

**AEROSOL INDIRECT RADIATIVE FORCING IN MARINE
WATER CLOUDS OVER THE OCEAN ADJACENT TO
INDIAN SUBCONTINENT**

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**Aerosol Indirect radiative forcing in marine water clouds over the ocean
adjacent to Indian subcontinent**

by

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Certificate

This is to certify that the thesis entitled “**Aerosol Indirect radiative forcing in marine water clouds over the Ocean adjacent to Indian subcontinent**” being submitted by Ms. **Sofiya Rao** for the award of the degree of **Doctor of Philosophy**, is a record of the original bonafide research work carried out by her. She 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 full to any University or Institution for award of any degree/diploma.

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Abstract

Aerosol-cloud interaction continues to be one of the most uncertain components of climate change. This uncertainty is even more prominent at the regional level because of the heterogeneity in aerosol and cloud properties (IPCC, 2013), especially over the Indian monsoon region due to heterogeneity in aerosol and cloud properties. Ever since the role of aerosols in altering the cloud characteristics was demonstrated during the Indian Ocean Experiment, efforts have increased exponentially to advance understanding aerosol-cloud-precipitation interaction using in-situ observations in stationery and campaign mode, satellite data, and models.

Despite decades of research, climate models still struggle in representing aerosol and cloud characteristics over the South Asian monsoon region. Subsequent observations from the surface, aircraft, and ship campaigns (e.g., BoBMEX, ARMEX, ICARB, ISRO-GBP, CAIPEEX, and CTCZ) provided critical inputs to the modelling community and even to the satellite community to improve the model outputs and satellite products. Better observations led to the robust estimates of aerosol direct radiative forcing at a local and regional scale. However, key gaps exist, particularly in (1) year-round evidence of aerosol-cloud interaction and (2) observationally-constrained estimates of aerosol indirect radiative forcing in the South Asian monsoon region.

This thesis aims to fill these two critical gaps by analyzing fifteen years (Mar 2000-Feb 2015) of daily satellite data over the oceans adjacent to the Indian subcontinent. The focus of the thesis is on marine low water clouds, as different cloud types have contrasting dynamics that might have impacted the interpretation. The results are presented for the three oceanic regions - the Arabian Sea (AS), Bay of Bengal (BoB), and South Indian Ocean (SIO). First, a monthly climatology of cloud and aerosol parameters from various satellite products has been developed to understand the seasonality. Since the satellite products do not provide

characteristics of natural and anthropogenic aerosols separately, a hybrid approach is proposed to first quantify the relative contributions of anthropogenic, dust, and maritime aerosols on total aerosol loading and use the data to understand the sensitivity of cloud characteristics to individual aerosol types. Anthropogenic aerosols contribute 31%, 29%, and 28%, and dust particles contribute 39%, 40%, and 24% to total aerosol optical depth over the AS, BoB, and SIO, with the remaining contributions from maritime aerosols.

Further, the dependency of cloud top pressure on cloud fraction in clean and polluted conditions is analyzed, which provided evidence of lifetime effect. Cloud cover has been found to increase with a decrease in cloud top pressure by a larger margin in the clean conditions than in the polluted condition for anthropogenic aerosols. The relationship is insensitive to marine aerosols. Evidence of semi-direct effect has been identified in three seasons except for the post-monsoon (Oct-Nov) season. In both AS and BOB, the aerosol-cloud interaction is strongly modulated by meteorology compared to the SIO, with a larger impact during the monsoon (Jun-Sep).

Previous studies in the Indian ocean provided evidence of aerosol impacts on cloud properties during the winter (Dec-Feb). This study confirms the presence of aerosol-cloud interaction throughout the year. The effective radius of clouds (R_{eff}) has been found to increase with an increase in Liquid Water Path (LWP) in clean and polluted conditions suggesting the meteorological impact on the cloud dynamics. However, the segregation of the data into various aerosol bins has allowed isolating the aerosol signal. One critical result is that the aerosol-cloud interaction is the most prominent in the middle range of the liquid water path of 150–350 gm/m² in these regions. This study suggested that better and explicit representations of aerosol-cloud interaction in the regional and climate model are required to reduce uncertainty since such interaction is sensitive to the LWP and meteorology.

Next, a theoretical framework has been proposed to analytically estimate aerosol indirect radiative forcing. This framework relies on observationally-constrained estimates of the aerosol-induced changes in cloud albedo (albedo or first indirect effect) and cloud fraction (lifetime or second indirect effect). Cloud albedo (R_c) increases with an increase in LWP (macrophysical pathway) and a decrease in R_{eff} (microphysical pathway) due to aerosols. The analysis has been carried out for total aerosols (aerosol optical depth, τ_a) and anthropogenic aerosols (anthropogenic aerosol optical depth, τ_{an}). Look-up tables are generated to quantify the changes in cloud albedo per unit change in aerosol optical depth ($dR_c/d\tau_a$) for narrow bins of LWP and R_{eff} by analyzing the MODIS cloud and aerosol products. In the theoretical construct, the macrophysical and microphysical pathways are separated. R_c response to an increase in τ_a is found to be the most sensitive in the range of LWP between 150-300 gm/m^2 for a range of R_{eff} varying from 8-24 μm .

