

MODELLING OF ORGANIC AEROSOLS OVER THE INDIAN REGION

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by

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Dedicated to my family and teachers

CERTIFICATE

This is to certify that the thesis entitled "**Modelling of Organic Aerosols over the Indian Region**" being submitted by **Mr. Pawan Vats** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of original bonafide research carried out by her. Mr. Pawan Vats has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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Pawan Vats

ABSTRACT

Organic aerosols (OA) constitute a significant fraction of total aerosols and especially are one of the major components of submicron-sized aerosols both over landmass and ocean. OA concentration is highly uncertain varying in between 20-90% of the total aerosol concentration depending upon the geographical locations. The OA is a crucial climate forcing agent due to their ability to interact with incoming shortwave radiation through absorption and scattering of radiation leading to direct radiative forcing and also they are capable of modifying the cloud properties such as cloud lifetime and cloud albedo thereby resulting in aerosol indirect radiative forcing of the climate. Robust investigation of life cycle of organic aerosols (OA) and associated compounds are needed to improve our scientific understanding regarding the implications of changing levels of atmospheric OA on air pollution, atmospheric chemistry and their impact on weather, climate, agriculture, and human health. Since the formation of secondary OA follows a highly complex mechanism, and is strongly dependent on of its precursors, and uncertainty associated with simulation of organic compounds could result in inaccurate estimation of their concentrations and distribution in the global atmosphere and hence incorrect estimation of their impacts on weather and climate using atmospheric chemistry-climate models. Therefore, continual evaluation of representation of organic aerosols concentrations simulated by state-of-the-art chemistry-climate models with observations across the globe is crucial for identifying the deficiencies in the representation of organic aerosols and their precursors to improve our understanding about the likely effects of these aerosols on weather and climate using these models as a tool. Present thesis uses different versions of sophisticated state of the art chemistry climate model named CESM in combination of different emission inventories for aerosols and their precursor gases for improving the simulation of organic aerosols and their precursors as well as estimating the radiative forcing caused by organic aerosols and their impact on the regional climate of south Asia.

Present thesis attempts to address some of the previously known uncertainties associated with simulation OA over the Indian region using a global chemistry climate model, find out the effect of improved emissions of precursors using a top-down approach in the estimation of OA over India, and also investigates the implications of changing emissions of OA and its precursor gases from Preindustrial (PI) to present day (PD) in terms of aerosol radiative forcing and impacts on the regional climate of India. The four primary objectives that are approached in

this thesis; a) attempting to improve the simulation of OA and its precursor gases by appropriately modifying the emissions of these precursor gases (VOCs and NO_x) used by the model using a top-down approach and updating the stoichiometric coefficients (SC) involved in the calculation of SOA by a global chemistry-climate model, b) investigating the impact of changing emissions of individual sources namely, anthropogenic, biomass burning, and biogenic sources of VOCs on the distribution and variability of the concentrations of VOCs and SOA over the Indian region, c) investigate the improvements in the simulation of SOA and precursor VOCs across the Indian region using two different versions of global chemistry-climate model namely, CESM1.2.2 and CESM2.0 and using emissions of OA its precursors from three different emission inventories namely, CMIP5, CMIP6, and SMOG-India, and d) assessment of the direct radiative forcing (DRF) and climate responses to change in the emission of OA and its precursor gases on the regional climate of south Asia.

A series of carefully designed simulations are performed by modifying SC values involved in the calculation of SOA, and using emission inventories developed for CMIP5 and CMIP6 activities as well as modified emissions of NO, and ArVOCs over India for understanding the consequences of these changes towards improvement in simulation SOA and its precursors over the Indian region. Our results show that changes in certain ArVOC emissions improved the simulated concentrations of these ArVOCs and the associated SOA significantly as compared to available observations from selected sites within India. We further find that the changes in VOC emissions from CMIP5 to CMIP6 has improved the simulation of VOCs and SOA formation, simulated by the chemistry-climate model. This happened due to improvements in the simulation of multi-oxidant products of ArVOCs such as toluene as well as oxidants such as OH and HO_2 radicals that further enhances the SOA production in the model.

A set of eight different systematically designed model sensitivity simulations are performed to understand the contribution of anthropogenic, biomass burning and biogenic (ANT, BB, and BNG respectively) VOC emission sources towards the concentration and distribution of VOCs and SOA over the Indian region. We show that lower emissions of isoprene (ISOP) over the Indian region in PD are caused by the combined effect of decreases in both downwelling solar flux (FSDS) and total leaf area index (TLAI) of plants, while changes in ANT and BB sources alone have insignificant contributions to the changes in ISOP emission with marginal increases emissions noted in PD.. Further, due to increases in emissions of aerosols and their precursors

from BB and ANT sources from PI to PD, their combined effect is to decrease in emissions of VOCs from BNG sources in PD as compared to PI. The changes in biogenic emissions from PI to PD have resulted in a significant decrease in the concentration of SOAI, however it has no impact over the changes in SOA (BTX). The surface concentrations of SOA (BTX) across the Indian region has significantly changed due to increases in emissions of VOCs and other precursor gases from ANT sources, followed by BB and BNG sources from PI to PD period. Present thesis discusses results from additional model sensitivity simulations performed using two different versions of CESM namely, CAM4-Chem and CAM6-Chem, using different emission inventories namely CMIP5, CMIP6, and a locally developed emission inventory called SMOG-India, to understand the impact of improved representation of SOA lifecycle in models and improved emissions used as input data in these models on the simulated concentrations of VOCs and associated SOA. Significant improvement in simulated concentrations of ArVOCs are noted using CAM6-Chem as compared to CAM4-Chem. Results of our model sensitivity simulations show that surface level ArVOCs across major metropolitan cities of India such as Delhi, Mumbai, etc. is are better simulated by the CAM6-Chem (SMoG-India) model due to better emissions of aerosols and their precursors considered in SMOG-India emission inventory. It is noted that generally simulated concentrations of the ArVOCs are found to be closest to observations within India using CAM6-Chem and SMOG-India emission data.

