Application of the WRF-CMAQ Model for Simulating Plume Rise During the 2019 Transboundary Haze in Peninsular Malaysia

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Abstract

Air quality across the Maritime Continent (MC) is substantially influenced by extensive biomass burning during the climatological burning season, which exerts significant transboundary impacts on Peninsular Malaysia (PMY). In 2019, the MC was subject to a weak El Niño event coupled with a strong positive phase of the Indian Ocean Dipole (pIOD), both of which enhanced the long-range transport of biomass burning emissions toward PMY. This study develops a plume rise modeling approach integrated within the WRF-CMAQ modeling framework to investigate the three-dimensional transport dynamics of biomass burning plumes during the 2019 transboundary haze episode. Three model configurations were evaluated: (1) WRF-$CMAQ_w$ (without grid nudging, using original FINN emissions), (2) WRF-$CMAQ_n$ (with grid nudging with original FINN emission), and (3) WRF-$CMAQ_a$ (with grid nudging and adjusted FINN). These configurations were used to simulate near-surface $PM_{2.5}$ and O_3 concentrations over PMY. Model results indicate that $PM_{2.5}$ was the dominant pollutant affecting air quality during the haze episode, with ozone playing a lesser role. Evaluations against surface meteorological observations revealed high model fidelity in reproducing key meteorological parameters, particularly temperature and wind profiles, with WRF-$CMAQ_a$ and WRF-$CMAQ_n$ achieving up to 95% correlation, while WRF-$CMAQ_w$ achieved up to 93%. For air quality simulations, WRF-$CMAQ_a$ is the best simulation, achieving 87.23% agreement with observed $PM_{2.5}$ concentrations, compared to 78.72% for WRF-$CMAQ_n$ and 62.41% for WRF-$CMAQ_w$. The enhanced transport was attributed to strong orographic lifting and convective activity over central Sumatra, leading to elevated plume injection heights and subsequent advection across the Malacca Strait. These findings highlight the importance of accurate fire emission representation and meteorological assimilation in modeling transboundary haze and the applicability of the WRF-CMAQ system for operational air quality forecasting and policy support in PMY.

Keywords: WRF-CMAQ, Nudging, FINN, Transboundary smoke event.