

CARBON DIOXIDE (CO₂) VARIABILITY AND ITS DRIVERS OVER SOUTH ASIA AND GLOBAL TROPICS

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by

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Dedicated to my parents
(Smt. Karabi Das and Late Shri Bishnupada Das)

Certificate

This is to certify that the thesis entitled “**Carbon dioxide (CO₂) variability and its drivers over South Asia and global tropics**” being submitted by **Mr. Chiranjit Das** for the award of the degree of **Doctor of Philosophy**, is a record of the original bonafide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis.

The results presented in this thesis have not been submitted in part or in full to any University or Institution for the award of any degree/diploma.



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Abstract

Atmospheric CO₂ is the most important greenhouse gas, causing global warming and climate change. The global land tropics are the most sensitive part of the global carbon cycle and are mainly responsible for global CO₂ variability. Lack of in-depth understanding of the underlying drivers limits understanding of the future changes in the tropical carbon cycle, its interaction with the climate system. This demands a thorough investigation for a better understanding of the underlying drivers explained by observational data products, chemical transport modelling, and statistical techniques. The objective of this thesis is to identify fundamental gaps in our knowledge of understanding CO₂ variability and its drivers in the global tropics and South Asia through the utilization of the state-of-the-art transport models and data products. Identifying the gap areas, the following three objectives have been formulated for this thesis, (a) Meridional propagation of CO₂ growth rate and flux anomalies from the tropics due to El Niño-Southern Oscillation (ENSO) (b) Characterizing regional hemispheric CO₂ variability in satellites and global chemistry-transport model using aircraft measurements (c) Regional fire dynamics and its contributions to carbon flux variability in South Asia.

The first chapter presents a comprehensive introduction to the global carbon cycle, followed by brief discussions on different observational platforms of measuring atmospheric CO₂ (in situ and remote sensing), global top-down inversion modelling, and how they contribute to the understanding of carbon concentration and flux variability, respectively. Next, it discusses different natural climatic oscillations controlling CO₂ variability in global tropics, followed by an in depth literature review that identifies existing research gaps in understanding the CO₂ variability and its drivers across South Asia and global tropics. It also presents the motivation behind each objective of the thesis, interconnection, and overall organisation of the thesis. The second chapter of the thesis describes modelling methodology, different statistical techniques

and datasets used to accomplish each objective of the thesis. It details the scientific steps of the Bayesian-based top-down inversion modelling, different sets of prior CO₂ fluxes from bottom-up models, and details about specific observations datasets (surface, aircraft, remote sensing datasets).

The third chapter describes inter-annual variability of land CO₂ flux, atmospheric CO₂ concentrations and their relationship with ENSO climatic modes across the latitude from tropics to the high latitudes of both hemispheres. We have utilised CO₂ observations from 43 surface sites from NOAA's obspack_co2_1_GLOBALVIEWplus_v6.1 product and WDCGG archive, as well as MIROC4-ACTM simulated fluxes for the period 2000 to 2019. The analysis shows that the southern hemisphere global land tropics are most sensitive to the changes of ENSO pattern. Results also revealed that an asymmetrical ENSO-CO₂ relationship exists between the northern and southern hemispheres, which originates in the southern hemisphere land tropics. It shows that the ENSO takes almost eight (four) months to impact the carbon cycle of high latitudes in the northern(southern) hemisphere from the tropics. This lag suggests a delayed teleconnection between ENSO and extratropical carbon flux responses. Among the key tracers activated during ENSO events, fire emissions and biospheric fluxes play a dominant role in driving these carbon cycle anomalies.