The direct radiative forcing (DRF) and climate responses to changes in emissions of VOCs and POM from PI to PD has been investigated in the present study using the CAM6-Chem model. Two separate sets of systemically designed model simulations has been successfully performed for calculation of DRF and climate responses using the standalone CAM6-Chem model and the CAM6-Chem model coupled with a SOM respectively. Our results show positive values of DRF at TOA due to POM over the snow covered Himalayan region and Tibetan plateau, while negative values of DRF are noted over rest of the south Asian region. This positive DRF and warming over the snow covered Himalayan region and Tibetan plateau is due to enhancement in absorption property of internally mixed aerosols considered in our model when they are present above reflecting surfaces like snow. Our results further show that the atmospheric DRF due to both POM and SOA is positive across the south Asian region thereby demonstrating an atmospheric heating caused by both POM and SOA over the Indian region. It is shown that DRF at surface and heating within the atmosphere due to POM is 3 to 6 times larger than due to SOA due to both differences in optical properties SOA and POM as well as differences in atmospheric burdens of both these types of OA over the study region. Over the Indian region

the contribution of POM to the DRF at TOA, and Surface has cooling effect with value -0.239 W/m^2 , -0.945 W/m^2 respectively, and warming in atmosphere with $+0.706 \text{ W/m}^2$. While DRF value for SOA at TOA, Surface, and Atmosphere are -0.184 W/m^2 , -0.335 W/m^2 , and $+0.097 \text{ W/m}^2$ respectively. Further, the atmospheric DRF having positive value for both POM and SOA that shows atmospheric heating caused by OA over the India region. Results of our simulations show significant cooling at the surface across India except over Central India and south east India due to changes in emissions of POM, while insignificant changes in surface temperature over the Indian region are noted due to changes in emissions of precursors of SOA from PI to PD. We find that increased emissions of POM and SOA precursors as well as increased cloud cover in PD as compared to PI further decrease the downwelling shortwave (SW) flux reaching to surface across the Indian region. This results in regional surface cooling by up to 1.8°C especially over the Himalayas and Tibetan Plateau. Increased emissions of emission of POM and VOC in PD as compared to PI have resulted in stronger cooling above 500 hPa up to the tropopause level over the south Asian region due to reduced convection in the lower troposphere and lesser heat getting transported to the upper troposphere region. Our results show that the diabatic heating rate changes induced by the increases in emissions of OA and its precursors causes changes in the atmospheric meridional circulation in such a way that it leads to slow down the summertime local Hadley circulation over $60\text{-}100^\circ\text{E}$. Finally, the results of our simulations show that increases in emissions of OA and its precursors in PD as compared to PI causes a significant reduction in mean summer monsoon precipitation over peninsular India, and eastern India and increases over north west India.

सारांश

कार्बनिक एरोसोल (ओए) कुल एरोसोल का एक महत्वपूर्ण अंश है और विशेष रूप से भूभाग और महासागर दोनों पर सबमाइक्रोन आकार के एरोसोल के प्रमुख घटकों में से एक है। भौगोलिक स्थानों के आधार पर कुल एरोसोल सांद्रता के 20-90% के बीच ओए सांद्रता अत्यधिक अनिश्चित होती है। ओए एक महत्वपूर्ण जलवायु बल एजेंट है जो विकिरण के अवशोषण और बिखरने के माध्यम से आने वाली शॉर्टवेव विकिरण के साथ बातचीत करने की उनकी क्षमता के कारण प्रत्यक्ष विकिरण बल के लिए अग्रणी है और साथ ही वे क्लाउड लाइफटाइम और क्लाउड अल्बेडो जैसे क्लाउड गुणों को संशोधित करने में सक्षम हैं, जिसके परिणामस्वरूप एरोसोल अप्रत्यक्ष रूप से होता है। जलवायु के विकिरणकारी बल। वायु प्रदूषण, वायुमंडलीय रसायन विज्ञान और मौसम, जलवायु, कृषि और मानव स्वास्थ्य पर उनके प्रभाव पर वायुमंडलीय ओए के बदलते स्तरों के प्रभावों के बारे में हमारी वैज्ञानिक समझ में सुधार के लिए कार्बनिक एरोसोल (ओए) और संबंधित यौगिकों के जीवन चक्र की मजबूत जांच की आवश्यकता है। चूंकि माध्यमिक ओए का गठन एक अत्यधिक जटिल तंत्र का अनुसरण करता है, और इसके अग्रदूतों पर दृढ़ता से निर्भर है, और कार्बनिक यौगिकों के अनुकरण से जुड़ी अनिश्चितता के परिणामस्वरूप वैश्विक वातावरण में उनकी सांद्रता और वितरण का गलत अनुमान हो सकता है और इसलिए उनके प्रभावों का गलत अनुमान लगाया जा सकता है। वायुमंडलीय रसायन विज्ञान-जलवायु मॉडल का उपयोग करते हुए मौसम और जलवायु पर। इसलिए, दुनिया भर में टिप्पणियों के साथ अत्याधुनिक रसायन विज्ञान-जलवायु मॉडल द्वारा सिमुलेटेड कार्बनिक एरोसोल सांद्रता के प्रतिनिधित्व का लगातार मूल्यांकन कार्बनिक एरोसोल और उनके अग्रदूतों के प्रतिनिधित्व में कमियों की पहचान करने के लिए हमारी समझ में सुधार करने के लिए महत्वपूर्ण है। एक उपकरण के रूप में इन मॉडलों का उपयोग करके मौसम और जलवायु पर इन एरोसोल के प्रभाव। वर्तमान थीसिस कार्बनिक एरोसोल और उनके अग्रदूतों के अनुकरण में सुधार के साथ-साथ कार्बनिक एरोसोल के कारण विकिरण बल का आकलन करने के लिए एरोसोल और उनके अग्रदूत गैसों के लिए विभिन्न उत्सर्जन सूची के संयोजन में सीईएसएम नामक अत्याधुनिक रसायन विज्ञान

जलवायु मॉडल के विभिन्न संस्करणों का उपयोग करता है। दक्षिण एशिया की क्षेत्रीय जलवायु पर उनका प्रभाव।