Using this framework, aerosol first and second indirect radiative forcing is calculated for the three oceanic regions. The mean ($\pm 1\sigma$) annual total aerosol indirect radiative forcing over the AS, BoB, and SIO are estimated as -6.7 ± 2.7 W/m^2 , -4.3 ± 1.1 W/m^2 , -3.6 ± 1.4 W/m^2 , respectively. The first aerosol indirect radiative forcing due to the microphysical pathway are estimated to be -3.4 ± 1.7 W/m^2 , -4.15 ± 2.04 W/m^2 , -4.72 ± 1.5 W/m^2 over the AS, BoB and SIO, respectively. In contrast, mean ($\pm 1\sigma$) annual aerosol indirect radiative forcing due to anthropogenic aerosols over the AS, BoB, and SIO are estimated as -5.96 ± 2.4 W/m^2 , -4.12 ± 1.7 W/m^2 , $-8.38 \pm .4$ W/m^2 , respectively, out of which the contributions due to the microphysical pathways are -5.9 ± 3.4 W/m^2 , -4.12 ± 2.1 W/m^2 , -8.6 ± 5.04 W/m^2 respectively.

The mean ($\pm 1\sigma$) annual aerosol indirect effect due to the lifetime effect over the AS, BoB, and SIO are estimated as -3.1 ± 1.4 W/m^2 , -2.5 ± 0.92 W/m^2 , and -0.75 ± 0.14 W/m^2 for total

aerosols, respectively. In contrast, the annual aerosol indirect radiative forcing due to the lifetime effect over the AS, BoB, and SIO are estimated as $-3.7 \pm 1.63 \text{ W/m}^2$, $-4.2 \pm 3.4 \text{ W/m}^2$, and $-0.5 \pm 0.09 \text{ W/m}^2$ for the anthropogenic aerosols.

The results, particularly, the separation of the microphysical and macrophysical pathways in the albedo effect and the comparative assessment relative to the lifetime effect would be critical to modelers who can assess the model performance at a disaggregated level in the aerosol-cloud interaction module. The approach can be applied to estimate aerosol indirect radiative forcing over land and also for other types of clouds in future, and is universally applicable.

सारांश

एरोसोल-क्लाउड इंटरैक्शन जलवायु परिवर्तन के सबसे अनिश्चित घटकों में से एक है। एरोसोल और क्लाउड प्रॉपर्टीज में विविधता के कारण क्षेत्रीय स्तर पर यह अनिश्चितता और भी अधिक प्रमुख है (IPCC, 2013), एरोसोल और क्लाउड प्रॉपर्टीज में विविधता के कारण विशेष रूप से भारतीय मानसून क्षेत्र में यह अधिक है। हिंद महासागर प्रयोग (INDOEX) के दौरान से क्लाउड विशेषताओं को बदलने में एरोसोल की भूमिका का प्रदर्शन किया गया है, और तभी से स्टेशनरी और अभियान मोड, सैटेलाइट डेटा और मॉडल में इन-सीटू अवलोकनों का उपयोग करके, एरोसोल-क्लाउड-प्रेसिपिटेशन कि बातचीत को समझने के प्रयासों में तेजी से वृद्धि भी हुई है।

दशकों के शोध के बावजूद, अभी भी दक्षिण एशियाई मानसून क्षेत्र में एरोसोल और क्लाउड विशेषताओं का प्रतिनिधित्व करने में क्लाउड मॉडल संघर्ष कर रहे हैं। सतह, विमान और जहाज अभियानों (जैसे, BoBMEX, ARMEX, ICARB, ISRO-GBP, CAIPEEX, और CTCZ) के लगातार अवलोकनों ने मॉडलिंग समुदाय और यहां तक कि उपग्रह समुदाय को मॉडल आउटपुट और सैटेलाइट उत्पादों में सुधार करने के लिए महत्वपूर्ण इनपुट प्रदान किए। बेहतर अवलोकनों ने स्थानीय और क्षेत्रीय स्तर पर एरोसोल प्रत्यक्ष विकिरण बल के मजबूत अनुमानों को जन्म दिया। हालांकि, कुछ मुख्य अंतराल मौजूद हैं इस फील्ड में, विशेष रूप से (1) एरोसोल-क्लाउड इंटरैक्शन के साल भर के साक्ष्य; और (2) दक्षिण एशियाई मानसून क्षेत्र में एरोसोल अप्रत्यक्ष विकिरण बल के अवलोकन-विवश अनुमान।