The fourth chapter is explored in two parts, Part-1: Investigates CO₂ variability using the latest satellite measurements (GOSAT, OCO-2), and Part-2: diagnoses errors in a single chemistry transport model (MIROC4-ACTM) through comparison with a multi-platform observations dataset (surface, aircraft, remote sensing). The results from Part-1 show OCO-2 is better at capturing regional scale variation of CO₂ as compared to the GOSAT. Part-2 describes the advantage of precise surface-based (GLOBALVIEWplus), and aircraft CO₂ measurements as “ground truth” over OCO-2 sampling location to assess MIROC4-ACTM transport model in

the altitude range of Earth's surface to upper troposphere. In this study, MIROC4-ACTM simulations, surface and aircraft observations (ATom, Amazon, and CONTRAIL projects) considered as ground truth, and Orbiting Carbon Observatory-2 (OCO-2) XCO₂ are used covering the period 2015-2021. Result shows MIROC4-ACTM simulation is able to capture the zonal mean CO₂ and XCO₂ concentration gradients within ± 1 ppm. MIROC4-ACTM and ATom profiles show mean differences of -0.1 ± 0.48 and 0.01 ± 0.3 ppm over land and ocean, respectively ($p < 0.05$), and those are -0.34 ± 1.07 and -0.2 ± 0.51 ppm for OCO-2 XCO₂ sampled at ATom profile locations. Altitude-wise analysis shows that CO₂ differences are concentrated in the lower troposphere (0-2 km), where model outputs are strongly influenced by surface fluxes. Over the Amazon, MIROC4-ACTM inversion does not have observations sites and limited vertical coverage of aircraft profiles ($\sim 0-4$ km), leading to poor ACTM and OCO-2 agreements. Over the airports in Asian megacities (i.e., emission hotspots), the model shows a higher difference with CONTRAIL (-1.06 ± 0.58 ppm) than OCO-2 (-0.15 ± 0.53 ppm). The larger ACTM-CONTRAIL difference reflects MIROC4-ACTM's coarse resolution (approx. $2.8^\circ \times 2.8^\circ$), which limits its ability to capture urban fossil fuel emissions, while the smaller ACTM-OCO-2 difference likely results from OCO-2's limited sensitivity below the boundary layer.

The fifth chapter describes fire emission during forest fire period and underlying dynamics through analysis of climatic drivers, anthropogenic activity and fire impacts on regional carbon budget in South Asia. Here, top-down inversion model NASA CMS-Flux output which assimilates the MOPITT satellite retrieved XCO to optimize biomass burning emission from GFED4.1s. Additionally, fire emission from two bottom-up models, global fire assimilation system or GFAS and Quick Fire Emissions Dataset or QFED to compare differences with top-down inversion. The fire dynamics and carbon flux variability over three fire prone key regions in South Asia, Region-1 (southwestern Nepal, Uttarakhand), Region-2 (Central India), and

Region-3 (Northeast India) for the period from 2010 to 2021 is analysed. The results show a high difference in fire emission between the CMS-Flux and bottom-up models in South Asia. Further, this chapter focused on the significant fire events that unfolded in February, March, and April (FMA) of 2021. We find high burned areas (5,000-10,000 km²), and fire carbon emissions (0.3-4 TgC season⁻¹) across these regions in FMA, 2021 as compared to a climatological mean from 2010-2020. Each of the three regions show distinct natural and anthropogenic drivers that preceded the fires. In Region-1, snow induced soil moisture deficits drive fire activity, leading to a subsequent decline in gross primary production (GPP). In Region-2, human activities, likely cropland burning, contributed to forest fire. In Region-3, the influence of climatic drivers is elusive, but the scattered distribution of burned areas suggests human activity is the likely cause of forest fire. During FMA 2021, fire emissions in Region-1 (~4 TgC) showed twice the fossil fuel emissions (~2.2 TgC), while in Region-2 (~3.8 TgC), it remained below fossil emissions (~16 TgC). In both regions, forests and croplands contributed equally to fire emissions. In Region-3, fire emissions exceeded fossil emissions in 2012 (~4.7 TgC), 2013 (~6.18 TgC), and 2014 (~9.75 TgC) but remained lower in 2021 (~3.37 TgC), with most emissions originating from forests. This analysis highlights the significant role of forest fire in the regional carbon budget and the need for careful forest carbon management practices to reduce their adverse impacts on the ecosystem. Finally, the sixth chapter summarizes the main findings of the present thesis. In addition, it provides limitations/challenges and future directions for the present research area.