वर्तमान थीसिस एक वैश्विक रसायन विज्ञान जलवायु मॉडल का उपयोग करके भारतीय क्षेत्र में सिमुलेशन ओए से जुड़ी कुछ पूर्व ज्ञात अनिश्चितताओं को दूर करने का प्रयास करता है, भारत पर ओए के आकलन में टॉप-डाउन दृष्टिकोण का उपयोग करके अग्रदूतों के बेहतर उत्सर्जन के प्रभाव का पता लगाता है, और एयरोसोल रेडिएटिव फोर्सिंग और भारत के क्षेत्रीय जलवायु पर प्रभावों के संदर्भ में प्रीइंडस्ट्रियल (पीआई) से वर्तमान दिन (पीडी) में ओए और इसके अग्रदूत गैसों के उत्सर्जन में बदलाव के प्रभावों की भी जांच करता है। इस थीसिस में जिन चार प्राथमिक उद्देश्यों पर संपर्क किया गया है; क) टॉप-डाउन दृष्टिकोण का उपयोग करके मॉडल द्वारा उपयोग की जाने वाली इन अग्रदूत गैसों (वीओसी और एनओएक्स) के उत्सर्जन को उचित रूप से संशोधित करके ओए और इसके अग्रदूत गैसों के अनुकरण में सुधार करने का प्रयास करना और गणना में शामिल स्टोइकोमेट्रिक गुणांक (एससी) को अद्यतन करना एसओए एक वैश्विक रसायन-जलवायु मॉडल द्वारा, ख) भारतीय क्षेत्र में वीओसी और एसओए की सांद्रता के वितरण और परिवर्तनशीलता पर अलग-अलग स्रोतों जैसे मानवजनित, बायोमास बर्निंग और वीओसी के बायोजेनिक स्रोतों के बदलते उत्सर्जन के प्रभाव की जांच करना, ग) वैश्विक रसायन विज्ञान-जलवायु मॉडल के दो अलग-अलग संस्करणों, सीईएसएम 1.2.2 और सीईएसएम 2.0 का उपयोग करके भारतीय क्षेत्र में एसओए और अग्रदूत वीओसी के अनुकरण में सुधार की जांच करना और तीन अलग-अलग उत्सर्जन सूची, सीएमआईपी 5 से ओए के अग्रदूतों के उत्सर्जन का उपयोग करना , सीएमआईपी6, और एसएमओजी-इंडिया, और डी) प्रत्यक्ष विकिरण बल (डीआरएफ) और ओए और इसके अग्रदूत के उत्सर्जन में परिवर्तन के लिए जलवायु प्रतिक्रियाओं का आकलन जी दक्षिण एशिया की क्षेत्रीय जलवायु पर।

एसओए की गणना में शामिल एससी मानों को संशोधित करके और सीएमआईपी5 और सीएमआईपी6 गतिविधियों के साथ-साथ एनऊ के संशोधित उत्सर्जन और सुधार की दिशा में इन परिवर्तनों के परिणामों को समझने के लिए एआरवीओसी का उपयोग करके सावधानीपूर्वक डिज़ाइन किए गए सिमुलेशन की एक

शृंखला का प्रदर्शन किया जाता है। अनुकरण एसओए और भारतीय क्षेत्र में इसके पूर्ववर्तियों में। हमारे परिणाम बताते हैं कि कुछ एआरवीओसी उत्सर्जन में परिवर्तन ने इन एआरवीओसी और संबंधित एसओए की नकली सांद्रता में भारत के भीतर चयनित साइटों से उपलब्ध टिप्पणियों की तुलना में काफी सुधार किया है। हम आगे पाते हैं कि सीएमआईपी5 से सीएमआईपी6 में वीओसी उत्सर्जन में परिवर्तन ने रसायन-जलवायु मॉडल द्वारा सिमुलेटेड वीओसी और एसओए गठन के अनुकरण में सुधार किया है। यह टोल्यानि जैसे एआरवीओसी के बहु-ऑक्सीडेंट उत्पादों के साथ-साथ ओएच और एचओ 2 रेडिकल जैसे ऑक्सीडेंट के अनुकरण में सुधार के कारण हुआ जो मॉडल में एसओए उत्पादन को और बढ़ाता है।

भारतीय क्षेत्र में वीओसी और एसओए की एकाग्रता और वितरण की दिशा में मानवजनित, बायोमास बर्निंग और बायोजेनिक (क्रमशः एएनटी, बीबी, और बीएनजी) वीओसी उत्सर्जन स्रोतों के योगदान को समझने के लिए आठ अलग-अलग व्यवस्थित रूप से डिज़ाइन किए गए मॉडल संवेदनशीलता सिमुलेशन का एक सेट किया जाता है। हम दिखाते हैं कि पीडी में भारतीय क्षेत्र में आइसोप्रीन (आईएसओपी) का कम उत्सर्जन डाउनवेलिंग सोलर फ्लक्स (एफएसडीएस) और पौधों के टोटल लीफ एरिया इंडेक्स (टीएलएआई) दोनों में कमी के संयुक्त प्रभाव के कारण होता है, जबकि एएनटी और बीबी स्रोतों में परिवर्तन अकेले पीडी में नोट किए गए मामूली वृद्धि उत्सर्जन के साथ आईएसओपी उत्सर्जन में परिवर्तन में महत्वहीन योगदान है। पीआई की तुलना में पीडी में बीएनजी स्रोतों से वीओसी। पइ से पडी में बायोजेनिक उत्सर्जन में परिवर्तन के परिणामस्वरूप सओअइ की सांद्रता में उल्लेखनीय कमी आई है, हालाँकि एसओए (बी टी एक्स) में परिवर्तन पर इसका कोई प्रभाव नहीं है। भारतीय क्षेत्र में एसओए (बी टी एक्स) की सतह की सांद्रता में काफी बदलाव आया है, क्योंकि अनटी स्रोतों से वीओसी और अन्य पूर्ववर्ती गैसों के उत्सर्जन में वृद्धि हुई है, इसके बाद पइ से पडी अवधि तक बीबी और बी.न.ग स्रोत आते हैं। वर्तमान थीसिस सीईएसएम के दो अलग-अलग संस्करणों, सीएसएम 4-केम और सीएसएम6-केम का उपयोग करके किए गए अतिरिक्त मॉडल संवेदनशीलता सिमुलेशन के परिणामों पर चर्चा करती है, जिसमें विभिन्न उत्सर्जन सूची जैसे सीएमआईपी 5, सीएमआईपी 6, और प्रभाव को समझने के लिए एसएमओजी-इंडिया नामक स्थानीय रूप से विकसित उत्सर्जन सूची का उपयोग किया

