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Remote Sensing and Modeling of forest fire in Dzukou Valley: A Satellite-WRF-Chem Approach

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Abstract

Investigation of the emission of pollutants emitted from forest fires is important for forecasting air quality as it can perturb the atmosphere significantly. An intense forest fire occurred over Dzukou Valley during 29th Dec, 2020 - 11th Jan, 2021. The smoke, fire detection and gaseous pollutant concentrations: NO_2, O_3, HCHO, SO_2, CH_4, and CO have been analyzed using satellite measurements. The fire count points were detected by MODIS, and VIIRS satellite sensors whereas the smoke was detected by Sentinel-2A (on 3rd Jan) and it was moving towards the East direction from the fire location. Sentinel-5P reveals CO, NO_2 concentration peaks on 5th Jan, 2021, whereas HCHO, CH_4, SO_2, peaked on 2nd Jan, 2021, and O_3 peaks on 2nd and 6th Jan, 2021. The Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem, V4.0) has well simulated the fire and shows good agreement with satellite observation with the best parametrization schemes. The model simulated concentration of the gaseous pollutant shows sporadic peaks during the intense fire period (2nd - 6th, Jan). The maximum surface level mixing ratios of the pollutants: PM_{10}, CO, NO_2, HCHO, SO_2 and O_3 is 242 $\mu g/m^3$, 2.04 ppmv, 0.03 ppmv 0.12 ppmv, 3.8×10^{-5} ppmv, 0.007 ppmv and 0.44 ppmv respectively. The vertical distribution of gaseous pollutants (CO, NO_2, O_3, SO_2) has been well simulated by the model. 40-50% reduction of these gaseous pollutants has been seen well below 500 m AGL except O_3.

1. Introduction

Forest fires are episodic ecosystem disturbances that play a vital role in shaping and regulating the overall terrestrial ecosystems [1, 2] and start from the ignition source and spread outwards, leaving behind only a burnt area. Emissions from forest fires are spatiotemporally episodic (unpredictable), in contrast to emissions from industry and transportation, and they emit large number of pollutants into the surrounding atmosphere, which may have significant effects on atmospheric chemistry/composition [3], human health [4] and the Earth's radiation budget [5] as well as degrades local, regional, and global air quality [6]. It can impact weather and climate directly through interaction with radiation [7], and indirectly by acting as Cloud Condensation Nuclei (CCN), changing cloud optical properties, lifetime, and capacity to initiate precipitation [8]. Forest fire is a globally significant source of carbonaceous aerosols like black carbon (BC), organic carbon (OC), and numerous trace substances committed with carbon dioxide (CO_2), including carbon monoxide (CO), methane (CH_4), oxides of nitrogen (NO_x = $NO+NO_2$), ammonia, volatile organic compounds (VOCs), oxygenated, nitrated, and halogenated compounds, carbonyl sulfide, sulfur dioxide, and sulfate-containing particles. In addition, forest fires can significantly influence the chemical weather by producing the secondary pollutant O_3, a greenhouse gas having potential climatic implications and an oxidizing agent [9, 10]. The production of O_3 from wildfire emissions remains mostly uncertain in assessing the tropospheric O_3 burden.

As winter approaches, several activities, including biomass burning (BB), industrial emissions, vehicle exhaust, and dust from Brahmaputra valley significantly foul the air in the northeastern part of India. Although there are many contributing sources of air pollution in the NEI, the pollution levels remain at critical levels to a considerable extent due to topographical and meteorological conditions [11, 12]. During the winter season, the calm winds prevail in North-East India (NEI), which is conducive for local confinement of the released atmospheric species, contributing to fog and haze formation. The present work aims to characterize a forest fire event taking place over Dzukou Valley during 29th Dec, 2020 - 11th Jan, 2021 and to investigate the emission of pollutants from this fire using satellite observation and WRF-Chem simulation.

2. Methodology

2.1. Study domain

The study location Dzukou Valley (25.56°N, 94.06°E) having an elevation of 2547–2635 m, is located between the states of Manipur and Nagaland, covering a total area of ~27 sq. km, surrounded by hilly terrain is mostly dominated by temperate to subalpine forest. It is one of the richest biodiversity hotspots in NEI. The pristine forests and the adjacent hills have been largely destroyed by frequent annual forest fires as a result of anthropogenic activities, posing a serious threat to biodiversity during the past few decades [13]. The valley is rich in native dwarf bamboo that grows abundantly and burns easily during the dry season is the primary reason of the forest fire. Moreover, the fire spreads rapidly due to the prevalent wind conditions and are difficult to put out because of

impassable terrain around the valley. The climatology of this region is well described elsewhere [14]. The WRF-Chem model domain is centered over the Dzukou valley illustrating the Leaf Area Index (Figure 1 a), and model detected fire (FIRE_AGEF) over Dzukou Valley is shown in dashed box (Figure 1 b).

