

**A NUMERICAL STUDY OF RECOVERY
PROCESSES IN OFFSHORE WIND FARMS**

TANVI GUPTA



**CENTRE FOR ATMOSPHERIC SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2022**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2022

**A NUMERICAL STUDY OF RECOVERY
PROCESSES IN OFFSHORE WIND FARMS**

by

TANVI GUPTA

Centre for Atmospheric Sciences

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER 2022

Dedicated to my Mother and Tai Ji

Certificate

This is to certify that the thesis entitled “**A Numerical Study of Recovery Processes in Offshore Wind Farms**” being submitted by **Ms. Tanvi Gupta** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of original bona fide research carried out by her. Ms. Tanvi Gupta 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.

(Prof. Somnath Baidya Roy)

Professor
Centre for Atmospheric Sciences
Indian Institute of Technology Delhi
New Delhi-110016, INDIA

Acknowledgements

I would like to express my sincere thanks to my supervisor Prof. Somnath Baidya Roy for giving me an opportunity to work in the area of wind energy meteorology and guiding me throughout this journey. Prof. Baidya Roy has always provided me with the required resources to carry out my research. I am thankful for the valuable time he has given for scientific discussions. The questions asked by him during the discussions helped me to understand my work better. His way of understanding and explaining science in a simplified manner would always be the trait I would like to imbibe myself throughout my life. I consider myself privileged to have gotten a chance to work with him.

I wish to acknowledge the SRC members Prof. Manju Mohan, Prof. Sagnik Dey, and Dr. Dibakar Rakshit for their critical comments and helping me with all the formalities during my Ph.D. I am thankful to Prof. Baidya Roy and Prof. Krishna AchutaRao for their valuable suggestions and critical comments during the group meetings. I owe thanks to Dr. Lee Miller, Earth Scientist, Pacific Northwest National Laboratory, for helping me to learn wind energy meteorology basics during the initial days of my Ph.D.

I express my sincere gratitude to all the serving HODs Prof. A. D. Rao, Prof. Manju Mohan, and Prof. Krishna AchutaRao for providing excellent research facilities which helped me in all aspects of my work. I am also obliged to HPC research team of IIT Delhi and all the non-teaching staff of CAS, IITD for their cooperation.

I am thankful to my labmates Dr. Dileepkumar R., Jaswant, Varunesh, Narender, and Aheli for their constant help. I am also grateful to Dr. Sachiko Mohanty and Dr. Tanuja Nigam, with whom I had scientific discussions which helped me to enhance my subject knowledge.

The acknowledgment is incomplete without thanking my husband, Ankur. He has mentored me, helped me keep patience, and meet deadlines. He motivated me to pursue my passion for research and supported me wholeheartedly during the ups and downs of Ph.D. journey. His optimistic approach, dedication, and ethics are something I always learn from. He made me live in the present instead of worrying about the future. The scientific discussions I had with him helped me to understand & organize my work and develop a problem-solving attitude. The unconditional love, care, and support he bestowed on me during my Ph.D. journey is something I will always remain indebted to. This accomplishment would not have been possible without him.

I consider myself extremely blessed to have Mrs. Shobha & Mr. Anil Gupta as my parents and Mrs. Alka and Sudhir Gupta as my Tai Ji and Tau Ji. My mother and Tai Ji are my first mentors who guided me all my life. They took care of my nutrition like a child during the tenure of my Ph.D. The unconditional love and support of my father and Tau Ji kept me going. I owe my confidence to my father Mr. Anil Gupta. The conviction by which he told me that *“a soldier, if afraid of bullets, can’t fight a war”* is something I always remember, and it helps me keep going in life. I express my immense gratitude to my elder brother Dr. Manish Gupta who mentored me in my Ph.D. journey. He sponsored my partially funded USA visit for AGU. I cherish the discussions I had with my sister-in-law Dr. Swati Shah, especially during the last years of my Ph.D. I am immensely thankful to my brother Mohit Gupta whose company, sense of humor, and love help me keep going. I am also thankful to my sister and brother-in-law Mukta and Anand for their best wishes. I am grateful to my grandparents Mrs. Suman Lata and Mr. M. C. Gupta for their blessings.