इस शोध का उद्देश्य इन दो महत्वपूर्ण अंतरालों को भरना है, जिसमें पंद्रह वर्षों (मार्च 2000-फरवरी 2015) का दैनिक सैटेलाइट डेटा का विश्लेषण भारतीय उपमहाद्वीप से सटे महासागरों पर किया गया है। इस शोध का ध्यान सिर्फ नीचले समुद्री पानी वाले बादलों पर है, क्योंकि विभिन्न प्रकार के बादलों में अलग-अलग गतिशीलता होती है, जो व्याख्या को प्रभावित कर सकती है। इस शोध के परिणाम तीन महासागरीय क्षेत्रों - अरब सागर

(AS), बंगाल की खाड़ी (BoB), और दक्षिण हिंद महासागर (SIO) के लिए प्रस्तुत किए गए हैं। सबसे पहले, विभिन्न सैटेलाइट उत्पादों से क्लाउड और एरोसोल मापदंडों का मासिक मौसम विज्ञान विकसित किया गया है। चूंकि सैटेलाइट उत्पाद प्राकृतिक और मानवजनित एरोसोल की विशेषताओं को अलग-अलग प्रदान नहीं करते हैं, इसलिए एक हाइब्रिड एप्रोच का इस्तेमाल किया गया है, जिसमें पहले मानवजनित, धूल, और समुद्री एरोसोल को टोटल एरोसोल के अनुसार विभाजित किया गया है और इन सभी एरोसोल प्रकारों का क्लाउड विशेषताओं की संवेदनशीलता को समझा गया है। टोटल एरोसोल लोडिंग में, एंथ्रोपोजेनिक एरोसोल का योगदान 31%, 29% और 28% है, धूल का योगदान 39%, 40% और 24% AS, BoB और SIO पर है, और शेष योगदान समुद्री एरोसोल का है।

इसके अलावा, आगे इस शोध में CTP की निर्भरता f_c पर स्वच्छ और प्रदूषित क्लाउड परिस्थितियों में देखी गयी है और विस्तार से उल्लेख किया गया है, जो की लाइफ टाइम इफ़ेक्ट का प्रमाण प्रदान करता है। अगर मानवजनित एरोसोल की बात किजाये तो प्रदूषित स्थिति की तुलना में स्वच्छ परिस्थितियों में एक बड़े अंतर से CTP में कमी के साथ क्लाउड कवर (f_c) में वृद्धि देखी गई है। जबकि यही रिश्ता समुद्री एरोसोल के प्रति असंवेदनशील है। पोस्ट-मानसून (अक्टूबर-नवंबर) मौसम को छोड़कर तीनो मौसमों में सेमी-डायरेक्ट इफ़ेक्ट के साक्ष्य की पहचान की गई है। AS और BoB दोनों में, एरोसोल-क्लाउड इंटरैक्शन को मौसम विज्ञान द्वारा दृढ़ता से संशोधित किया गया है SIO की तुलना में, जिसमें मानसून (जून-सितंबर) के दौरान एक बड़ा प्रभाव होता है।

हिंद महासागर में पिछले अध्ययनों ने सर्दियों (दिसंबर-फरवरी) के दौरान बादलों के गुणों पर एरोसोल प्रभावों के प्रमाण प्रदान किए। यह अध्ययन पूरे वर्ष एरोसोल-क्लाउड इंटरैक्शन की उपस्थिति की पुष्टि करता है। स्वच्छ और प्रदूषित परिस्थितियों में तरल जल पथ (LWP) में वृद्धि के साथ बादलों की प्रभावी त्रिज्या (R_{eff}) में वृद्धि पाई गई है, जो बादल की गतिशीलता पर मौसम संबंधी प्रभाव का सुझाव देती है। हालांकि, विभिन्न एरोसोल

बिन्स में डेटा के पृथक्करण ने एरोसोल सिग्नल को अलग करने की अनुमति दी गयी है। इस शोध का एक महत्वपूर्ण परिणाम यह है कि एरोसोल-क्लाउड इंटरैक्शन सबसे प्रमुख इन LWP ($150-350 \text{ gm/m}^2$) क्षेत्रों में साफ़ तौर पर दिखाई दिया है।

इसके बाद, एरोसोल इंडिरेक्ट रेडिएटिवे फोर्सिंग का विश्लेषणात्मक रूप से अनुमान लगाने के लिए एक सैद्धांतिक ढांचा प्रस्तावित किया गया है। यह ढांचा, अवलोकन-विवश अनुमानों पर निर्भर करता है, जिसमें की एरोसोल-प्रेरित परिवर्तनों से क्लाउड अल्बेडो (अल्बेडो / पहला इंडिरेक्ट इफ़ेक्ट) और क्लाउड फ़ैक्शन (लाइफटाइम या दूसरा इंडिरेक्ट इफ़ेक्ट)। एरोसोल के कारण क्लाउड अल्बेडो (R_c) बढ़ता है LWP (मैक्रोफिजिकल पाथवे) में वृद्धि के साथ और R_{eff} (माइक्रोफिजिकल पाथवे) में कमी के साथ। यह विश्लेषण टोटल एरोसोल ऑप्टिकल डेप्थ (τ_a) और मानवजनित एरोसोल ऑप्टिकल डेप्थ (τ_{an}) के लिए किया गया है। प्रति यूनिट परिवर्तन R_c का प्रति यूनिट परिवर्तन τ_a ($dR_c/d\tau_a$) के साथ सभी रिलेशन्स के लिए लुक-अप टेबल्स तैयार किया गया है, जिसमें MODIS क्लाउड और एरोसोल उत्पादों का विश्लेषण करके LWP और R_{eff} के संकीर्ण बिन बनाये गए हैं। सैद्धांतिक निर्माण में, मैक्रोफिजिकल और माइक्रोफिजिकल रास्ते अलग-अलग हो जाते हैं। R_c की प्रतिक्रिया τ_a की वृद्धि में सबसे संवेदनशील LWP की ($150-300 \text{ gm/m}^2$) रेंज में और R_{eff} ($8-24 \mu\text{m}$) रेंज के लिए पाया गया है।