जाता है। मॉडल में एसओए जीवनचक्र के बेहतर प्रतिनिधित्व और वीओसी और संबद्ध एसओए के सिमुलेटेड सांद्रता पर इन मॉडलों में इनपुट डेटा के रूप में उपयोग किए जाने वाले बेहतर उत्सर्जन। सीएएम4-केम की तुलना में सीएएम6-केम का उपयोग करके एआरवीओसी की नकली सांद्रता में महत्वपूर्ण सुधार नोट किया गया है। हमारे मॉडल संवेदनशीलता सिमुलेशन के परिणाम बताते हैं कि भारत के प्रमुख महानगरीय शहरों जैसे दिल्ली, मुंबई, आदि में सतह के स्तर के एआरवीओसी को सीएएम 6-केम (एसएमओजी-इंडिया) मॉडल द्वारा बेहतर तरीके से अनुकरण किया जाता है क्योंकि एरोसोल और उनके अग्रदूतों के बेहतर उत्सर्जन पर विचार किया जाता है। समओग-भारत उत्सर्जन सूची में। यह नोट किया गया है कि आम तौर पर एआरवीओसी की नकली सांद्रता सीएएम6-केम और एसएमओजी-इंडिया उत्सर्जन डेटा का उपयोग करके भारत के भीतर टिप्पणियों के सबसे करीब पाई जाती है।

वर्तमान अध्ययन में सीएएम6-केम मॉडल का उपयोग करते हुए प्रत्यक्ष विकिरण बल (डीरफ) और वीओसी और पीओएम के उत्सर्जन में पड़ से पडी में परिवर्तन के लिए जलवायु प्रतिक्रियाओं की जांच की गई है। व्यवस्थित रूप से डिज़ाइन किए गए मॉडल सिमुलेशन के दो अलग-अलग सेटों को क्रमशः स्टैंडअलोन सीएएम6-केम मॉडल और सीएएम6-केम मॉडल के साथ मिलकर डीरफ और जलवायु प्रतिक्रियाओं की गणना के लिए सफलतापूर्वक प्रदर्शन किया गया है। हमारे परिणाम बर्फ से ढके हिमालयी क्षेत्र और तिब्बती पठार पर पीओएम के कारण टीओए में डीआरएफ के सकारात्मक मूल्यों को दर्शाते हैं, जबकि डीआरएफ के नकारात्मक मूल्यों को दक्षिण एशियाई क्षेत्र के बाकी हिस्सों में नोट किया गया है। यह सकारात्मक डीआरएफ और बर्फ से ढके हिमालयी क्षेत्र और तिब्बती पठार पर वार्मिंग हमारे मॉडल में माने गए आंतरिक मिश्रित एरोसोल की अवशोषण संपत्ति में वृद्धि के कारण है, जब वे बर्फ जैसी परावर्तक सतहों के ऊपर मौजूद होते हैं। हमारे परिणाम आगे बताते हैं कि पीओएम और एसओए दोनों के कारण वायुमंडलीय डीआरएफ दक्षिण एशियाई क्षेत्र में सकारात्मक है, जिससे भारतीय क्षेत्र में पीओएम और एसओए दोनों के कारण वायुमंडलीय तापन का प्रदर्शन होता है। यह दिखाया गया है कि सतह पर डीआरएफ और पीओएम के कारण वातावरण के भीतर हीटिंग एसओए की तुलना में एसओए और पीओएम दोनों में अंतर के साथ-साथ इन दोनों प्रकार के

ओए के वायुमंडलीय बोझ में अंतर के कारण एसओए की तुलना में 3 से 6 गुना बड़ा है। अध्ययन क्षेत्र। भारतीय क्षेत्र में टीओए पर डीआरएफ में पीओएम का योगदान, और सतह का शीतलन प्रभाव क्रमशः -0.239 डब्ल्यू/एम-2, -0.945 डब्ल्यू/एम2 है, और +0.706 डब्ल्यू/एम2 के साथ वातावरण में वार्मिंग है। जबकि TOA, सरफेस और एटमॉस्फियर पर एसओए के लिए डीरफ मान क्रमशः -0.184 डब्ल्यू/एम-2, -0.335 डब्ल्यू/एम2 और +0.097 डब्ल्यू/एम2 है। इसके अलावा, वायुमंडलीय डीआरएफ का पीओएम और एसओए दोनों के लिए सकारात्मक मूल्य है जो भारत क्षेत्र में ओए के कारण वायुमंडलीय ताप को दर्शाता है। हमारे सिमुलेशन के परिणाम पीओएम के उत्सर्जन में बदलाव के कारण मध्य भारत और दक्षिण पूर्व भारत को छोड़कर पूरे भारत में सतह पर महत्वपूर्ण शीतलन दिखाते हैं, जबकि भारतीय क्षेत्र में सतह के तापमान में मामूली बदलाव एसओए के अग्रदूतों के उत्सर्जन में बदलाव के कारण नोट किए जाते हैं। पीआई से पीडी। हम पाते हैं कि पीओएम और एसओए अग्रदूतों के उत्सर्जन में वृद्धि के साथ-साथ पीआई की तुलना में पीडी में क्लाउड कवर में वृद्धि से भारतीय क्षेत्र में सतह पर पहुंचने वाले डाउनवेलिंग शॉर्टवेव (एसडब्ल्यू) प्रवाह में और कमी आई है। इसके परिणामस्वरूप विशेष रूप से हिमालय और तिब्बती पठार पर क्षेत्रीय सतह 1.8°डिग्री तक ठंडा हो जाती है। पीआई की तुलना में पीडी में पीओएम और वीओसी के उत्सर्जन में वृद्धि के परिणामस्वरूप निचले क्षोभमंडल में संवहन कम होने और ऊपरी क्षोभमंडल क्षेत्र में कम गर्मी के परिवहन के कारण दक्षिण एशियाई क्षेत्र में ट्रोपोपॉज़ स्तर तक 500 एचपीए से अधिक मजबूत शीतलन हुआ है। . हमारे परिणामों से पता चलता है कि ओए और इसके अग्रदूतों के उत्सर्जन में वृद्धि से प्रेरित मधुमेह ताप दर में परिवर्तन वायुमंडलीय मेरिडियन परिसंचरण में इस तरह से परिवर्तन का कारण बनता है कि यह 60-100° पूर्व से अधिक गर्मियों में स्थानीय हैडली परिसंचरण को धीमा कर देता है। अंत में, हमारे सिमुलेशन के परिणाम बताते हैं कि पीआई की तुलना में पीडी में ओए और इसके अग्रदूतों के उत्सर्जन में वृद्धि से प्रायद्वीपीय भारत और पूर्वी भारत में गर्मियों में मानसून की वर्षा में उल्लेखनीय कमी आती है और उत्तर पश्चिम भारत में वृद्धि होती है।