I am immensely thankful to my mother-in-law and father-in-law, Mrs. Urmila Devi and Mr. Arun Verma for the support and understanding they showed. I extend my heartfelt thanks to

my grandmother-in-law and grandfather-in-law, Mrs. Krishna Verma and Mr. B. R. Verma. The childlike inquisitiveness of my grandfather-in-law always surprised me. The questions he asked “*how a pawanchaki works and what’s the use of my research?*” will always stay with me. I am grateful to my siblings-in-law: Anshul and Nidhi. Their presence at home helped me focus on my research better. I am also thankful to my other siblings-in-law: Prachi, Gaurav, Ayushi, Nutan, Preeti, and Late Ashwani for the immense love they bestowed on me.

No actions or words would suffice to express thankfulness to Dr. M. C. Misra, Mr. Yadav, Dr. Poonam Nayar, and Dr. Neeraja Sood for encouraging, guiding and believing in me during difficult times in my Ph.D. I owe thanks again to my family doctors: Dr. Renu Misra, Dr. M. C. Misra, Dr. D.K. Singh, Dr. Antriksh Baiswar, Dr. Neeraj Verma, and Dr. Rekha Verma for taking care of me and my family that helped me to focus on my research work.

The friends I made during this period are one of the best things that happened during these past seven years. They kept me motivated to pursue my Ph.D. journey and at the same time helped me forget the associated worries. I cherish the memories I made with my IITD friends Priya, Janmejai, Navin, Vivek, Ankur Srivastava, Preeti, Jyoti, Ankur Dixit, Puneet, Shubra and Anu. I consider myself extremely blessed to have the company of Richa, Bhavna, and Swati who have always been a constant source of emotional support for all spheres of my life. I was blessed to get company of some great human beings: Prashant, Sudipta, and Debasish Bhaiya. The interactions with them during my corporate stint before Ph.D. had a great bearing on my thought process and life goals.

Above all, I thank the almighty for blessing our family with lovely babies: Advik, Yash, and Agastya. Just the sight of them translates all our worries into happiness. Baby Agastya cooperated with me to write all the papers, thesis, and did a lot of hard work for his mumma’s Ph.D.

Abstract

Wind turbines in a wind farm extract energy from the atmospheric flow and convert it into electricity, resulting in a localized momentum deficit in the wake that reduces energy availability for downwind turbines. Atmospheric momentum convergence from above, below, and the sides into the wakes replenishes the lost momentum, at least partially, so that turbines deep inside a wind farm can continue to function. In this thesis, I quantitatively explore the behaviour and recovery processes in a hypothetical deep offshore wind farm and a coastal offshore wind farm under sea breeze conditions.

The particular emphasis in this study is on comparing the spatial patterns and magnitudes of horizontal- and vertical-recovery processes and understanding the role of mesoscale processes in momentum recovery in offshore wind farms. For this purpose, I use the Weather Research and Forecasting (WRF) model, a state-of-the-art mesoscale model equipped with a wind turbine parameterization, to simulate the dynamics and thermodynamic of atmospheric flow within and around hypothetical offshore wind farms with different wind turbine spacings under realistic initial and boundary conditions. The wind farms consist of wind turbines with 84 m hub heights, 112 m rotor diameter (D), and rated capacity of 3.075 MW. Different inter-turbine spacings range from a densely packed wind farm (case I: low inter-turbine distance of 0.5 km \sim 5 rotor diameter) to a sparsely packed wind farm (case III: high inter-turbine distance of 2 km \sim 20 rotor diameter).

