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SATELLITE BASED DETECTION OF VOLCANIC SO_2 OVER PAKISTAN

MAHMOOD I.[*]
SHAHZAD M.I.
IQBAL M.F.
ULLAH K.
WAQAS A.
KIDWAI A.A.

Earth & Atmospheric Remote Sensing Research Group (EARS)
Department of Meteorology,
COMSATS Institute of Information Technology
Islamabad, Pakistan

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*to whom all correspondence should be addressed:
e-mail: irfan.mahmood@comsats.edu.pk

ABSTRACT

The present study is carried out to explain the presence of large concentrations of SO_2 in atmosphere of Pakistan during June, 2011. Large volcanic eruptions are a major source of greenhouse and trace gases. The eruption of Mount Nabro in June, 2011 injected large amount of SO_2 into stratosphere. Nabro volcanic eruption generated a layer of sulfate aerosols, which resided in stratosphere for months. The total amount of SO_2 that was injected into the atmosphere was estimated to be 1.3-2.0 Tg. Data products of Global Ozone Monitoring Experiment (GOME-2), Ozone Monitoring Instrument (OMI) and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) were used to study SO_2 concentrations and plume movement over Pakistan. HYSPLIT backward trajectory model is utilized to study the origin of SO_2 plume. The study confirms that SO_2 plume originated from Nabro volcanic eruption and caused significant atmospheric perturbations and affected the air quality of Pakistan. SO_2 emissions from volcanic eruptions can pose serious hazard to population as well as global climate.

Keywords: Mount Nabro; Volcanic SO_2; HYSPLIT; Air quality; Sulfate Aerosols; Stratospheric perturbation

1. Introduction

Active volcanoes are a major source of greenhouse, acid and trace gases (Carn *et al.* 2005). The biggest source of natural pollution in the stratosphere is the injection of trace gases from volcanic eruptions. SO_2 is the main component of trace gases from volcanic eruptions and it can lead to increase in optical thickness in stratospheric heights, hence exerting a cooling effect on earth's atmosphere (Shin *et al.*, 2015). Large volcanic eruptions lead to injection of SO_2 into stratosphere, which can persist for months and years (Fairlie *et al.,* 2014). Injection of SO_2 in the atmosphere effects the chemical composition and radiative balance of Earth's atmosphere. SO_2 is a precursor to Atmospheric Sulfate Aerosols and because of their large dispersion and longer residence time; stratospheric aerosols have notable effect on global climate (Hoffman *et al.*, 2009). Therefore, their global monitoring is of importance. A total of ~ 20 Tg of SO_2 was injected into the atmosphere after the powerful eruption of Mount Pinatubo in June of 1991 (Fairlie *et al.,* 2014). The injection of SO_2 from Mount Pinatubo eruption led to global mean tropospheric cooling effect by 0.5-0.8 K in 1992 (Shin *et al.,* 2015). SO_2 converts into Sulphuric acid, which after condensation forms fine sulfate aerosols in stratosphere.

Microphysical & Radiative properties, occurrence frequencies and altitudes of ice clouds can be modified by Stratospheric Sulfate Aerosols (Meyer *et al.,* 2015). One of the most important factors altering the global greenhouse effect is the anthropogenic emission of SO_2 (Graf *et al.,* 1997). Natural resources contribute to ~25 Tg of sulfur per year whereas around ~ 80 Tg of sulfur per year is contributed from anthropogenic sources. Most volcanic emissions of SO_2 take place in the northern hemisphere as it houses about 82% of all active volcanoes (Graf *et al.,* 1997). Impact on radiative fluxes increase due to proximity of natural sulfur resources to oceans as sulfate aerosols strongly affect the maritime clouds (Graf *et al.,* 1997). Combustion of fossil fuels is a direct source of SO_2 into troposphere.