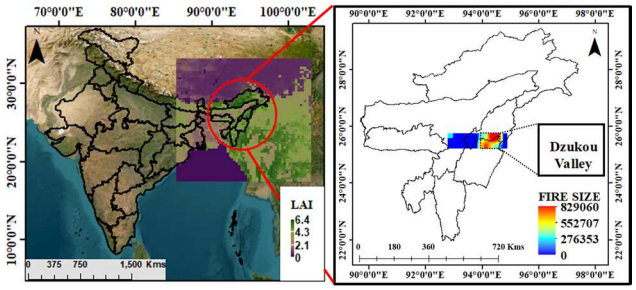

Figure 1. (a) Location of the domain used in WRF-Chem simulation showing Leaf Area Index, (b) Fire Size given by WRF-Chem output over Dzukou valley represented by dashed box.

2.2. Satellite measurements

Sentinel-2A is a high-resolution multi-spectral imaging satellite equipped with a multi-spectral imager for terrestrial monitoring and is used to detect fire smoke, Terra and Aqua MODIS, and SNPP-VIIRS instruments are used to detect active fire counts consisting of Fire Radiative Power (FRP) values with spatial resolution of 1 km and 375 m respectively. The variation of gaseous pollutants NO_2, O_3, HCHO, SO_2, CH_4, and CO over the Dzukou valley during the fire have been investigated from model simulation and are validated using satellite observation. Copernicus Sentinel-5P satellite gives the daily concentration of air pollutants: NO_2, O_3, HCHO, SO_2, CH_4, and CO [15]. Aqua AIRS and OMI gives the CH_4 and O_3 and SO_2 daily concentration.

2.3. WRF-Chem model simulation

In this study, we used an online mesoscale model Weather Research and Forecasting model coupled with chemistry (WRF-Chem version 4.0), capable of simulating meteorological and chemical processes simultaneously [16], to study the emission of gaseous pollutants over the Dzukou Valley during the fire event. The model domain is defined on a Mercator projection and is centered at 24.5°N, 94.0° E with 60 × 60 grid points in the East-West and North-South directions, respectively, at the horizontal resolution of 30 km × 30 km and with 32 vertical levels from surface up to 50 hPa. GFS-FNL data available at 1°×1° spatial and 6-hourly temporal resolutions were used for initializing the meteorology, boundary conditions, and nudging in the model. Details regarding the physical parameterization schemes are given elsewhere [17] whereas the chemical emissions inventories are provided in Table 1. We have performed two simulations with different emission scenarios, one with standard BB emissions (Mod-BB) and the other without BB emissions (Mod-NoBB). The model was run for a duration of 21 days from 20th Dec, 2020 to 11th Jan, 2021 out of which the first 5 days were discarded due to spin-up, and outputs from 25th Dec, 2020 to 11th Jan, 2021 were further analyzed

Table 1. Chemical Schemes

Chemistry scheme	MOZART
Aerosols scheme	MOSAIC
Fire emission	FINN 2.5
Biogenic emissions	MEGAN v2.04
Anthropogenic emissions	EDGAR
Initial & boundary conditions	WACCM

3. Results and Discussion

3.1 Satellite Observation

Sentinel 2A with a spatial resolution of 10 m, captured the smoke (Figure 1 a) during the fire event on 3rd Jan 2021. The fire counts (Figure 1 b) were detected by both MOIDS and SNPP sensors during the fire event period, where the noticeable peak of FRP during the period of 4th-6th Jan marked an intense fire period (Figure 1 c). The movement of the smoke is towards the East and some of it moved in the North direction. The smoke is not so prominent because the valley consists of vegetation of lower biomass.