इस ढांचे का उपयोग करते हुए, तीन महासागरीय क्षेत्रों के लिए एरोसोल पहले और दूसरे इंडिरेक्ट रेडिएटिवे फोर्सिंग की गणना की गयी है। क्रमशः, औसत वार्षिक ($\pm 1\sigma$) कुल पहले इंडिरेक्ट रेडिएटिवे फोर्सिंग (माइक्रोफिजिकल + मैक्रोफिजिकल) AS, BoB और SIO पर $-6.7 \pm 2.7 \text{ W/m}^2$, $-4.3 \pm 1.1 \text{ W/m}^2$, $-3.6 \pm 1.4 \text{ W/m}^2$ अनुमानित की गयी हैं। पहला एरोसोल इंडिरेक्ट रेडिएटिवे फोर्सिंग केवल माइक्रोफिजिकल पाथवे के कारण $-3.4 \pm 1.7 \text{ W/m}^2$, $-4.15 \pm 2.04 \text{ W/m}^2$, $-4.72 \pm 1.5 \text{ W/m}^2$ AS, BoB और SIO पर होने का

अनुमान लगाया गया है। इसके विपरीत, औसत वार्षिक ($\pm 1\sigma$) AS, BoB और SIO पर मानवजनित एरोसोल के कारण इंडिरेक्ट रेडिएटिवे फोर्सिंग (माइक्रोफिजिकल + मैक्रोफिजिकल) का अनुमान है $-5.96 \pm 2.4 \text{ W/m}^2$, $-4.12 \pm 1.7 \text{ W/m}^2$, $-8.38 \pm .4 \text{ W/m}^2$ क्रमशः, जिनमें से केवल माइक्रोफिजिकल पाथवे के कारण योगदान हैं $-5.9 \pm 3.4 \text{ W/m}^2$, $-4.12 \pm 2.1 \text{ W/m}^2$, $-8.6 \pm 5.04 \text{ W/m}^2$ क्रमशः।

अंत में, औसत वार्षिक लाइफटाइम प्रभाव के कारण कुल एरोसोल दूसरे इंडिरेक्ट रेडिएटिवे फोर्सिंग ($\pm 1\sigma$) AS, BoB और SIO पर $-3.1 \pm 1.4 \text{ W/m}^2$, $-2.5 \pm 0.92 \text{ W/m}^2$, और $-0.75 \pm 0.14 \text{ W/m}^2$ का अनुमान है। इसके विपरीत, AS, BoB और SIO पर लाइफटाइम प्रभाव के कारण वार्षिक मानवजनित एरोसोल दूसरे इंडिरेक्ट रेडिएटिवे फोर्सिंग के रूप में अनुमानित हैं $-3.7 \pm 1.63 \text{ W/m}^2$, $-4.2 \pm 3.4 \text{ W/m}^2$, और $-0.5 \pm 0.09 \text{ W/m}^2$ ।

परिणाम, विशेष रूप से, अल्बेडो इफेक्ट में माइक्रोफिजिकल और मैक्रोफिजिकल पाथवे को अलग करना और लाइफटाइम इफेक्ट के सापेक्ष तुलनात्मक मूल्यांकन उन मॉडलर्स के लिए महत्वपूर्ण होगा जो एयरोसोल-क्लाउड इंटरैक्शन मॉड्यूल में एक अलग स्तर पर मॉडल के प्रदर्शन का आकलन कर सकते हैं। भूमि पर और भविष्य में अन्य प्रकार के बादलों के लिए भी एरोसोल इंडिरेक्ट रेडिएटिवे फोर्सिंग का अनुमान लगाने के लिए यह दृष्टिकोण लागू किया जा सकता है, और यह सार्वभौमिक रूप से लागू होता है।