First, I study a wind farm located deep offshore where the atmospheric flow is not directly influenced by land masses. Apart from the inter-turbine spacings, I also explore the role of different ranges of background wind speeds over which the wind turbines operate, ranging from a low wind speed range of 3–11.75 ms^{-1} (case A) to a high wind speed range of 11–18 ms^{-1} (case C). Results show that vertical turbulent transport of momentum from aloft is the main

contributor to recovery in deep offshore wind farms except in cases with high-wind-speed range and sparsely packed wind farms, where horizontal advective momentum transport can also contribute equally. Vertical recovery shows a systematic dependence on wind speed and wind farm density that is quantified using low-order empirical equations. Wind farms alter the mesoscale flow patterns, especially for densely packed wind farms under high-wind-speed conditions. In these cases, the mesoscale circulations created by the wind farms can transport high-momentum air from aloft into the atmospheric boundary layer (ABL) and thus aid in recovery in wind farms.

Most of the current offshore wind installations are located in coastal regions where they are often affected by sea-breezes. Hence, I further quantitatively study the behaviour and recovery processes for coastal offshore wind farms under sea-breeze conditions. I use a modified Borne's method to identify sea breeze days off the west coast of India in the Arabian Sea. For the identified sea breeze days, I simulate a hypothetical wind farm covering 50 x 50 km² area using the Weather Research and Forecasting (WRF) model, again driven by realistic initial and boundary conditions. I use three wind farm layouts with the turbines spaced 0.5 km, 1 km, and 2 km apart. The results show an interesting power generation pattern with a peak at the upwind edge and another peak at the downwind edge due to sea breeze. Wind farms affect the circulation patterns, but the effects of these modifications are very weak compared to the sea breezes. Vertical recovery is the dominant factor with more than half of the momentum extracted by wind turbines being replenished by vertical turbulent mixing. However, horizontal recovery can also play a strong role for sparsely packed wind farms. Horizontal recovery is stronger at the edges where the wind speeds are higher whereas vertical recovery is stronger in the interior of the wind farms.

To the best of my knowledge, this is one of the first studies to look at wind farm replenishment processes under realistic meteorological conditions including the role of mesoscale processes. Also, this study for the first time examines replenishment processes in offshore wind farms under sea breeze conditions. Overall, this study makes a significant contribution in advancing our understanding of recovery processes in wind farms and wind farm–ABL interactions.

सार

पवन फार्म में पवन चक्कियाँ वायुमंडलीय प्रवाह से ऊर्जा निकालती हैं और इसे बिजली में परिवर्तित करती हैं, जिसके परिणामस्वरूप स्थानीय गति में कमी होती है जो पवन फार्म में बाद की पवन चक्कियों के लिए पवन ऊर्जा की उपलब्धता को कम करती है। वेक में ऊपर, नीचे, और किनारों से वायुमंडलीय गति अभिसरित होकर गति में हुई कमी की आंशिक रूप से भरपाई कर देती है, जिससे पवन फार्म के काफी भीतर की पवन चक्कियाँ कार्य करने में सक्षम रहती हैं। इस थीसिस में, मैं एक काल्पनिक गहरे अपतटीय पवन फार्म और समुद्री हवा की स्थिति के तहत एक तटीय पवन फार्म में पुनर्प्राप्ति प्रक्रियाओं का पता लगाती हूँ।

इस थीसिस में, क्षैतिज और ऊर्ध्वाधर-पुनर्प्राप्ति प्रक्रियाओं के स्थानिक प्रतिरूप और परिमाण की तुलना करने और पवन खेतों में गति पुनःपूर्ति में मेसोस्केल प्रक्रियाओं की भूमिका को समझने पर विशेष जोर दिया गया है। इस उद्देश्य के लिए मैंने पवन चक्की मानकीकरण से लैस एक अत्याधुनिक मेसोस्केल मॉडल, मौसम अनुसंधान और पूर्वानुमान (डब्ल्यूआरएफ) मॉडल का प्रयोग करके काल्पनिक अपतटीय पवन फार्मों के भीतर और आसपास वायुमंडलीय प्रवाह की गतिशीलता और थर्मोडायनामिक का अनुकरण यथार्थवादी प्रारंभिक और सीमा स्थितियों के तहत किया है। पवन फार्मों में 84 मी हब ऊंचाई, 112 मी रोटर व्यास (D), और 3.075 मेगा वाट की रेटेड क्षमता वाली पवन चक्कियाँ हैं। सघन पवन फार्म (केस I: 0.5 किमी ~ 5 रोटर व्यास की कम अंतर-पवन चक्की दूरी) से लेकर विरल पवन फार्म (केस III: 2 किमी ~ 20 रोटर की उच्च अंतर-पवन चक्की दूरी) तक अलग-अलग अंतर-पवन चक्की दूरियाँ अनुकरणित की गयी हैं।