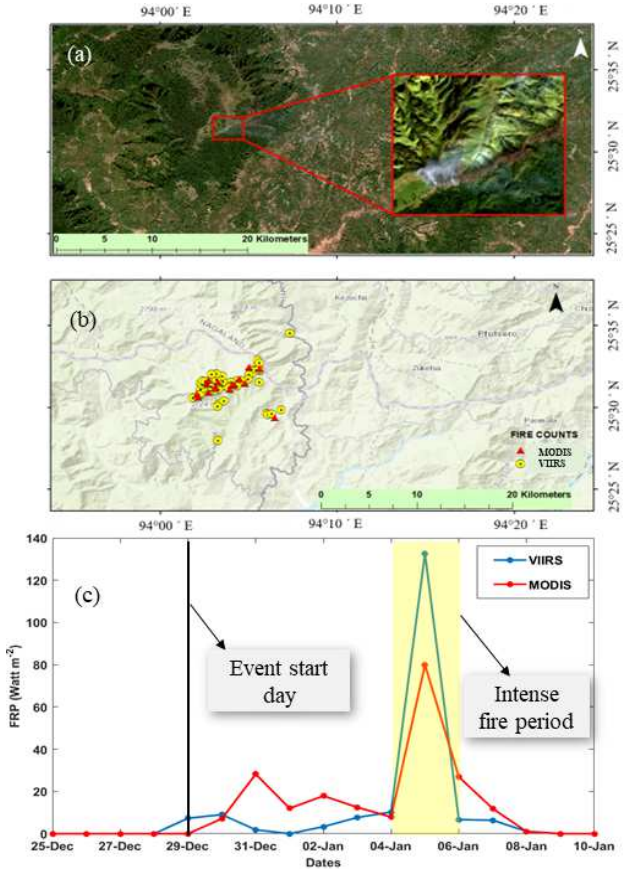

Figure 2. (a) Fire smoke (b) spatial FRP counts, and (c) temporal FRP counts detected by Sentinel-2A VIIRS, and MODIS sensors respectively.

3.2. Temporal variation of pollutants: satellite and model

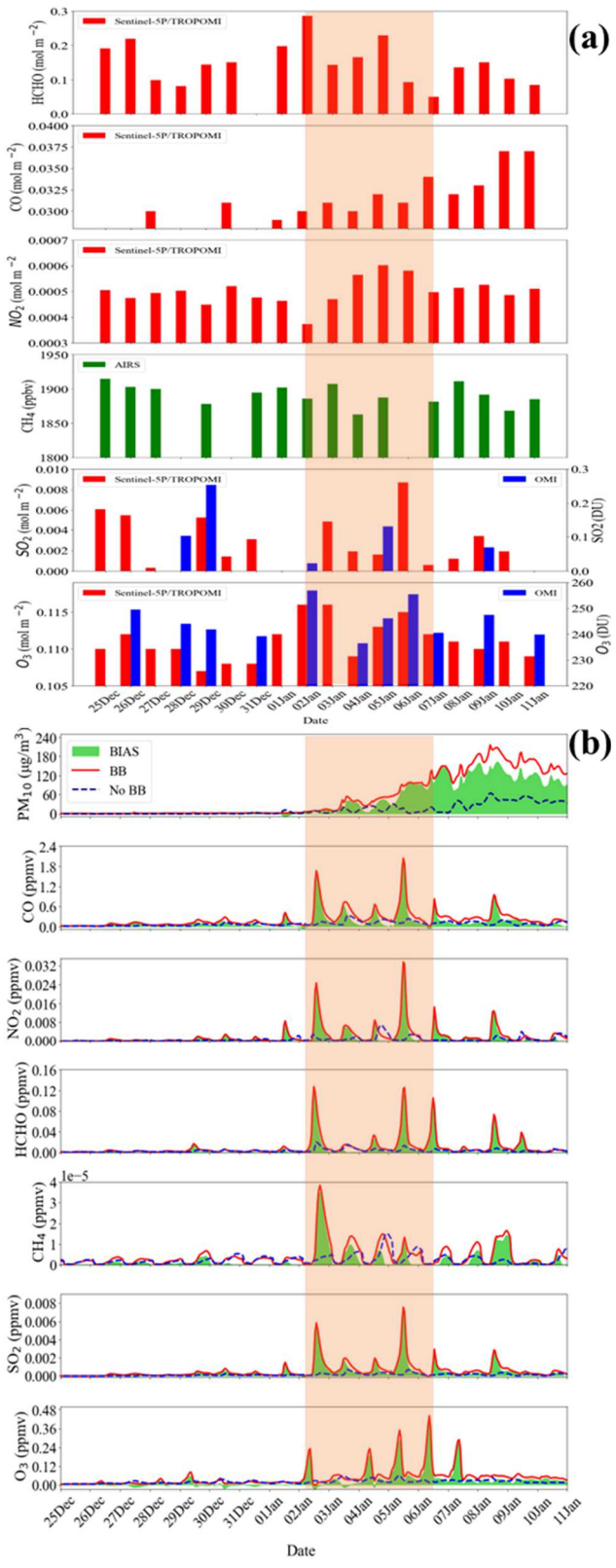

Figure 3. Temporal variation of gaseous pollutants over the Dzukou Valley obtained from (a) Sentinel 5P, OMI and AIRS satellite (b) WRF-CHEM model output showing variation with and without BB emission and its bias.