Contents

Certificate.....	i
Acknowledgements.....	iii
Abstract.....	v
Hindi Abstract.....	ix
Contents.....	xiii
List of Figures.....	xvii
List of Tables.....	xxiii
Chapter 1: Introduction.....	1
1.1 Aerosols and clouds in the atmosphere.....	3
1.1.1 Aerosol formation, types, and climatology.....	3
1.1.2 Clouds in the present day climate system: Cloud formation and types.....	6
1.1.3 Radiative forcing and feedbacks-Aerosol response to climate change.....	8
1.2 Aerosol-Cloud interaction: a largest source of uncertainty.....	13
1.3 Literature Review.....	15
1.3.1 In situ observations.....	16
1.3.2 Satellite observations.....	17
1.3.3 Model observations.....	22
1.4 Definition of the problem.....	23
1.5 Objectives of the thesis.....	24
1.6 Thesis structure.....	25
Chapter 2: Climatology of macrophysical properties of marine water clouds and aerosol properties over the Indian Ocean: Sensitivity to meteorology.....	27
2.1 Background.....	29
2.2 Study area and data used.....	29
2.2.1 Study area.....	29
2.2.2 Data used.....	31
2.3 Climatology of aerosol and cloud properties.....	32

2.3.1 15-years (Mar 2000-Feb 2015) climatology of aerosol and cloud properties.....	32
2.3.2 Concept of cloud albedo and monthly climatology.....	34
2.4 Identification of aerosol types.....	35
2.4.1 Approach.....	35
2.4.2 Monthly climatology of speciated aerosols.....	38
2.5 Hint of lifetime effect.....	39
2.5.1 Modulation in cloud properties due to total aerosol in clear and polluted clouds.....	39
2.5.2 $CTP-f_c$ relation for aerosol types.....	40
2.5.2.1 Anthropogenic.....	40
2.5.2.2 Dust.....	41
2.5.2.3 Maritime.....	42
2.6 Sensitivity check of cloud properties to meteorology and aerosol forcing.....	43
2.6.1 Approach to understand the relative roles of meteorology and aerosol forcing on macrophysical properties of low clouds.....	43
2.6.2 Sensitivity of cloud properties to total aerosol.....	45
2.6.3 Sensitivity of cloud properties to speciated aerosol.....	48
2.6.3.1 Anthropogenic.....	48
2.6.3.2 Dust.....	51
2.6.3.3 Maritime.....	53
2.7 Summary.....	55
Chapter 3: Examine aerosol-cloud interaction over the oceanic regions.....	57
3.1 Background.....	59
3.2 Climatology of aerosol and cloud microphysical properties of low marine water clouds.....	60
3.3 Evidence of aerosol first indirect effect using satellite datasets for fifteen years.....	62
3.3.1 Binned approach to check the effect of aerosols on cloud coverage.....	62
3.3.2 Effect of total aerosols on cloud microphysical properties.....	63
3.3.3 Sensitivity analysis of speciated aerosols with microphysical properties of Clouds.....	66
3.4 Examining the variation on cloud microphysical properties with aerosol loading.....	68
3.4.1 How cloud Albedo respond to microphysical properties of clouds (LWP and R_{eff}).....	69

3.4.2 Aerosol invigoration.....	72
3.5 Climatology of Absorbing Aerosol Index (AI), and a relationship of aerosol loading with AI.....	74
3.5.1 Monthly climatology of AI.....	74
3.5.2 Response of absorbing aerosols to total aerosols.....	74
3.6 Potential evidence of the semi-direct effect through observational analysis.....	76
3.6.1 Hint of semi-direct effect: interrelationship between AI with LWP.....	77
3.6.2 Absorbing aerosol effect on cloud coverage for marine water clouds.....	78
3.7 Role of meteorology in modulating cloud properties.....	81
3.7.1 SST and f_c relationships.....	81
3.7.2 RH and f_c relationships.....	83
3.8 Summary.....	84
 Chapter 4: Observationally constrained estimates of aerosol indirect forcing due to albedo effect.....	87
4.1 Background.....	89
4.2 Analytical framework to estimate aerosol indirect radiative forcing due to albedo effect.....	91
4.2.1 Theoretical Framework for calculate the aerosol indirect radiative forcing through microphysical and macrophysical pathways.....	91
4.2.2 Theoretical Framework for calculate the aerosol indirect radiative forcing through microphysical pathways.....	94
4.3 Generation of lookup tables.....	95
4.3.1 Lookup tables for $dR_c/d\tau_a$ values (microphysical + macrophysical) pathways.....	96
4.3.2 Lookup tables for $dR_c/d\tau_a$ values due to microphysical pathways.....	101
4.4 Indirect radiative forcing due to aerosol albedo effect.....	105
4.4.1 Annual variability of first indirect forcing for total aerosol.....	105
4.4.2 First indirect radiative forcing due to microphysical pathway.....	108
4.4.3 Separating microphysical from macrophysical pathway in the first aerosol indirect radiative forcing.....	111
4.5 Indirect radiative forcing due to albedo effect for anthropogenic aerosols.....	112
4.5.1 Look up tables for anthropogenic aerosol induced cloud albedo change.....	115
4.5.1.1 Generation of the lookup table due to microphysical and macrophysical pathways.....	116