सबसे पहले, मैंने गहरे अपतटीय स्थित पवन फार्म का अध्ययन किया है जहां वायुमंडलीय प्रवाह सीधे भूमि द्रव्यमान से प्रभावित नहीं होता है। अंतर-पवन चक्की दूरी के अलावा, मैंने पृष्ठभूमि की हवा की गति की विभिन्न श्रेणियों की भूमिका का भी पता लगाया, जिस पर पवन चक्कियाँ संचालित होती हैं।

पृष्ठभूमि हवाएँ कम गति ३-११.७५ मीटर प्रति सेकण्ड (केस ए) की श्रेणी से ज्यादा गति ११-१८ मीटर प्रति सेकण्ड (केस सी) की श्रेणी तक मानी गयी हैं। परिणाम बताते हैं कि उच्च-पवन-गति सीमा और विरल पवन फार्म के मामलों को छोड़कर, जहां क्षैतिज संवेगात्मक गति परिवहन भी समान रूप से योगदान कर सकता है, अन्य सभी परिस्थितियों में ऊपर से गति का ऊर्ध्वाधर अशांत परिवहन गहरे अपतटीय पवन खेतों में पुनर्प्राप्ति के लिए मुख्य योगदानकर्ता है। ऊर्ध्वाधर पुनर्प्राप्ति की हवा की गति और पवन फार्म घनत्व पर एक व्यवस्थित निर्भरता देखी गयी है। इस निर्भरता को निम्न-क्रम के अनुभवजन्य समीकरणों का उपयोग करके निर्धारित किया गया है। पवन फार्म मेसोस्केल प्रवाह प्रतिरूप को महत्वपूर्ण रूप से, विशेषकर उच्च-हवा-गति की स्थितियों के तहत सघन पवन फार्म के लिए परिवर्तित कर देते हैं। इन मामलों में, पवन फार्म द्वारा बनाए गए मेसोस्केल परिसंचरण उच्च गति वाली हवा को वायुमंडलीय सीमा परत (एबीएल) में ले जा सकते हैं और इस प्रकार पवन फार्म में पुनर्प्राप्ति में सहायता कर सकते हैं।

अधिकांश वर्तमान अपतटीय पवन प्रतिष्ठान तटीय क्षेत्रों में स्थित हैं जहां वे अक्सर समुद्री हवाओं से प्रभावित होते हैं। इसलिए, मैंने समुद्री हवा की स्थितियों से सम्बंधित तटीय पवन फार्म के व्यवहार एवं पुनर्प्राप्ति प्रक्रियाओं का मात्रात्मक अध्ययन किया है। मैंने अरब सागर में भारत के पश्चिमी तट से दूर समुद्री हवा के दिनों की पहचान करने के लिए एक संशोधित बोरन विधि का उपयोग किया है। पहचाने गए समुद्री हवा के दिनों के लिए, मैंने मौसम अनुसंधान और पूर्वानुमान (डब्ल्यूआरएफ) मॉडल का उपयोग करके 50 x 50 वर्ग किमी क्षेत्र के एक काल्पनिक पवन फार्म का अनुकरण किया है, जो फिर से यथार्थवादी प्रारंभिक और सीमा स्थितियों द्वारा संचालित होता है। मैंने तीन पवन फार्म नक्शों का उपयोग करते हैं जिसमें पवन चक्कियाँ 0.5 किमी, 1 किमी और 2 किमी की दूरी पर हैं। इस अध्ययन के परिणाम एक दिलचस्प बिजली उत्पादन प्रतिरूप दिखाते हैं। पवन फार्म में आगे की ओर अधिकतम बिजली उत्पादन देखा गया है। साथ ही में समुद्र की हवा के कारण पवन फार्म में पीछे की ओर भी