1.1. Mount Nabro Eruption

Mount Nabro is a 2218m high volcano that erupted on 12 June 2011 and injected large amount of SO_2 into the atmosphere. The total amount of SO_2 that was injected into atmosphere was estimated to be 1.3-2.0 Tg (Fairlie *et al.,* 2014). Nabro Volcano (13.37^o N, 41.7^o E) is located in Eritrea, East Africa. Nabro Volcano is situated to the east of Afar Rift Zone, which is situated at the triple junction between Arabian, Somalian and Nubian tectonic plates. It is the largest volcano in 110 Km long Nabro Volcanic range (Hamlyn *et al.,* 2014; Sawamura *et al.,* 2012; Shin *et al.*, 2015). Regional sensors detected significant seismicity prior to eruption. Earthquakes several hours before the eruption prompted a rapid evacuation of population (Goitom *et al.,* 2015). The eruption lasted for two weeks and created ash clouds that reached the height of 15-17 Km and disrupted aviation routes (Hamlyn *et al.,* 2014). The eruption of Nabro Volcano generated a layer of sulfate aerosols, which resided in stratosphere for months (Sawamura *et al.,* 2012). During the first 15 hours, a large fraction of total SO_2 was released (Meyer *et al.,* 2015).

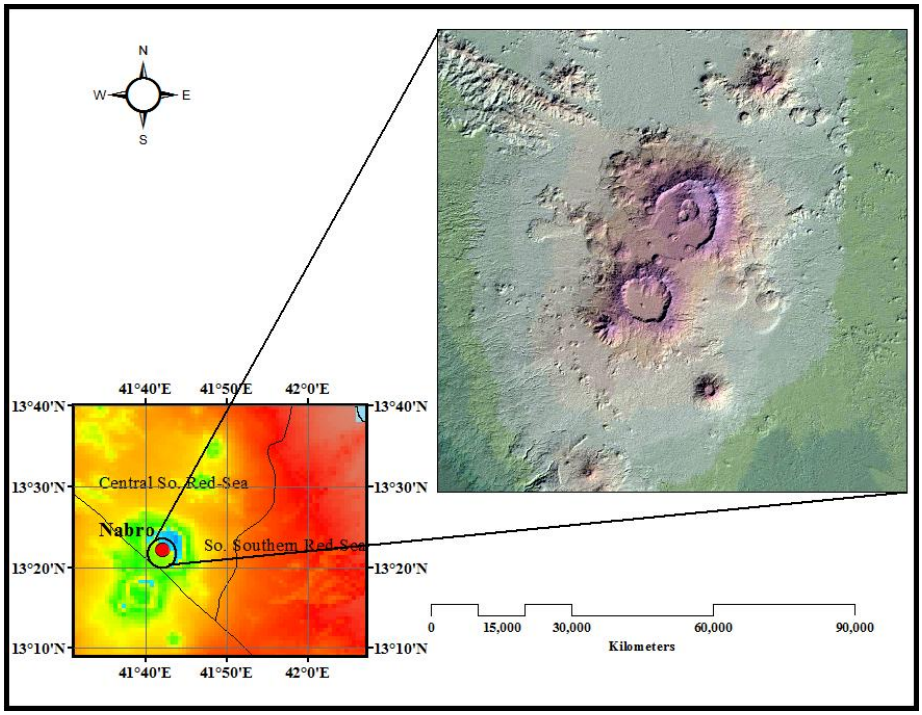

Figure 1. Terra ASTER Map of Nabro Volcano Caldera

2. Data

SO_2 vertical column data product of Global Ozone Monitoring Experiment (GOME-2) was obtained from website www.sacs.aeronomie.be of the Tropospheric Emission Monitoring Internet Service. The Global Ozone

Monitoring Experiment-2 (GOME-2) is one of the new-generation European instruments carried on Met-Op. The Met-Op satellite was launched by European Space Agency to study Atmospheric phenomena. GOME-2 is a nadir-viewing spectrometer. It retrieves SO_2 from Sun-synchronous, low earth orbits utilizing backscattered radiation in near UV. GOME-2 has a spectral coverage of 240-790 nm whereas spectral resolution is 0.26-0.51 nm (Fioletov *et al.,* 2013). This instrument utilizes Differential Optical Absorption Spectroscopy (DOAS) technique to measure SO_2 slant column density in wavelength range of 315-326 nm (Fioletov *et al.,* 2013).

Level-2 Ozone Monitoring Instrument (OMI) Sulphur dioxide (OMSO2) data product was obtained using GIOVANNI – Interactive Visualization and Analysis Tool from NASA. Ozone Monitoring Instrument (OMI) is a joint collaboration of the Netherlands's Agency for Aerospace Programs (NIVR) and Finnish Meteorological Institute (FMI). It is mounted on Aura Platform. It utilizes Differential Optical Absorption Spectroscopy (DOAS), Hyperspectral BUV Retrievals and forward modeling to extract OMI data products. OMI is a Nadir Solar backscatter spectrometer with a spatial resolution of 13km × 25km (Levelt *et al.,* 2006).