सारांश

वायुमंडलीय कार्बन डाईऑक्साइड सबसे महत्वपूर्ण ग्रीनहाउस गैस है, जो वैश्विक जलवायु परिवर्तन का कारण बनती है। वैश्विक भूमि उष्णकटिबंधीय वैश्विक कार्बन चक्र का सबसे संवेदनशील हिस्सा है और वैश्विक कार्बन डाईऑक्साइड परिवर्तनशीलता के लिए मुख्य रूप से जिम्मेदार है। अंतर्निहित चालकों की गहन समझ का अभाव उष्णकटिबंधीय कार्बन चक्र में भविष्य के परिवर्तनों, जलवायु प्रणाली के साथ इसकी बातचीत की समझ को सीमित करता है। यह अवलोकन डेटा उत्पादों, संख्यात्मक मॉडलिंग और सांख्यिकीय तकनीकों द्वारा समर्थित अंतर्निहित चालकों की बेहतर समझ के लिए गहन जांच की मांग करता है। इस थीसिस का उद्देश्य वैश्विक उष्णकटिबंधीय और दक्षिण एशिया में कार्बन डाईऑक्साइड परिवर्तनशीलता और इसके चालकों को समझने के हमारे ज्ञान में मौलिक अंतराल की पहचान करना और इन अंतरालों को भरने के लिए अत्याधुनिक परिवहन मॉडल और डेटा उत्पादों का उपयोग करना है। अंतराल क्षेत्रों की पहचान करते हुए, इस थीसिस के लिए निम्नलिखित तीन उद्देश्य तैयार किए गए हैं, (ए) एल नीनो-दक्षिणी दोलन (ईएनएसओ) के कारण उष्णकटिबंधीय से सीओ कार्बन डाईऑक्साइड विकास दर और प्रवाह विसंगतियों का मेरिडियन प्रसार (बी) उपग्रहों में क्षेत्रीय-गोलार्ध कार्बन डाईऑक्साइड परिवर्तनशीलता और विमान माप का उपयोग करके वैश्विक रसायन विज्ञान-परिवहन मॉडल की विशेषता (सी) क्षेत्रीय अग्नि गतिशीलता और दक्षिण एशिया में कार्बन प्रवाह परिवर्तनशीलता में इसका योगदान।

पहला अध्याय वैश्विक कार्बन चक्र का एक व्यापक परिचय प्रस्तुत करता है, इसके बाद कार्बन डाईऑक्साइड मापन (इन सीटू और रिमोट सेंसिंग), वैश्विक टॉप-डाउन उलटा मॉडलिंग के विभिन्न प्लेटफार्मों पर संक्षिप्त चर्चा, और वे क्रमशः कार्बन एकाग्रता और प्रवाह परिवर्तनशीलता की समझ में कैसे योगदान करते हैं। इसके बाद, यह वैश्विक उष्णकटिबंधीय में कार्बन डाईऑक्साइड परिवर्तनशीलता को नियंत्रित करने वाले विभिन्न प्राकृतिक

जलवायु दोलनों पर चर्चा करता है थीसिस का उद्देश्य, अंतर्संबंध और थीसिस का समग्र संगठन। थीसिस का दूसरा अध्याय मॉडलिंग पद्धति, विभिन्न सांख्यिकीय तकनीकों और थीसिस के प्रत्येक उद्देश्य को पूरा करने के लिए उपयोग किए जाने वाले डेटासेट का वर्णन करता है। यह बायेसियन-आधारित टॉप-डाउन इनवर्जन मॉडलिंग के वैज्ञानिक चरणों, बॉटम-अप मॉडल से पिछले कार्बन डाईऑक्साइड फ्लक्स के विभिन्न सेट और विशिष्ट अवलोकन डेटासेट (सतह, विमान, रिमोट सेंसिंग डेटासेट) के बारे में विवरण देता है।