Contents

Certificate

Acknowledgements

Abstract	.....	i-ix
Contents	.....	x-xii
List of Figures	.....	xiii-xvii
List of Tables	xviii
List of acronyms	xix-xxi

Chapter 1 Introduction

1.1 Introduction	1
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Chapter 2: Simulation of aromatic volatile organic compounds (VOCs) and associated secondary organic aerosols (SOA) by CAM4-Chem model over the Indian region.

2.1 Introduction	.....	14
2.2 Model description	.....	16
2.3 Emission details	.....	18
2.4 Satellite data	.....	19
2.5 Ground measurements	.....	20
2.6 Experiment design and methodology	.....	20
2.7 Model evaluation	.....	25
2.7.1 Reference height temperature	.....	25
2.7.2 Wind speed and wind direction at 850 and 200 hPa	.....	25
2.7.3 Precipitation and Surface pressure	.....	26
2.7.4 NO ₂ column burden and surface concentrations of ArVOCs	.....	30
2.8 Discussion on the results of model sensitivity experiments	.....	31
2.8.1 Spatial distribution of VOCs	.....	32
2.8.2 Spatial distribution of ArSOA	.....	39
2.8.3 Monthly cycle of ArSOA	.....	40
2.8.3 SOAT production mechanism	.....	42
2.8.4 Observations and simulated results	.....	46
2.8.4.1 Surface measurements and results of models pertaining to aromatic VOC (ArVOC)	.....	46

2.8.4.2 Comparison of NO ₂ column burden of Satellite and Simulations	48
2.8.5 Vertical profile of SOAB	50
2.9 Summary and Conclusions	52

Chapter 3: Contribution of emissions from different types of sources (Anthropogenic, Biomass burning, and Biogenic) towards the production of secondary organic aerosols over the India

3.1 Introduction	54
3.2 Model Description	58
3.3 Emission details	58
3.4 Experiment design and methodology	59
3.5 Results and discussions	61
3.6 Summary and Conclusions	81

Chapter 4: Simulated AVOCs and associated SOAs with emissions from CMIP5, CMIP6, and locally Indian inventory

4.1 Introduction	84
4.2 Model description	87
4.3 Experiment design and methodology	89
4.3.1 Aerosols representation	90
4.3.2 SOA production scheme in models	91
4.3.2.1 Two-product scheme	91
4.3.2.2 Volatility basis set scheme	92
4.4 Results and discussions	93
4.4 Summary and Conclusions	103

Chapter 5: Direct radiative forcing and climate responses over the Indian region to changes in emissions of organic aerosols and their precursors from Pre-Industrial to Present-day

5.1 Introduction	106
5.2 Experiment design and methodology	108
5.3 Results and discussions	111
5.3.1 Radiative forcing	111
5.3.2 Climate response	115

5.3.2.1 Global mean responses	115
5.3.2.2 Aerosol optical depth	116
5.3.2.3 Surface Temperature	118
5.3.2.4 Atmospheric temperature	120
5.3.2.5 Atmospheric circulation.....	120
5.3.2.5 Cloud	121
5.3.2.6 Precipitation	123
5.4 Summary and conclusions	124

Chapter 6: Summary, Conclusions and future scope

6.1 Summary and Conclusions	128
6.1.1 Simulation of ArVOC and associated SOA by CAM4-Chem model.....	129
6.1.2 Contribution of emissions from individual sources to SOA production.....	130
6.1.3 Simulated ArVOCs and associated SOAs with emissions from CMIP5, CMIP6, and locally Indian inventory	131
6.1.4 DRF and climate responses with change in the emission of OA and its precursors from PI to PD	132
6.2 Future scope	133
Reference:.....	135