4.5.1.2 Generation of the lookup table due to microphysical pathways.....	118
4.5.2 Annual radiative forcing due to anthropogenic aerosols.....	119
4.5.2.1 First indirect radiative forcing due to microphysical and macrophysical pathways for anthropogenic aerosols.....	120
4.5.2.2 First indirect radiative forcing due to microphysical pathways for anthropogenic aerosols.....	122
4.5.3 First indirect radiative forcing due to macrophysical pathways for anthropogenic aerosols.....	124
4.6 Summary.....	128
Chapter 5: Aerosol indirect radiative forcing due to lifetime effect.....	131
5.1 Background.....	133
5.2 Framework to estimate aerosol indirect radiative forcing due to lifetime effect.....	134
5.2.1 Lookup table to calculate $df_c/d\tau_a$	135
5.3 Forcing due to lifetime effect.....	136
5.3.1 Second indirect radiative forcing due to total AOD.....	136
5.3.2 Contribution of anthropogenic aerosols in second indirect radiative forcing...	139
5.4 Comparison in forcing values due to total AOD and anthropogenic forcing due to life time Effect.....	140
5.5 Summary.....	141
Chapter 6: Summary and future direction.....	143
6.1 Summary and Conclusion of thesis.....	145
6.2 Limitations.....	149
6.3 Future prospects.....	150
References.....	153
Annexure I: Abbreviations.....	173
Annexure II: Glossary.....	177
Annexure III: List of Publications from the thesis.....	181

List of Figures

Figure captions	Page No.
Figure 1.1 Aerosol types and Mechanism in the atmosphere	4
Figure 1.2 Cloud types in the atmosphere based on COD and CTP relationship	7
Figure 1.3 Aerosol-cloud-climate interaction	8
Figure 1.4 Aerosol-Radiation interaction (a) Direct effect; (b) Semi direct effect	9
Figure. 1.5 Schematic diagram of Aerosol-Cloud Interaction (a) albedo effect; (b) lifetime effect (Second indirect effect); (c) hypothesis behind cloud invigoration (Ramanathan et al., 2008).	10
Figure 1.6 Aerosol Indirect forcing (a) IPCC AR 4; (b) IPCC AR5.	14
Figure 1.7 (a) Aerosol direct radiative forcing for the North Indian Ocean, (b) direct and indirect forcing values using models; ship based measurements and satellite observation (Ramanathan et al., 2001).	17
Figure 2.1 Study region	30
Figure 2.2 Monthly statistics of (a) Total Aerosol Optical Depth (τ_a), (b) Fine mode fraction (fmf) (c) Cloud fraction (f_c), (d) Cloud top pressure (CTP) for low clouds over the AS, BoB and SIO, box plots show 5 th to 95 th percentile range.	33
Figure 2.3 Schematic illustration of the influence of the different types of clouds on the Earth's radiation budget	34
Figure 2.4 Monthly statistics of Cloud Optical Depth (τ_c), Cloud albedo (R_c) for low clouds over the AS, BoB, and SIO, box plots show 5 th to 95 th percentile range	35
Figure 2.5 Inter-annual variations of mean monthly (top panel) and relative contributions of fraction of anthropogenic (upper middle), dust (lower middle), and maritime (lower panel).	39
Figure 2.6 The dependence of mean CTP on f_c for four quartiles of total Aerosol Optical Depth- τ_a	40

Figure 2.7 The dependence of mean CTP on f_c for four quartiles of Anthropogenic $-\tau_{an}$ (upper panel), Dust- τ_d (middle panel), Maritime- τ_{ma} (Lower panel)	42
Figure 2.8 Sensitivity of $\ln(CTP)$ to $\ln(f_c)$ (top panel); sensitivity of $\ln(f_c)$ to $\ln(\tau_a)$ (middle panel); sensitivity of $\ln(CTP)$ to $\ln(\tau_a)$ (bottom panel) over Arabian Sea, Bay of Bengal and South Indian Ocean	46
Figure 2.9 Anthropogenic aerosol: Sensitivity of $\ln(CTP)$ to $\ln(f_c)$ (top panel); sensitivity of $\ln(f_c)$ to $\ln(\tau_{an})$ (middle panel); sensitivity of $\ln(CTP)$ to $\ln(\tau_{an})$ (bottom panel) over Arabian Sea, Bay of Bengal and South Indian Ocean.	50
Figure 2.10 Dust aerosol: sensitivity of $\ln(f_c)$ to $\ln(\tau_{du})$ (upper panel), sensitivity of $\ln(CTP)$ to $\ln(\tau_{du})$ (lower panel) over Arabian Sea, Bay of Bengal and South Indian Ocean.	52
Figure 2.11 Maritime aerosol: sensitivity of $\ln(f_c)$ to $\ln(\tau_{ma})$ (upper panel), sensitivity of $\ln(CTP)$ to $\ln(\tau_{ma})$ (bottom panel) over Arabian Sea, Bay of Bengal and South Indian Ocean.	54
Figure 3.1 Monthly statistics of (a) R_{eff} and (b) LWP for low clouds over the AS, BoB and SIO. Box plots show 5 th to 95 th percentile ranges.	61
Figure 3.2 Variation of f_c with an increase in AOD with Error bars are $\pm 1\sigma$	62
Figure 3.3 Variation of R_{eff} with an increase in LWP for four aerosol quartiles. The panels from the top represent winter, pre-monsoon, monsoon, and post-monsoon seasons, respectively over Arabian Sea, Bay of Bengal and South Indian Ocean	65
Figure 3.4 Variation of cloud effective radius across different aerosol types (a) Arabian Sea, (b) Bay of Bengal, and (c) South Indian Ocean	68
Figure 3.5 Cloud albedo (R_c) as a function of Cloud optical depth (τ_c) over Arabian Sea for winter season.	69
Figure 3.6 Variation of cloud albedo with an increase in R_{eff} for different ranges of LWP . The panels from the top represent winter, pre-monsoon, monsoon, and post-monsoon seasons, respectively over Arabian Sea, Bay of Bengal and South Indian Ocean.	71
Figure 3.7 Variation of R_{eff} with an increase in cloud top pressure for different ranges of τ_a . The panels from the top to bottom represents winter, pre-monsoon, monsoon and post-monsoon seasons, respectively over Arabian Sea (left column), Bay of Bengal (right column).	73