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data was acquired fromNASA CALIPSO Lidar Browse Images website (http://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/). CALIPSO is an environmental satellite launched jointly by National Aeronautics and Space Administration (NASA) and Centre National d' etudes spatiales (CNES). It was launched in 2006 with a primary purpose of studying the roles of clouds and aerosols. CALIPSO has three instruments namely Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP Lidar), the Imaging Infrared Radiometer (IIR) and the Wide Field Camera (WFC) (Winker *et al.,* 2010).

3. Results and Discussion

Nabro volcano erupted on midnight of June 12, 2011 which was the largest since Mount Pinatubo in 1991 in terms of stratospheric SO_2 injection. SO_2 plume advected in to lower stratosphere due to deep convection from Asian monsoon (Bourassa *et al.,* 2012). SO_2 plume is tracked in this study using GOME-2 data sets as shown in the Figure 2. Stratospheric SO_2 remained significantly high over Asia for a month after the eruption (Figure 2a; Meyer *et al.,* 2015). Initially, the SO_2 plume was mainly concentrated along East Africa until June 13, 2011 which later traveled a great distance to central Asia on June 15, 2011 (Figure 2b). On June 16, the plume spread into northern Pakistan while on June 17 it splitted into two and spread into Southern Pakistan (Figure 2c and 2d). However, until June 22, 2011 concentration of SO_2 was confined into Northern-Upper Central Pakistan (Figure 2i). In the days following, its concentration decreased (Figure 2j).

Spatial mean concentration of atmospheric SO_2 over Pakistan for the period of March, 2011 to October, 2011 excluding the eruption episode is 0.004 DU, using the level-2 OMI Sulphurdioxide (OMSO2) data product (Figure 3). However, Nabro Volcanic eruption considerably increased the concentration of SO_2 over the study area in June, 2011 with mean and maximum loading of atmospheric SO_2 was 1.16 DU and 3.78 DU respectively during the eruption episode. The maximum loading of atmospheric SO_2 during eruption episode was 945 times larger than normal SO_2 loadings. This indicates that the increase in SO_2 concentration is consistent with Nabro Volcanic eruption and its plume movement over Pakistan.

Backward Trajectory Analysis was performed in order to verify the origin of SO_2 plume over Pakistan. The analysis is performed utilizing the Hybrid Single – Particle Lagrangian Integrated Trajectory (HYSPLIT) Model that is designed by National Oceanic And Atmospheric Administration (NOAA), USA (Draxler and Rolph, 2013; Rolph, 2013). Back trajectory analysis is performed for 16 and 17 of June 2011. The trajectory is calculated 160 hours backward at a height of 500, 6000 and 9000 m AGL.