तीसरा अध्याय भूमि कार्बन डाईऑक्साइड प्रवाह, वायुमंडलीय कार्बन डाईऑक्साइड सांद्रता की अंतर-वार्षिक परिवर्तनशीलता और उष्णकटिबंधीय से लेकर दोनों गोलार्धों के उच्च अक्षांशों तक एल नीनो-दक्षिणी दोलन जलवायु मोड के साथ उनके संबंधों का वर्णन करता है। हमने राष्ट्रीय समुद्री और वायुमंडलीय संचालन के ऑब्जर्वेशनल पैकेज_कार्बनडाईऑक्साइड_ग्लोबलव्यूफ्लस_संस्करण 6.1 उत्पाद और ग्रीनहाउस गैसों के लिए विश्व डेटा सेंटर संग्रह से 83 सतही साइटों से कार्बन डाईऑक्साइड अवलोकन का उपयोग किया है, साथ ही 2000 से 2019 की अवधि के लिए मिरोक8 - एक्टम सिम्युलेटेड फ्लक्स का भी उपयोग किया है। विश्लेषण से पता चलता है दक्षिणी गोलार्ध का वैश्विक भू-क्षेत्र पैटर्न में होने वाले परिवर्तनों के प्रति सबसे अधिक संवेदनशील है। परिणामों से यह भी पता चला कि उत्तरी और दक्षिणी गोलार्ध के बीच एक विषम ईएनएसओ -कार्बन डाईऑक्साइड संबंध मौजूद है, जो दक्षिणी गोलार्ध के भू-क्षेत्रों में उत्पन्न होता है। यह दर्शाता है कि ईएनएसओ को उष्णकटिबंधीय क्षेत्रों से उत्तरी (दक्षिणी) गोलार्ध में उच्च अक्षांशों के कार्बन चक्र को प्रभावित करने में लगभग आठ (चार) महीने लगते हैं। यह अंतराल ईएनएसओ और अतिरिक्त उष्णकटिबंधीय कार्बन प्रवाह प्रतिक्रियाओं के बीच एक विलंबित टेलीकनेक्शन का सुझाव देता है। ईएनएसओ घटनाओं के दौरान सक्रिय होने वाले प्रमुख ट्रेसरों में से, अग्नि उत्सर्जन और जैवमंडलीय प्रवाह इन कार्बन चक्र विसंगतियों को चलाने में प्रमुख भूमिका निभाते हैं।

चौथा अध्याय दो भागों में खोजा गया है- भाग १: नवीनतम उपग्रह माप (गोसाट, ओको -२) का उपयोग करके कार्बन डाईऑक्साइड परिवर्तनशीलता की जांच करता है, और भाग २: एक बहु-प्लेटफ़ॉर्म अवलोकन डेटासेट (सतह, विमान, रिमोट सेंसिंग) के साथ तुलना के माध्यम से एकल रसायन परिवहन मॉडल (मिरोक४ - एक्टम) में त्रुटियों का निदान करता है। भाग-१ के परिणाम बताते हैं कि भाग २, गोसाट की तुलना में कार्बन डाईऑक्साइड के क्षेत्रीय पैमाने पर भिन्नता को पकड़ने में बेहतर है। भाग 2 पृथ्वी की सतह से ऊपरी क्षोभमंडल की ऊँचाई सीमा में मिरोक४-एक्टम परिवहन मॉडल का आकलन करने के लिए ओको -२ नमूना स्थान पर "ग्राउंड ट्रुथ" के रूप में सटीक सतह-आधारित (वैश्विकदृश्य प्लस) और विमान कार्बन डाईऑक्साइड माप के लाभ का वर्णन करता है। इस अध्ययन में, मिरोक४-एक्टम सिमुलेशन, सतह और विमान अवलोकन (एटीओएम, एमज़ॉन, और कंट्रोल प्रोजेक्ट) को जमीनी सच्चाई के रूप में माना जाता है, और ऑर्बिटिंग कार्बन ऑब्जर्वेटरी-2 (ओको -२) स्तंभ कार्बन डाईऑक्साइड का उपयोग २०१५-२०२१ की अवधि को कवर करने के लिए किया जाता है। परिणाम दिखाते हैं कि मिरोक४-एक्टम सिमुलेशन ± 1 पीपीएम के भीतर ज़ोनल मीन कार्बन डाईऑक्साइड और स्तंभ कार्बन डाईऑक्साइड सांद्रता ग्रेडिएंट को पकड़ने में सक्षम है। मिरोक४-एक्टम और एटीओएम प्रोफाइल क्रमशः भूमि और महासागर पर -0.1 ± 0.4 और 0.1 ± 0.3 पीपीएम के औसत अंतर दिखाते हैं (पी < 0.05), और ATom प्रोफाइल स्थानों पर ओको-२ स्तंभ कार्बन डाईऑक्साइड के लिए ये -0.38 ± 0.06 और -0.1 ± 0.49 पीपीएम हैं। ऊँचाई के अनुसार विश्लेषण से पता चलता है कि कार्बन डाईऑक्साइड अंतर निचले क्षोभमंडल (०-२ किमी) में केंद्रित है, जहां मॉडल आउटपुट सतह के प्रवाह से दृढ़ता से प्रभावित होते हैं। अमेज़न के ऊपर, मिरोक४ - एक्टम व्युत्क्रम में अवलोकन स्थल नहीं हैं और विमान प्रोफाइल ($\sim 0-5$ किमी) का सीमित ऊर्ध्वाधर कवरेज है, जिससे खराब एक्टम - ओको-२ समझौते होते हैं। एशियाई मेगासिटीज (यानी, उत्सर्जन हॉटस्पॉट) के हवाई अड्डों पर, मॉडल ओको -२ (-0.15 ± 0.43 पीपीएम) की तुलना में कंट्रोल (-1.06 ± 0.44 पीपीएम) के साथ