अधिकतम बिजली उत्पादन देखा गया है। पवन फार्म परिसंचरण प्रतिरूप को प्रभावित करते हैं, लेकिन इन संशोधनों के प्रभाव समुद्री हवाओं की तुलना में बहुत कमजोर होते हैं। ऊर्ध्वाधर पुनर्प्राप्ति गति पुनःपूर्ति का प्रमुख कारक है जो कि पवन चक्कियों द्वारा निकाले गए गति के आधे से अधिक को ऊर्ध्वाधर अशांत मिश्रण द्वारा भर देता है। हालाँकि, क्षैतिज पुनर्प्राप्ति भी विरल पवन फार्म के लिए एक मजबूत भूमिका निभा सकती है। क्षैतिज पुनर्प्राप्ति पवन फार्म के किनारों पर अधिक मजबूत होती है जहां हवा की गति अधिक होती है जबकि पवन खेतों के अंदरूनी हिस्सों में ऊर्ध्वाधर पुनर्प्राप्ति अधिक मजबूत होती है।

मेरी जानकारी के अनुसार, मेसोस्केल प्रक्रियाओं की भूमिका सहित यथार्थवादी मौसम संबंधी स्थितियों के तहत पवन फार्म पुनर्प्राप्ति प्रक्रियाओं को देखने के लिए यह पहला अध्ययन है। इसके अलावा, यह अध्ययन पहली बार समुद्री हवा की स्थिति के तहत अपतटीय पवन खेतों में पुनर्प्राप्ति प्रक्रियाओं की जांच करता है। कुल मिलाकर, यह अध्ययन पवन फार्म और पवन फार्म-एबीएल परस्पर क्रिया में पुनर्प्राप्ति प्रक्रियाओं की हमारी समझ को आगे बढ़ाने में महत्वपूर्ण योगदान देता है

Table of Contents

Certificate.....	i
Acknowledgements.....	ii
Abstract.....	v
List of Figures.....	xiv
List of Tables.....	xix
List of Abbreviations.....	xx
CHAPTER 1.....	1
1. Introduction.....	2
1.1 Wind Farm Modeling Approaches.....	7
1.1.1 Analytical wake models.....	7
1.1.2 Large Eddy Simulations (LES).....	8
1.1.3 Numerical Weather Prediction (NWP) models.....	8
1.1.4 Wind experimental setups.....	9
1.1.5 Field studies.....	10
1.2 Literature Review.....	11
1.2.1 Recovery in the wind farm.....	11
1.2.2 WRF model improvements.....	14
1.2.3 Offshore wind farm - ABL interactions.....	16
1.3 Gaps in the Literature and Research Motivation.....	17
1.4 Objectives and Outline of the Work.....	18
CHAPTER 2.....	23
2. Methodology.....	24
2.1 Description of NWP Model WRF.....	24
2.2 Wind Farm Parameterization in WRF.....	31
2.3 Power Generation and Turbulent Kinetic Energy Coefficient Calculations.....	33
2.3.1 Power generation calculations.....	33
2.3.2 Calculation for C_{TKE}	34
2.4 Fluxes, Recovery, Momentum Loss Rate and Stability Calculations.....	35