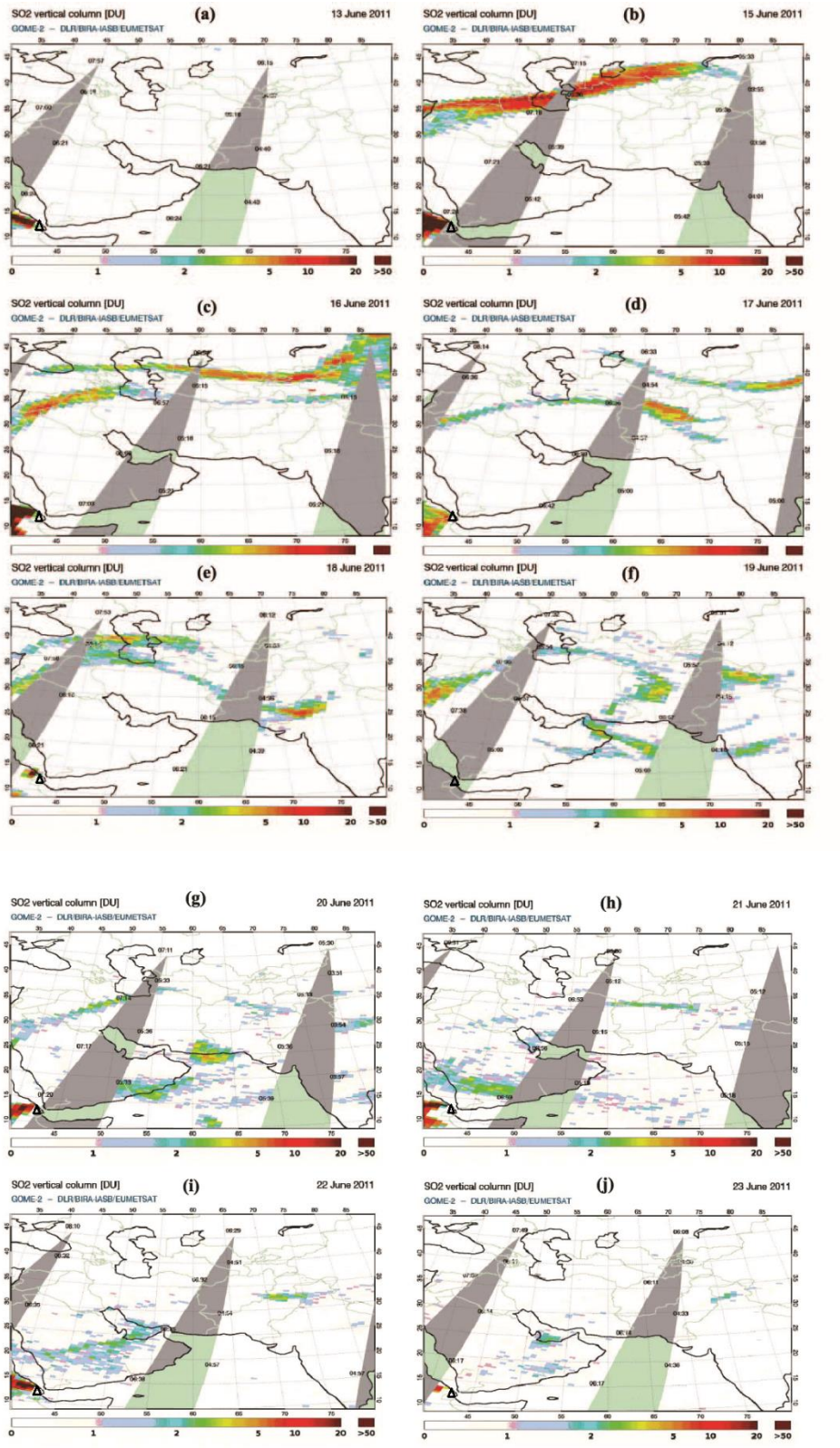

Figure 2. Daily observations of volcanic SO_2 from GOME-2. Black triangle shows the location of Nabro Volcano. Grey areas shows the regions without satellite observations

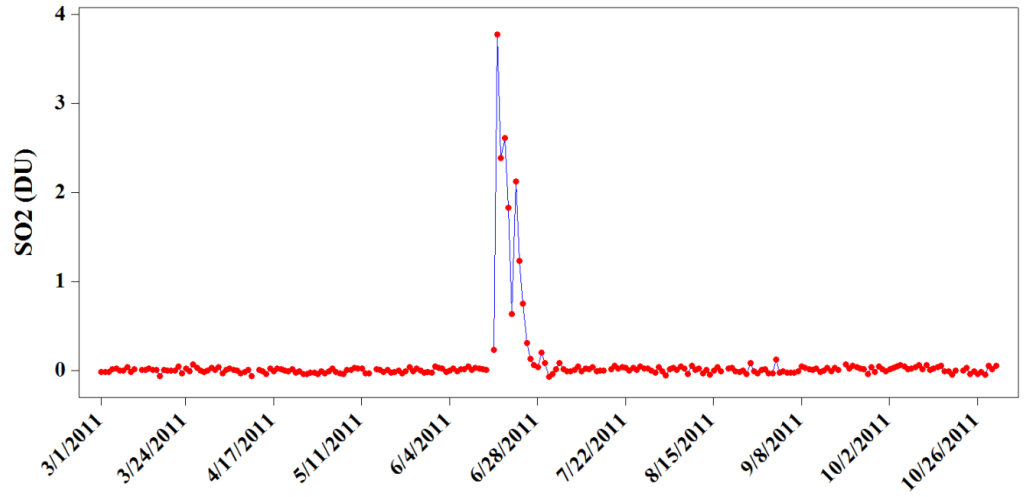

Figure 3. Time Series Plot of SO_2 concentration over Pakistan. SO_2 concentration is given in Dobson Units (DU) (1 DU = 2.69×10^{16} molecules/cm^2)

HYSPLIT model can compute trajectories for complex dispersion and deposition of volcanic plume in four dimensions of space and time using meteorological data from NOAA NCEP (Draxler and Rolph, 2014). Hysplit back trajectories in this study were computed at spatial resolution of 1^0 x 1^0 with multiple vertical levels up to 20 hPa using three hourly meteorological reanalysis data from NCEP to analyze the transport path and height of the plume before and after entering the Pakistan.