List of Figures

Figure No.	Title	Page No.
Figure 2. 1:	Scatterplot between annual mean concentration of NO and NO ₂ at all grid points across India as simulated by the model in CAM4C-CMIP6 experiment.	23
Figure 2. 2	Spatial distribution of seasonal mean reference height (2m above surface) temperature climatology (2008 to 2015) simulated by the CAM4-Chem and CRU data over the Indian sub-continent.	27
Figure 2. 3	Spatial distribution of seasonal (JJAS) mean wind vectors climatology (2008 to 2015) at 850 and 200 hPa from CAM4-Chem and ERA-Interim.	28
Figure 2. 4	Spatial distribution of seasonal (JJAS) mean (a) precipitation climatology (2008 to 2015) from CAM4-Chem and IMD data along with (b) surface pressure climatology (2008 to 2015) from CAM4-Chem and ERA-Interim data.	29
Figure 2. 5	Spatial distribution of annual mean NO ₂ column burden climatology (2008 to 2015) from satellite observations made using OMI and CAM4-Chem model over the Indian region.	29
Figure 2. 6	Comparison of annual cycle of monthly mean surface level mixing ratios of selected ArVOCs namely, benzene, toluene, and xylene simulated by the CAM4-Chem model and in-situ observations available from Mohali and Udaipur for the years 2012 to 2013, and 2015 respectively.	30
Figure 2. 7	Eight years annual mean surface concentration of Benzene (mol/mol) in various simulation, a) CAM4C-CMIP6, b) CAM4C-CMIP5, c) CAM4C-CMIP6-E, d) CAM4C-CMIP6-S e) CAM4C-CMIP6-N, and f) CAM4C-CMIP6-A with common colour bar. While change simulated concentration of benzene from all experiments with respect to CAM4C-CMIP6 (control) simulation are shown in sub-figures (g) to (k). which represents the difference between the control and sensitivity experiments where black dots represents the regions where the anomalies are at 95% confidence level or exceeds it (computed using the Student's t-test).	34
Figure 2. 8	Same as Figure 2.7, except for change in Toluene.	35
Figure 2. 9	Same as Figure 2.7, except for change in Xylene.	36
Figure 2. 10	Same as Figure 2.3, except for change in Isoprene.	37
Figure 2. 11	Same as Figure 2.3, except for change in Monoterpenes (C ₁₀ H ₁₆)	38
Figure 2. 12	Same as Figure 2.7, except for change in total aromatic SOA (sum of SOAB, SOAT, and SOAX) with unit (Kg/Kg).	41
Figure 2. 13	Monthly average surface concentration of ArSOA as predicted by various CAM4-Chem simulations for the period of 2008 to 2015 over India for (a) SOAT (b) SOAB (c) SOAX and (d) sum of ArSOA.	42
Figure 2. 14	continue ..	43
Figure 2. 15	Comparison between model simulated results and monthly measurements of aromatic VOCs at two different location (Mohali and Udaipur). Mohali	

observation data is available for a period of March 2012 to February 2013 whereas for Udaipur it is available for January to December 2015. For Udaipur, observation data for January, July and November is not available. 47

- Figure 2. 16 (a) Plot of spatial distribution annual average total column burden of NO₂ for 2008 to 2015 of OMI Satellite, (b), (c), (d), (e), (f) and (g) represent annual average NO₂ column burden (troposphere and stratosphere) for all the six simulations for the same period as satellite (unit of all the panel plots is given in molecules/cm⁻²). 49
- Figure 2. 17 Latitude–pressure structure of SOAB concentration (averaged for monsoon season JJAS for 2008 to 2015 eight-year average) averaged over 60–100°E has been compared among all the six simulations 51
- Figure 3. 1 Annual cycle of monthly mean values averaged across the Indian region corresponding to PI (1850) and PD (2010) periods for (a) emission rates of BTX from anthropogenic sources, (b) emission rates of BTX and Isoprene plus Monoterpene from biomass burning sources, (c) emission rates of Isoprene from biogenic sources, d) emission rates of Monoterpene from biogenic sources, and e) incident solar radiation. 63
- Figure 3. 2 Change in annual mean ISOP+MTERP emissions over the Indian region noted in various experiments w.r.t. PD (CTL) in (a) ANT emission from PI period, (b) BB emission from PI period, (c) BNG emission from PI period (d) both ANT and BB emission from PI period, (e) both ANT and BNG emission from PI period, (f) both BB and BNG emission from PI period, and in (g) all ANT, BB and BNG emission from PI period. , Here black dots in figures indicate the anomalies are at 95% confidence level or exceed it (calculated from the Student’s t-test). 64
- Figure 3. 3 Same as Figure 3.2, except for changes in the all sky downwelling shortwave flux (FSDS) at surface from simulations results. Here black dots in figures indicate the anomalies are at 95% confidence level or exceed it (calculated from the Student’s t-test). 65
- Figure 3. 4 Same as Figure 3.2, except for changes in the Total Leaf area Index (TLAI) calculated by CML4.5 from simulations results, here black dots in figures indicate the anomalies are at 95% confidence level or exceed it (calculated from the Student’s t-test). 65
- Figure 3. 5 Same as Figure 3.4, except for changes in the surface mass mixing ratio of (ISOP + MTERP) from simulations results, here black dots in figures indicate the anomalies are at 95% confidence level or exceed it (calculated from the Student’s t-test). 67
- Figure 3. 6: Same as Figure 3.5 except for BTX surface concentration in term of mmr. 68
- Figure 3. 7 Ozone production through free radical reaction in presence of sunlight and NO_x. 71
- Figure 3. 8 (a) Isoprene to SOAI formation mechanism via beta- IEPO_x. 72
- Figure 3. 9 The change in annual mean spatial distribution of ISOP (top row), ISOPO₂ (second row), NO (third row), OH radical (fourth row), HO₂ (fifth row), ISOPOOH (sixth row), NO₃ (seventh row), XO₂(eight row), XOOH(ninth