Figure 3.8 Monthly statistics of Absorbing Aerosol (AI) over the AS, BoB and SIO. Box plots show 5 th to 95 th percentile ranges.	75
Figure 3.9 AOD and AI relationships for ten years over the AS and BoB.	75
Figure 3.10 Variation of LWP (g m^{-2}) with an increase in AAI in the three regions. The panels from the top represent winter, pre-monsoon, monsoon and post-monsoon seasons. The error bars represent 5 th -95 th percentile ranges.	78
Figure 3.11 Change in f_c with increase in AI for all the four seasons: winter (top panel), Pre monsoon (upper middle panel), Monsoon (lower middle panel) and Post monsoon(lower panel) over Arabian Sea (left column), Bay of Bengal (middle column) and South Indian Ocean (right column).	80
Figure 3.12 The relationship with f_c for different bins of SST .	82
Figure 3.13 (a) Climatology of wind speed over Arabian Sea, Bay of Bengal and South Indian Ocean for fifteen years (Mar 2000-Feb 2015) and (b) lower panel (RH) with Error bars are $\pm 1\sigma$.	84
Figure 4.1 15 years monthly climatology of $dR_c/d\tau_a$ where both the microphysical and macrophysical pathways are included over the Arabian Sea, Bay of Bengal and South Indian Ocean using the formula mentioned in eq. 8.	93
Figure 4.2 15 years monthly climatology of $dR_c/d\tau_a$ where only microphysical pathways are considered over the Arabian Sea, Bay of Bengal and South Indian Ocean using the formula mentioned in eq.10.	95
Figure 4.3. (a) variation of R_{eff} with an increase in LWP for different ranges of τ_a ; (b) $dR_c/d\tau_a$ values for every possible link of R_{eff} ($8-28 \mu\text{m}$) – LWP ($0-550 \text{ gm/m}^2$).	96
Figure 4.4. $\frac{dR_c}{d\tau_a}$ values (microphysical + macrophysical pathways) for every possible link of R_{eff} ($8-28 \mu\text{m}$) – LWP ($0-550 \text{ gm/m}^2$) over the Arabian Sea.	98
Figure 4.5. $\frac{dR_c}{d\tau_a}$ values (microphysical + macrophysical pathways) for every possible link of R_{eff} ($8-28 \mu\text{m}$) – LWP ($0-550 \text{ gm/m}^2$) over the Bay of Bengal.	99
Figure 4.6. $\frac{dR_c}{d\tau_a}$ values (microphysical + macrophysical pathways) for every possible link of R_{eff} ($8-28 \mu\text{m}$) – LWP ($0-550 \text{ gm/m}^2$) over the South Indian Ocean.	100
Figure 4.7. $\frac{dR_c}{d\tau_a}$ values (microphysical pathways) for every possible link of R_{eff} ($8-28 \mu\text{m}$) – LWP ($0-550 \text{ gm/m}^2$) over the Arabian Sea.	102