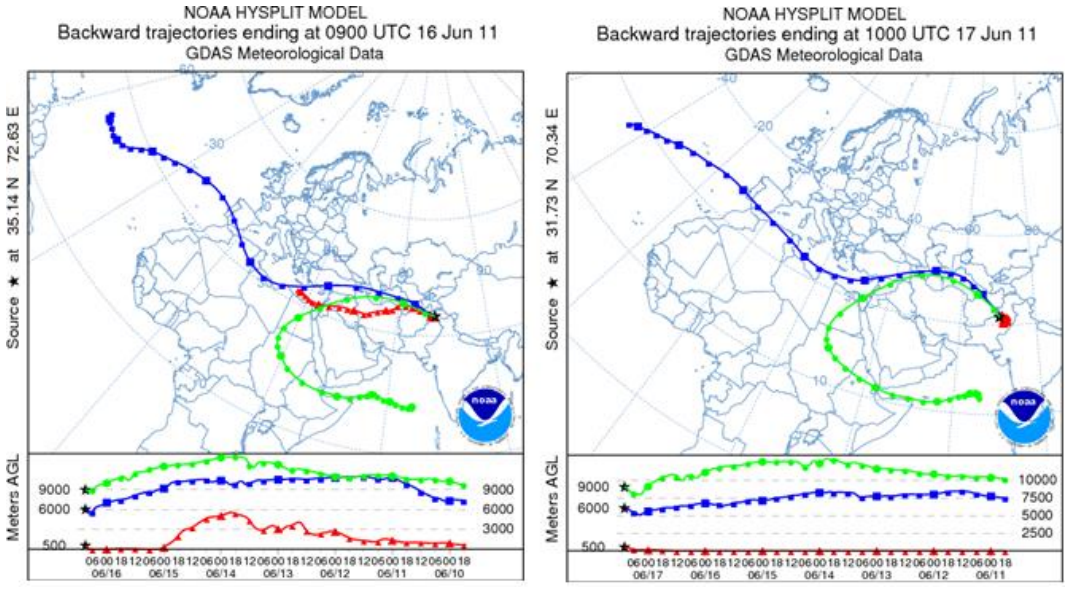

Figure 4. HYSPLIT Backward trajectories for 16 & 17 June, 2011

Satellite observation from GOME-2 (Figure 2) indicates that the volcanic SO_2 appeared to enter in Pakistan on 16 June 2011. Therefore, back trajectory analysis was performed for 16 and 17 of June 2011 to confirm the intrusion of volcanic plume in atmosphere of Pakistan. These trajectories are calculated 160 hours backward and the trajectory at a height of 9000 m AGL showed best agreement with the forward spread of volcanic

plume observed by GOME-2 (Figure 2). This was also in agreement with Clarisse *et al.*, (2014) who estimated the plume height of SO_2 during this eruption over west/southwest Asia between 5 – 11 km using Infrared Atmospheric Sounding Interferometer (IASI). Therefore, it can be suggested that backward trajectory confirms presence of volcanic plume originated from Nabro Volcanic eruption in Pakistan at a height of 9000 – 9500 m AGL in June 2016 (Figure 4).

In order to further investigate the approach of Nabro's volcanic plume in to Pakistan, available data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) was acquired. For the current study, CALIPSO's Vertical Feature Masks (VFM) image was used which can show the types of aerosols using aerosol classification algorithm. VFM uses attenuated backscatter profiles and depolarization ratio to first screen the aerosols and cloud layers (Liu *et al.*, 2005). Later each aerosol layer is assigned aerosol type depending on latitude, longitude, land use and land cover (LULC), altitude at which aerosols are observed and depolarization ratio (Omar *et al.*, 2009). Studies have reported the usefulness of VFM for analyzing the distribution of different aerosol types (Adams *et al.,* 2012; Chen *et al.*, 2012). In this study the available data of VFM (Figures 5 & 6) significantly show the polluted dust accompanied with smoke over Southern and Upper-Central Pakistan on 18 and 22 June 2011. Presence of these aerosols corresponds with presence of SO_2 plume over southern and upper-central Pakistan detected by GOME-2 as shown in Figure 2. Moreover, the location and altitude of the detected aerosol layer corresponds well to back trajectories as shown in Figure 4.