- row), H(tenth row), SOAI_PROD (second last row), and SOAI (last row) in simulations ANT_PI (first column), BB_PI (second column), BNG_PI (third column), ANT_BB_PI (fourth column), ANT_BNG_PI (fifth column), BB_BNG_PI (second last column), and All_PI (last column) w.r.t CTL for the period of 2008-2014 over the Indian region. 76
- Figure 3. 10 Same as figure 3.5 except the change in annual mean spatial distribution of surface concentration of SOA from (Isoprene + Mono-terpene). 77
- Figure 3. 11 The change in annual mean spatial distribution of xylene (top row), OH (second row), XYLO2 (third row), HO2 (fourth row), XYLOOH (fifth row), NO (sixth row), SOAX_PROD (seventh row), SAD_TROP (second last row), and SOAX (last row) in simulations ANT_PI (first column), BB_PI (second column), BNG_PI (third column), ANT_BB_PI (fourth column), ANT_BNG_PI (fifth column), BB_BNG_PI (second last column), and All_PI (last column) w.r.t CTL for the period of 2008-2014 over the Indian region. 79
- Figure 3. 12 Same as figure 3.6 except surface SOA concentration from BTX emission 81
- Figure 4. 1 The spatial distribution of the annual mean of benzene emission from three different emission inventories (CMIP5, CMIP6, SMOG-India) in the first row, while the second row represents their difference with respect to CMIP6 emission over the India region. 93
- Figure 4. 2 Seven-year annual mean spatial distribution of AOD from four different simulations as well as two different satellites (MODIS/Terra and MISER) over the Indian region. 94
- Figure 4. 3 The spatial distribution of annual mean surface concentration of benzene from a different set of simulations and their difference between the various experiments and control simulation over the Indian region from 2008 to 2015 Here, black dots in difference plots indicates that the dataset is statically significant at 95% confidence level. 96
- Figure 4. 4 Seven years mean annual cycle of benzene surface concentration from all four simulations in a) panel, while b) represent difference with respect to control simulation over the Indian region. 97
- Figure 4. 5 The monthly mean of benzene, toluene, and xylene from the in-situ observation, and simulations outcome for the Udaipur, and Mohali cities. 99
- Figure 4. 6 The spatial distribution of annual mean surface concentration of Isoprene from a different set of simulations and their difference between the various experiments and control simulation over the Indian region from 2008 to 2015 Here, black dots in difference plots indicates that the dataset is statically significant at 95% confidence level. 101
- Figure 4. 7 The spatial distribution of annual mean surface concentration of total SOA from a different set of simulations and their difference between the various experiments and control simulation over the Indian region from 2008 to 2015 Here, black dots in difference plots indicates that the dataset is statically significant at 95% confidence level. 102

- Figure 5. 1 Description of the method used to estimate direct Atmospheric Radiative Forcing (both old and new mechanisms) 111
- Figure 5. 2 Annual mean climatology (2008–2014) of direct radiative forcing ($W m^{-2}$) (a) at surface, (b) at TOA, and (c) within the atmosphere, whereas (d) at surface, (e) at TOA, and (f) within the atmosphere due to POM and SOA emissions respectively over the Indian region as estimated by the CAM6-Chem model by using SMOG-India emission inventory over India. 112
- Figure 5. 3 Annual mean DRF at TOA, Surface, and Atmosphere due to SOA and POM shown in Whisker boxes plot with black line show standard deviation in its DRF over the globe and also over the Indian region. 114
- Figure 5. 4 Scatter plot of monthly mean direct radiative forcing (W/m^2) at TOA, surface, and atmosphere with increase in column burden of SOA and POM (kg/m^2) at each grid point of model over India, where panel (a), (b), and (c) represent TOA, Surface, Atmosphere respectively due to SOA, while panel (d), (e), and (f) is same as (a), (b), and (c) except for POM from the all the sensitivity simulation for the period 2008–2014. 114
- Figure 5. 5 Annual mean time series of global mean surface temperature, where black, blue, red, and green colours represent control PI simulation, PD SOA, PD POM, and PD SOA POM respectively from CESM2-SOM experiments. 116
- Figure 5. 6 Annual mean change in the AOD at 550 nm relative to PI due to change in the emissions of (a) PD_POM, across the global, (b) PD_SOA, across the global, and (c) PD_SOA_POM across the global, while PD emission of SOA precursors for PD taken from India SMOG-India emission inventory. Where the different cluster of black dots in the panel figures indicate the regions where the anomalies are at 95% confidence level or above it (Same is calculated by Student's t-test). 116
- Figure 5. 7 same as figure 5.6 except for JJAS and over Indian region along with change in the anomalous wind vectors plotted at 850 hPa. 118
- Figure 5. 8 Same as figure 5.6 except for variable reference height temperature (K) and JJAS period. Anomalies in time mean vertically integrated total cloud relative to PI are also shown as green contour lines with positive and negative intervals of 1, 2, and 5%. Here green solid contour indicate regions with increase, while green dotted line indicate regions to the vertically integrated total cloud fraction. 119
- Figure 5. 9: Zonal mean (average calculated over the 60 to 100o E) response to atmospheric temperature (K) along with pressure (1000 to 5) hPa during monsoon season (JJAS) from various sensitivity simulations relative to the Expt – PI (Control) due to change in the emission of POM and SOA precursors over the Indian region, where panel (a) change in POM emission for PD, (b) change in SOA emission for PD, and change in both SOA and POM together. Enhancement in zonal mean heating rate (which is a linear summation of vertical diffusion, moist processes and radiative heating rates) w.r.t control simulation i.e PI are shown by solid black line contours, while the reduction in the heating rate are denoted by dotted solid

line contours. While black dotted regions in the figures demonstrate where the anomalies are at 95% confidence level or above it (Same is calculated by Student's t-test). 119

Figure 5. 10 Difference in the zonally averaged (same as shown in Figure 5.9, an average taken from 60 to 100 °E) meridional circulation shown by $(v, -\omega)$, where $-\omega$ is the vertical velocity in hPa/day and v is the meridional winds in m/s. Changes in vertical velocity under various POM and VOC emission simulations relative to the Expt - PI simulations are demonstrated by the shaded region on the backside of the Fig. 122

Figure 5. 11 Average change in Zonal mean cloud fraction (%) response due to change in VOC, POM emission from PI to PD period for monsoon season over 60–100°E, where the panel (a), (b), and (c) represent change in POM emission, SOA precursors emission, and both emission together respectively. Variation in the time mean grid box average of concentrations both cloud ice & cloud liquid number represent by Strawberry and Forest Green colour contour lines respectively, while solid(dotted) line shows increases (decreases) for both colours. 123

Figure 5. 12 Same as Figure 5.7, except for changes in the precipitation (mm/day) along with anomalous wind vectors at 850 hPa. 124