Figure 4.8. $\frac{dR_c}{d\tau_a}$ values (microphysical + macrophysical pathways) for every possible link of R_{eff} (8-28 μm) – LWP (0-550 gm/m^2) over the Bay of Bengal.	103
Figure 4.9. $\frac{dR_c}{d\tau_a}$ values (microphysical pathways) for every possible link of R_{eff} (8-28 μm) – LWP (0-550 gm/m^2) over the South Indian Ocean.	104
Figure 4.10. Fifteen-years (Mar 2000-Feb 2015) averaged first indirect radiative forcing (a) both microphysics and macrophysics are counted; (b) only microphysics over the Arabian Sea, Bay of Bengal and South Indian Ocean.	106
Figure 4.11 Fifteen years (Mar 2000-Feb 2015) monthly averaged climatology of radiative forcing due to cloud albedo aerosol effect (W/m^2).	108
Figure 4.12 Fifteen years (Mar 2000-Feb 2015) monthly averaged climatology of radiative forcing due to cloud albedo aerosol effect when only microphysical properties of clouds considered (W/m^2).	110
Figure 4.13. Fifteen years (Mar 2000-Feb 2015) monthly averaged difference in cloud properties in radiative forcing due to cloud albedo over the Arabian Sea, Bay of Bengal and the South Indian Ocean.	112
Figure 4.14. (a) variation of R_{eff} with an increase in LWP for different ranges of τ_{an} ; (b) $dR_c/d\tau_{an}$ values for every possible link of R_{eff} (8-28 μm) – LWP (0-550 gm/m^2).	116
Figure 4.15. $\frac{dR_c}{d\tau_{an}}$ values (microphysical + macrophysical pathways) for every possible link of R_{eff} (8-28 μm) – LWP (0-550 gm/m^2) over AS, BoB and SIO.	117
Figure 4.16. $\frac{dR_c}{d\tau_{an}}$ values (microphysical pathways) for every possible link of R_{eff} (8-28 μm) – LWP (0-550 gm/m^2) over the South Indian Ocean.	118
Figure 4.17. Fifteen-years (Mar 2000-Feb 2015) averaged first indirect radiative forcing (a) both microphysics and macrophysics are counted; (b) only microphysics for anthropogenic aerosols over the Arabian Sea, Bay of Bengal and South Indian Ocean.	119
Figure 4.18. Fifteen years (Mar 2000-Feb 2015) monthly averaged climatology of radiative forcing due to cloud albedo aerosol effect (W/m^2).	122
Figure 4.19. Fifteen years (Mar 2000-Feb 2015) monthly averaged climatology of radiative forcing due to cloud albedo aerosol effect (W/m^2).	124

Figure 4.20. Fifteen years (Mar 2000-Feb 2015) monthly microphysical Vs macrophysical pathways in cloud albedo effect over the Arabian Sea, Bay of Bengal and the South Indian Ocean.	125
Figure 4.21. Fifteen years (Mar 2000-Feb 2015) first Indirect radiative forcing due to macrophysical pathways as a function of LWP and R_{eff} (W/m ²) (a) Annual forcing, (b) Monthly forcing; (c) Forcing values respective to LWP and R_{eff} .	127
Figure 5.1. lookup table for $df_c/d\tau_a$	135
Figure 5.2 Fifteen-years (Mar 2000-Feb 2015) averaged second indirect radiative forcing	136
Figure 5.3 Fifteen years (Mar 2000-Feb 2015) monthly averaged climatology of radiative forcing due to lifetime effect (W/m ²).	137
Figure 5.4 Fifteen-years (Mar 2000-Feb 2015) averaged second indirect radiative forcing due to anthropogenic aerosol	138
Figure 5.5 Fifteen years (Mar 2000-Feb 2015) monthly averaged climatology of anthropogenic aerosol radiative forcing due to lifetime effect (W/m ²).	140

List of Tables

Table caption	Page No.
Table 2.1 Monthly averaged of MODIS Fine Mode Fraction (FMF) of total aerosol optical depth (f_a), fine mode fraction of anthropogenic (f_{an}), dust (f_d) and maritime (f_{ma}) over AS, BoB and SIO combined (Thomas et al., 2007).	37
Table 2.2 Residual values over the Arabian Sea, Bay of Bengal and South Indian oceans for different seasons based on sensitivity correlation between CTP, f_c, τ_a .	47
Table 2.3 Residual values over the Arabian Sea, Bay of Bengal and South Indian oceans for different seasons based on sensitivity correlation between CTP, f_c, τ_{an} .	51
Table 2.4 Residual values over the Arabian Sea, Bay of Bengal and South Indian oceans for different seasons based on sensitivity correlation between CTP, f_c, τ_{du} .	52
Table 2.5 Residual values over the Arabian Sea, Bay of Bengal and South Indian oceans for different seasons based on sensitivity correlation between CTP, f_c, τ_{ma} (maritime aerosol).	54
Table 4.1 Seasonal averaged values of radiative forcing due to albedo effect for fifteen-years (Mar 2000-Feb 2015) where both microphysics and macrophysics are counted.	107
Table 4.2 Seasonal averaged values of radiative forcing due to albedo effect for fifteen-years (Mar 2000-Feb 2015) only microphysics counted.	109
Table 4.3. Seasonal averaged values of radiative forcing due to albedo effect for total aerosols when both microphysics and macrophysics are counted.	120
Table 4.4. Seasonal averaged values of anthropogenic aerosol radiative forcing due to albedo effect when both microphysics and macrophysics are counted.	123
Table 5.1. Seasonal averaged values of total aerosol radiative forcing due to lifetime effect	136

Table 5.2. Seasonal averaged values of anthropogenic aerosol radiative forcing due to lifetime effect	140
Table 5.3. Comparison in forcing values	141