2.4.1	Synoptic, mesoscale and turbulent fluxes	35
2.4.2	Horizontal and vertical recovery	36
2.4.3	Momentum loss rate.....	38
2.4.4	Stability calculations	38
2.5	Vector difference along the Prevailing Wind Direction.....	39
2.6	Identification of Sea Breeze Days	39
2.7	Changes Made in WRF Source Code for Recovery Calculations.....	42
CHAPTER 3		44
3.	Wind Farm Behaviour and Interactions with the Atmosphere for a Deep Offshore Wind Farm	45
3.1	Design of Experiments	45
3.2	Model Evaluation	49
3.3	Sensitivity Study to determine appropriate domain size.....	49
3.4	Wind Farm Behaviour	50
3.4.1	Power generation in wind farms	50
3.4.2	Stability conditions in numerical experiments.....	52
3.5	Wind Farm - Atmosphere Interactions	53
3.5.1	Wind farm wakes	53
3.5.2	Circulation patterns around offshore wind farms	57
3.5.3	Effect of wind farms on synoptic, meso, and micro-scale momentum fluxes...59	
3.6	Summary	62
CHAPTER 4		64
4.	Recovery Processes in Deep Offshore Wind Farm.....	65
4.1	Quantitative Assessment of Vertical and Horizontal Recovery	66
4.2	Characterization of Vertical Recovery	72
4.3	Dependence of Vertical Recovery on Mesoscale Fluxes	73
4.4	Effect of Stability on Vertical Recovery	75

4.5	Effect of TKE Advection on Recovery Processes	77
4.6	Summary	80
CHAPTER 5		82
5.	Behaviour and Recovery Processes in Coastal Offshore Wind Farm under Sea Breeze Conditions	83
5.1	WRF Model Configuration to Generate Meteorological Dataset for Sea Breeze Identification	85
5.2	Validation of Sea Breeze Days using METAR Data	87
5.3	Behaviour of Offshore Wind Farms under Sea Breeze Conditions	89
5.4	Power Production under Sea Breeze Conditions.....	91
5.5	Circulation Patterns and Fluxes around an Offshore Wind Farm under Sea Breeze Condition.....	100
5.6	Recovery Processes under Sea Breeze Conditions	103
5.7	Summary	106
CHAPTER 6		108
6.	Conclusions & Future Scope of Work	109
6.1	Conclusions	109
6.1.1	Wind farm behaviour and its interaction with atmosphere for a large deep offshore wind farm.....	109
6.1.2	Quantification of recovery processes for a large offshore wind farm	109
6.1.3	Behaviour and recovery processes for coastal offshore wind farm under sea- breeze conditions	110
6.2	Future Scope of Work	111
References.....		114
Curriculum-Vitae		130

List of Figures

Figure 1.1: (a) New wind capacity installation in GW till the year 2021, and (b) Projected offshore new wind capacity installation in GW (GWEC, 2021)	3
Figure 1.2: Schematic diagram of vertical and horizontal recovery processes.....	5
Figure 1.3: Different flow scales for wind energy (Porté-Agel et al., 2020).....	7
Figure 1.4: Wind farm locations for deep offshore wind farm (Chapter 3 and 4), and coastal offshore wind farm under sea breeze conditions (Chapter 5)	19
Figure 2.1: Arakawa- C grid used in WRF model	29
Figure 2.2: Interactions between different physics schemes used in WRF (Skamarock et al., 2019)	30
Figure 2.3: Kinetic Energy of air passing through rotor per unit time	33
Figure 2.4: Energy balance within the kinetic Energy of air that passes through rotor per unit time	34
Figure 2.5: Flow chart of Borne’s algorithm for identification of sea-breeze days.....	41
Figure 3.1: Model domain showing the three nested grids. The small rectangle in the centre shows the wind farm.	46
Figure 3.2: (a) Wind farm layouts for case I, case II and case III with inter-turbine distance of 0.5 km, 1 km and 2 km where the red dots represent the wind turbines. (b) Power curve (blue), power coefficient (green) and thrust coefficient (red) of 3.075 MW Vestas turbine as a function of wind speeds. The horizontal bar represents the wind speed ranges during 3 cases (A, B and C) simulated.....	48
Figure 3.3: Scatter plot of (a) wind speed (WS), ms^{-1} and (b) wind direction, degree observed by ASCAT and simulated by WRF along with the best fit line (blue) and expected fit (red).	49