The concentration of HCHO, CO, NO_2, CH_4, SO_2, O_3 during the event period increased as observed from satellite retrieval (Figure 3a). CO, NO_2 concentration peaks 5th Jan, 2021, HCHO, CH_4, SO_2, peak on 2nd Jan, 2021, while O_3 peaks between 2nd-7th Jan, 2021. The high levels of pollutants concentration before fire event are due to winter time meteorology and other anthropogenic activities. The model output (Figure 3b) shows sporadic peaks in CO, NO_2, HCHO, CH_4, SO_2 and O_3 mixing ratios and consistent increase in PM_{10} during 1st-7th Jan, 2021. The peaks are more prominent on 2nd and 5th Jan, 2021. The model simulated maximum surface level mixing ratio of the pollutants goes up to 242μg/m^3 for PM_{10}, 2.04 ppmv for CO, 0.03 ppmv for NO_2, 0.12 ppmv for HCHO, 3.8×10^{-5} ppmv for CH_4, 0.007 ppmv for SO_2 and0.44 ppmv for O_3. The bias (BB - No BB) indicates the impact of BB on increasing pollution level, with maximum concentration of pollutants reaching up to 163.3μg/m^3 (PM_{10}), 1.9 ppmv (CO), 0.03 ppmv (NO_2), 0.12 ppmv (HCHO), 3.51×10^{-5} ppmv (CH_4), 0.007 ppmv (SO_2) and 0.42 ppmv (O_3).

3.3. Vertical distribution of spatial map during the intense fire period

The vertical distribution of gaseous pollutants (CO, NO_2, O_3, SO_2) has been well simulated by the model as evident from the Figure 4. 40-50% reduction of these gaseous pollutants has been seen well below 500 m AGL except O_3. The O_3 mixing ratio is prominent vertically up to >2km. Moreover, NO_2 and CO are the prime precursors of tropospheric ozone. Thus, the spatial variation of tropospheric ozone at different altitudes is well in line with NO_2 and CO variation.

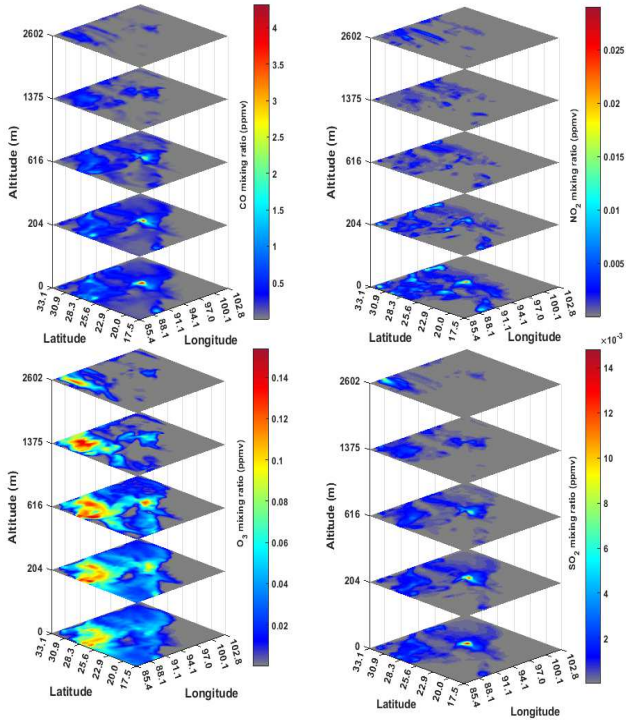

Figure 4. Vertical distribution of gaseous pollutants.

5. Conclusion

The episode of forest fire has been well simulated by the WRF-Chem model using the best parameterization schemes over Dzukou Valley from 29th Dec 2020 to 11th Jan 2021. The model has been well validated and quantified the variation of gaseous pollutants using remote sensing techniques. The spreading of smoke has been well captured by Sentinel-2A and the FRP values are significant during the extreme fire event period (4th-6th Jan 2021). The temporal variation of gaseous pollutants getting from the model output is in line with satellite observation. Thus, an extremely intense forest fire event can alter the vertical distribution of gaseous pollutants by going up to 2 km and alter the chemistry climate and partially up to hundreds of km making the region and its adjoining areas vulnerable to air quality.

6. Acknowledgements

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