अधिक अंतर दिखाता है। बड़ा एक्टम- कंट्रोल अंतर मिरोक8 - एक्टम के मोटे रिजॉल्यूशन (लगभग २. ८°×२. ८°) को दर्शाता है, जो शहरी जीवाश्म ईंधन उत्सर्जन को पकड़ने की इसकी क्षमता को सीमित करता है, जबकि छोटा एक्टम - ओको -२ अंतर संभवतः सीमा परत के नीचे ओको -२ की सीमित संवेदनशीलता के कारण होता है।

पाँचवें अध्याय में दक्षिण एशिया में क्षेत्रीय कार्बन बजट पर जलवायु चालकों, मानवजनित गतिविधि और आग के प्रभावों के विश्लेषण के माध्यम से जंगल की आग की अवधि के दौरान अग्नि उत्सर्जन और अंतर्निहित गतिशीलता का वर्णन किया गया है। यहां, टॉप-डाउन इनवर्जन मॉडल नेशनल एयरोनॉटिक्स एंड स्पेस एडमिनिस्ट्रेशन सीएमएस -फ्लक्स आउटपुट जो मोपिट उपग्रह को आत्मसात करता है, ने जीएईडी४.१एस से बायोमास जलने के उत्सर्जन को अनुकूलित करने के लिए स्तंभ कार्बन मोनोआक्साइड को पुनः प्राप्त किया। इसके अतिरिक्त, दो बॉटम-अप मॉडल, ग्लोबल फायर एसिमिलेशन सिस्टम या जीएफएएस और क्विक फायर एमिशन डेटासेट या क्यूएफईडी से अग्नि उत्सर्जन, टॉप-डाउन इनवर्जन के साथ अंतर की तुलना करने के लिए। २०१० से २०२१ की अवधि के लिए दक्षिण एशिया के तीन अग्नि-प्रवण प्रमुख क्षेत्रों, क्षेत्र-१ (दक्षिण-पश्चिमी नेपाल, उत्तराखंड), क्षेत्र-२ (मध्य भारत), और क्षेत्र-३ इसके अलावा, इस अध्याय में २०२१ के फरवरी, मार्च और अप्रैल (एफएमए) में हुई महत्वपूर्ण आग की घटनाओं पर ध्यान केंद्रित किया गया है। हम २०१०-२०२० के जलवायु संबंधी औसत की तुलना में एफएमए, २०२१ में इन क्षेत्रों में उच्च जले हुए क्षेत्र (५,०००-१०,००० वर्ग किमी) और आग कार्बन उत्सर्जन (०.३-४ टीजीसी/सीजन) पाते हैं। तीनों क्षेत्रों में से प्रत्येक में अलग-अलग प्राकृतिक और मानवजनित चालक दिखाई देते हैं जो आग से पहले हुए थे। क्षेत्र-१ में, बर्फ से प्रेरित मिट्टी की नमी की कमी आग की गतिविधि को बढ़ाती है, जिससे सकल प्राथमिक उत्पादन (जीपीपी) में बाद में गिरावट आती है। क्षेत्र-२ में, मानवीय गतिविधियों, संभवतः फसल भूमि के जलने, ने जंगल की आग में योगदान दिया। क्षेत्र-३ में, जलवायु