Figure 3.4: Wind speed difference (CTRL-WF) for domain size of (a) 300 km x 300 km simulation and (b) 1000 km x 1000 km simulation. The arrows represent the vector difference between the CTRL case and WF case.....50

Figure 3.5: (a) Wind rose diagrams depicting hub-height wind speeds, WS (ms^{-1}) over the wind farm area for the CTRL case, (b) averaged power (MW) generated in the WF cases for (A) January, (B) June, and (C) July with (I) 0.5 km, (II) 1 km and (III) 2 km inter- turbine spacings. In (b), the plot depicts the wind farm only.....52

Figure 3.6: Averaged difference in wind speed, ΔWS (ms^{-1}) over the rotor depth (28m-140m) (WF-CTRL) for (A) January, (B) June, and (C) July with (I) 0.5 km, (II) 1 km and (III) 2 km inter-turbine spacings. The black square depicts the wind farm. Only the statistically significant results ($p < 0.01$) are shown. White coloured regions represent areas where the wind speed differences are not statistically significant. The vectors represent the wind in the corresponding CTRL cases; every 250th vector is shown.....56

Figure 3.7: (a) Difference in horizontal wind velocity, ΔV (ms^{-1}) (WF-CTRL) and, (b) Difference in vertical wind velocity, Δw (ms^{-1}) (WF-CTRL) on a vertical cross-section along the predominant wind direction for case: (A) January, (B) June, and (C) July with (I) 0.5 km, (II) 1 km, and (III) 2 km turbine spacings. Only the statistically significant results ($p < 0.01$) are shown here. The white coloured regions represent areas where the differences are not significant. The black dashed box depicts the wind farm cross-section. The red dashed line depicts ABL height (WF case) and red solid line depicts ABL height (CTRL case). The arrows represent the predominant wind direction.....58

Figure 3.8: Difference (WF-CTRL) in vertical profiles of vertical synoptic (solid line), mesoscale (dashed dotted line), and microscale fluxes (dashed line) averaged over the wind farm for the simulation period for (A) January, (B) June and (C) July. Horizontal black dotted line shows the height of the upper tip of the wind turbine rotor.....61

Figure 4.1: (a) Vertical recovery (normalized by power) and (b) Horizontal recovery (normalized by power) for case (A) January, (B) June, and (C) July with (I) 0.5 km, (II) 1 km, and (III) 2 km turbine spacings over the wind farms. Black arrows (scaled to the magnitude of averaged wind speed) show the prevailing wind direction from the CTRL case.69

Figure 4.2: Momentum loss rate (ms^{-2}) over the wind farm71

Figure 4.3: Speed, ms^{-1} (WF) over the wind farm71

Figure 4.4: Scatter plot of vertical replenishment with (a) absolute momentum loss rate for all cases; and upwind wind speed for (b) case A-I, B-I and C-I, (c) case A-II, B-II and C-II and (d) case A-III, B-III and C-III. The solid blue line indicates the best fit and dashed blue line indicates the 99% prediction intervals. The total number of data points in Fig. 4.4a are $9 \times 50 \times 50 \times 48$ and in Fig. 4.4b–d are $3 \times 50 \times 50 \times 48$73

Figure 4.5: Scatter plot of averaged vertical recovery (at hub-height) on averaged vertical mesoscale flux of u momentum (integrated between 1000–2500 m) for case C-I. The values are averaged over the wind farm. The solid blue line shows the best-fit and the dashed blue lines show the 95% prediction intervals.74

Figure 4.6: (a–i) Relationship between vertical recovery (ms^{-2}) and Rf for all the nine cases. The recovery data is segregated for different wind speed (WS) ranges. U, N and S depicts unstable, near-neutral and stable atmospheric conditions, respectively, (j–l) same as Fig. 4.4b, c and d, but the vertical recovery (ms^{-2}) is spatially averaged over 50 km x 50 km wind farm points for each hour and data is binned as per different static stability conditions that are calculated using Rf . The total number of data points in Fig. 4.6j–l are 3×48 each.....76

