lidar emits laser beams at 532 and 1064nm downward along its polar orbit. Light scattered back towards the spacecraft by molecules and particles in the atmosphere was collected by a telescope. Using this vertical backscatter profile data, we inferred the 3D location of clouds and aerosols. Additionally, we used depolarization measurements at 532nm to determine the effect of the particles on light polarization. The backscatter and depolarization ratio on 9 November 2010 showed extended layers of volcanic aerosols at altitudes around 15–16km between 10–30°S (see Figure 1). These volcanic aerosols demonstrated minimal depolarization values (0.1–0.2) compared to the surrounding clouds. Furthermore, based on back trajectories, we confirmed that these particles originated from the Mount Merapi eruption six days earlier. Thus, based on these optical properties, we could isolate the position of the volcanic plume using CALIPSO observations.

We next assimilated the CALIPSO data in quasi-real time within the MIMOSA horizontal transport model to generate a prediction of the plume position. MIMOSA is a fine resolution (horizontal grid of 0.5 x 0.5°) isentropic transport model using meteorological field (2.5 x 2.5°) from the European Center for Medium-Range Weather Forecast. MIMOSA also combines an aerosol module to simulate the microphysical evolution and optical properties of particles along their transport. During our calculations of the aerosol load, we incorporated the available information from CALIPSO on the vertical position and density of the volcanic plume. The MIMOSA optical module assimilated and produced a backscatter ratio (BR) field, considered to be proportional to an aerosol mixing ratio. Figure 2(a-c) shows the assimilated BR field, where the model used observations to produce an estimation of the Mount Merapi plume location at 380K (16–17km). By 10 November 2010, seven days after the eruption, the Mount Merapi plume had expanded over the Indian ocean. The plume moved westwards and reached Africa by 20 November, after which it continued to spread over the

\textit{Figure 2.} Mount Merapi plume position on different dates. (a) 10 November, (b) 20 November, (c) 10 December, and (d) 20 December 2010. The backscatter ratio was calculated at 532nm (B.R.532nm) and gives the relative presence of volcanic aerosols. This simulation uses meteorological data up to 15 December 2010 (a-c), before forecasting the plume position from 15–20 December (d).
tropics. During this simulation, we assimilated CALIPSO observations up to 15 December 2010 to produce an estimation the plume position on 20 December 2010—see Figure 2(d). CALIPSO later confirmed the accuracy of our prediction. Inclusion of the latest satellite measurements in MIMOSA allowed the successful forecast of the multiple plumes associated with the transport of air masses outside the tropics. Additionally, the model rendered atmospheric filaments—even on the global scale.

In summary, this study represents a step toward accurate forecasting of volcanic plume transport. We achieved this by coupling high resolution, vertical information from the CALIPSO lidar to the horizontal transport model MIMOSA. After a necessary validation step of the model with ground-based lidar measurements, we plan to develop a more sophisticated tool to improve the detection of volcanic plumes. In particular, plumes at lower levels—where mixing with clouds and other aerosols occurs—significantly complicates measurement. As CALIPSO is flying with multiple satellites, the opportunity exists to combine other data sets, including sulfur dioxide and ash infrared emission information, to better characterize volcanic plumes before their assimilation into the model.

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