चालकों का प्रभाव मायावी है, लेकिन जले हुए क्षेत्रों का बिखरा हुआ वितरण बताता है कि मानवीय गतिविधियाँ जंगल की आग का संभावित कारण हैं। एफएमए २०२१ के दौरान, क्षेत्र-१ (~४ टीजीसी) में आग उत्सर्जन जीवाश्म ईंधन उत्सर्जन (~२.२ टीजीसी) से दोगुना दिखाता है, जबकि क्षेत्र-२ (~३.८ टीजीसी) में, यह जीवाश्म उत्सर्जन (~१६ टीजीसी) से कम रहा। दोनों क्षेत्रों में, जंगलों और फसल भूमि ने आग उत्सर्जन में समान रूप से योगदान दिया। क्षेत्र-३ में, आग उत्सर्जन २०१२ (~४.७ टीजीसी), २०१३ (~६.१८ टीजीसी) और २०१४ (~९.७५ टीजीसी) में जीवाश्म उत्सर्जन से अधिक था, लेकिन २०२१ (~३.३७ टीजीसी) में कम रहा, जिसमें अधिकांश उत्सर्जन जंगलों से उत्पन्न हुआ। यह विश्लेषण क्षेत्रीय कार्बन बजट में जंगल की आग की महत्वपूर्ण भूमिका और पारिस्थितिकी तंत्र पर उनके प्रतिकूल प्रभावों को कम करने के लिए सावधानीपूर्वक वन कार्बन प्रबंधन प्रथाओं की आवश्यकता पर प्रकाश डालता है। अध्याय छह वर्तमान थीसिस के मुख्य निष्कर्षों का सारांश देता है। इसके अलावा, यह वर्तमान शोध क्षेत्र के लिए सीमाएँ और भविष्य की दिशाएँ प्रदान करता है।

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List of Abbreviations

Greenhouse Gases (**GHG**)

Carbon di-oxide Growth Rate (**CGR**)

Sea Surface Temperature (**SST**)

El Niño-Southern Oscillation (**ENSO**)

Multivariate ENSO Index (**MEI**)

World Data Centre for Greenhouse Gases (**WDCGG**)

Greenhouse gases Observing SATellite (**GOSAT**)

Orbiting Carbon Observatory 2 (**OCO-2**)

Total Carbon Column Observing Network (**TCCON**)

Comprehensive Observation Network for Trace gases by AIrLiner (**CONTRAIL**)

Atmospheric Tomography (**ATom**)

Model for Interdisciplinary Research on Climate version 4 Atmospheric Chemistry-Transport Model (**MIROC4-ACTM**)

Principal Component Analysis (**PCA**)

Gridded Fossil Emissions Dataset (**GridFED**)

Carnegie-Ames-Stanford Approach (**CASA**)

Vegetation Integrative Simulator for Trace Gases (**VISIT**)

Gross Primary Productivity (**GPP**)

Measurements of Pollution in the Troposphere (**MOPITT**)

Moderate Resolution Imaging Spectroradiometer (**MODIS**)

Global Fire Emissions Database (**GFED**)

Global Fire Assimilation System (**GFAS**)

Quick Fire Emissions Dataset (**QFED**)

Carbon Monitoring System-Flux (**CMS-Flux**)