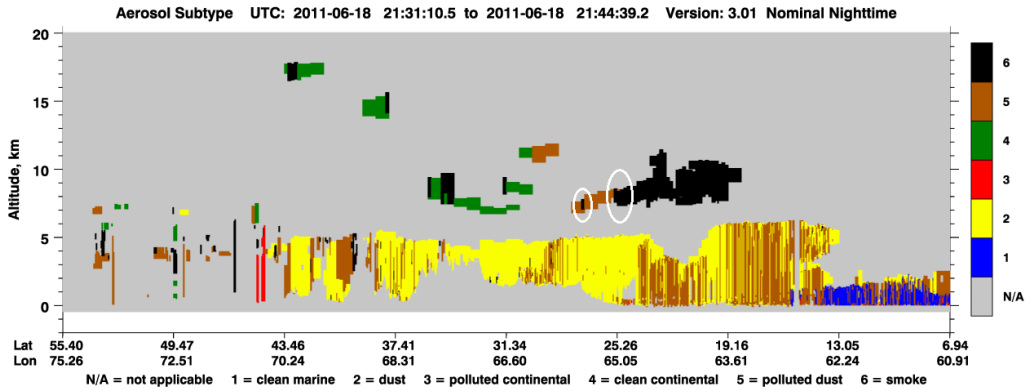

Figure 5. CALIPSO Vertical Feature Masks Image for 18 June, 2011. The white circle represents the location and altitude of Sulfur aerosols over Southern and Offshore Pakistan

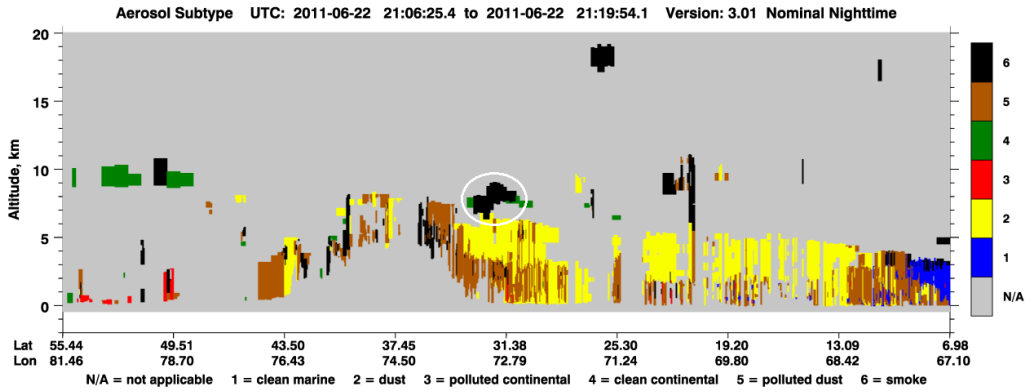

Figure 6. CALIPSO Vertical Feature Masks Image for 22 June, 2011. The white circle represents the location and altitude of Sulfur aerosols over Upper Central Pakistan

Thus results of this study based on satellite and numerical modeling suggest that eruption of Nabro's volcano significantly increased the concentration of atmospheric SO_2 in Pakistan during June, 2011.

4. Conclusions

Volcanoes are an important source of atmospheric trace gases including SO_2 that plays a significant role in global SO_2 cycle and radiative forcing. The Nabro volcanic eruption may have significant environmental consequences, atmospheric perturbations and affected the air quality of Pakistan. Data from GOME-2 and OMI has shown presence of significantly high levels of atmospheric SO_2 over Pakistan in days following the Nabro Volcano eruption. Back trajectories derived from HYSPLIT model showed good agreement with the location of SO_2 observed from GOME-2 in these days over Pakistan. Moreover, altitude of the incoming SO_2 trajectory was in agreement with the dust and smoke detected by the VFM from CALIPSO. This study shows that the sulfate aerosols injected in to stratosphere can travel longer distances. Greater residence time of such aerosols can affect the regional climate and environment which can lead to hazardous conditions for the health and aviation sectors.

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