List of Tables

Table No.	Title	Page No.
Table-2.1	List of experiment names, arvoc emissions, no emissions, and choice of stoichiometric coefficients (sc) involved in the calculation of soa mass yield by the model	21
Table-2.2	Stoichiometric coefficients used in the present study in various experiments.	24
Table-2.3	Chemical reaction employing toluene and oxidants for production of multigeneration oxidized compounds of toluene which further converts into soat	45
Table-3.1	List of experiment names and choice of anthropogenic, biomass burning and biogenic emissions of vocs made in each of these experiments	61
Table-3.2:	Consists details of some relevant chemical reactions for soa production and its precursors used in the model, for more information (lamarque et al., 2012; tilmes et al., 2016).	69
Table-4.1	List of various numerical experiments with cesm1.2.2 and cem2.0.0 carried out in the present study.	90
Table-5.1	Complete description of various sensitivity simulations performed in this chapter for the estimation of atmospheric radiative forcing due to pom and soa.	110
Table-5.2	Complete description of various sensitivity simulations performed in this chapter for the calculation of climate change because of pom and soa.	110

List of acronyms

AGCM	Atmospheric Global Climate Models
AOD	Aerosol Optical Depth
ARF	Aerosol Radiative Forcing
ANT	Anthropogenic
AVOC	Anthropogenic Volatile Organic Compounds
ArVOC	Aromatic Volatile Organic Compound
ArSOA	Aromatic Secondary Organic Aerosols
AWB	Agricultural Waste Burning
BC	Black Carbon
BB	Biomass Burning
BAM	Bulk Aerosol Model
BNG	Biogenic
BVOC	Biogenic Volatile Organic Compounds
BTX	Benzene, Toluene, and Xylene
CAM4	Community Atmospheric Model version 4
CAM6	Community Atmospheric Model version 6
CAM4-Chem	Community Atmospheric Model Version 4 With Tropospheric and Stratospheric Chemistry
CCN	Cloud Condensation Nuclei
CEDS	Community Emissions Data System
CESM1.2.2	Community Earth System Model version 1.2.2
CESM2	Community Earth System Model version 2
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CLUBB	Cloud Layers Unified by Binormals
CLM	Community Land Model
CLM 4	Community Land Model Version 4
CLM 4.5	Community Land Model Version 4.5
CLM 5	Community Land Model Version 5
CRU	Climatic Research Unit
DOMINO	Dutch OMI NO ₂
DRF	Direct Radiative Forcing
FINN	Fire Inventory from NCAR
FireMIP	Fire Model Intercomparison Project
FSDS	Downwelling Solar Flux
GCM	Global Climate Model
GFED4	Global Fire Emissions Database Version 4
GHG	Green House Gases
GSM	Global Circulation Model

HO ₂	Hydroperoxyl Radical
ISR	Incident Solar Radiation
IEPOX	Isoprene Epoxy-diols
IGP	Indo Gangetic Plain
IPCC	Inter-Governmental Panel on the Climate Change
ISOP	Isoprene
ISOPNO ₃	Peroxy radical from isoprene NO ₃ oxidation
ISOPOOH	Isoprene Hydroxy-hydroperoxides
IVOC	Intermediate VOC
JJAS	June, July, August, September
LAI	Leaf Area Index
MAM	Modal Aerosol Module
MEK	Methyl Ethyl Ketone
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MEGAN	Model of Emissions of Gases and Aerosols from Nature
MISR	Multi-Angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOZART	Model for Ozone and Related Chemical Tracers
MTERP	Mono-Terpene
MVK	Methyl Vinyl Ketone
NCAR	National Centre for Atmospheric Research
NMVOC	Non-Methane VOC
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Nitrogen Oxides
OA	Organic Aerosols
OH	Hydroxyl radicals
OMI	Ozone Monitoring Instrument
OVOC	Oxidized VOC
PD	Present Day
PFT	Plant Function Type
PI	Pre-Industrial
POA	Primary Organic Aerosols
POM	Primary Organic Matter
RCP	Representative Concentration Pathway
RCP8.5	Representative Concentration Pathway Scenario 8.5
RETRO	Reanalysis of the Tropospheric Chemical Composition
SAD_TROP	Surface Area Density of Troposphere
SC	Stoichiometric Coefficients
SIVOC	Semi-Volatile Organic Compounds
SMoG-India	Speciated Multi Polluter Generator-India
SOA	Secondary Organic Aerosols
SOAG	Secondary Organic Aerosols Gases

SOAI	Secondary Organic Aerosols by Isoprene
SOAM	Secondary Organic Aerosols from Mono-terpene
SOAX	Secondary Organic Aerosols from Xylene
SOAB	Secondary Organic Aerosols from Benzene
SOAT	Secondary Organic Aerosols from Toluene
SOM	Slab Ocean Model
SSA	Single Scatting Albedo
SW	Shortwave
TLAI	Total Leaf Area Index
TOA	Top of Atmosphere
TOLOOH	Bicyclic Hydroperoxide from Toluene
	Bicyclic Peroxy Radical from Toluene
TOLO ₂	bicyclic Peroxy Radical from Toluene
UTLS	Upper Troposphere and Lower Stratosphere
VSL	Very Short-Lived
VOC	Volatile Organic Compounds
VBS	Volatility Basis Set
XO ₂	Peroxy Radical From ISOPOOH, IEPOX, HPALD
XOOH	Lumped Hydroperoxide from XO ₂ Chemistry
XYLOOH	Bicyclic Hydroperoxide from OH+XYLOL Chemistry
XYLO ₂	Bicyclic Peroxy Radical from OH+XYLOL Chemistry
soa1_a1	SOA Bin 1, MAM Accumulation Mode
soa1_a2	SOA Bin 1, MAM Aitken Mode
soa2_a1	SOA Bin 2, MAM Accumulation Mode
soa2_a2	SOA Bin 2, MAM Aitken Mode
soa3_a1	SOA Bin 3, MAM Accumulation Mode
soa3_a2	SOA Bin 3, MAM Aitken Mode
soa4_a1	SOA Bin 4, MAM Accumulation Mode
soa4_a2	SOA Bin 4, MAM Aitken Mode
soa5_a1	SOA Bin 5, MAM Accumulation Mode
soa5_a2	SOA Bin 5, MAM Aitken Mode