Figure 4.7: Same as Fig. 4.6, but the stability classification is done using non-local lapse rate method.....77

Figure 4.8: Same as Fig. 4.1 but with horizontal TKE advection turned ‘off’.79

Figure 5.1: WRF simulation domain for identifying sea-breeze days86

Figure 5.2: Hodograph depicting wind speed (ms^{-1}) and wind direction for five sea-breeze days	88
Figure 5.3: Time series of simulated (CTRL) and observed wind speed (WS) and wind direction (WD) at 11.27 m for the five sea breeze days.....	89
Figure 5.4: WRF simulation domains showing the location of the 50 km x 50 km wind farm within domain 3. The red star shows the METAR station location at Mumbai airport.....	91
Figure 5.5: Averaged power (MW) generated in the WF cases: I, II and III. Power is averaged over 5 sea-breeze days for 1230 to 1730 IST. The black arrow represents the prevailing wind direction.	94
Figure 5.6: (a) Wind anomalies, (b) power production for case I, (c) power production for case II and (d) power production for case III for May 04, 2018 at (i) 1230 IST, (ii) 1430 IST, and (iii) 1630 IST. White color inside the wind farm depicts no power generation.	95
Figure 5.7: (a) Wind anomalies, (b) power production for case I, (c) power production for case II and (d) power production for case III for April 07, 2019 at (i) 1230 IST, (ii) 1430 IST, and (iii) 1530 IST. White color inside the wind farm depicts no power generation.	96
Figure 5.8: (a) Wind anomalies, (b) power production for case I, (c) power production for case II and (d) power production for case III for April 08, 2019 at (i) 1230 IST, (ii) 1330 IST, and (iii) 1430 IST. White color inside the wind farm depicts no power generation.	97
Figure 5.9: (a) Wind anomalies, (b) power production for case I, (c) power production for case II and (d) power production for case III for April 09, 2019 at (i) 1230 IST, (ii) 1430 IST, and (iii) 1630 IST. White color inside the wind farm depicts no power generation.	98
Figure 5.10: (a) Wind anomalies, (b) power production for case I, (c) power production for case II and (d) power production for case III for April 21, 2019 at (i) 1230 IST, (ii) 1330 IST, and (iii) 1430 IST. White color inside the wind farm depicts no power generation.....	99

Figure 5.11: Difference (WF-CTRL) in (a) horizontal wind velocities, ΔV (ms^{-1}) and, (b) vertical wind velocity, Δw (ms^{-1}) on a vertical cross-section along the predominant wind direction for (I) case: I, (II) case II, and (III) case III. Only the statistically significant differences ($p < 0.01$) are shown here. The white-colored regions represent areas where the differences are not significant. The black dashed box depicts the wind farm cross-section. The red dashed line depicts ABL height in the corresponding WF case. The black arrow represents the prevailing wind direction. Difference in wind velocities is averaged over 5 sea-breeze days for 1230 to 1730 IST..... 101

Figure 5.12: Difference (WF-CTRL) in vertical profiles of mesoscale (solid line), and microscale fluxes (-o- line) averaged over the wind farm and 5 sea-breeze days for 1230 to 1730 IST, for different cases. Horizontal black dotted line shows the height of the upper and lower tip of the wind turbine rotor. 102

Figure 5.13: (a) Vertical recovery (normalized by power) and (b) Horizontal recovery (normalized by power) for case with (I) 0.5 km, (II) 1 km, and (III) 2 km turbine spacing over the wind farms. The black arrow represents the prevailing wind direction. Vertical and horizontal recovery are averaged over 5 sea-breeze days for 1230 to 1730 IST..... 105

List of Tables

Table 3.1: Physics settings used in simulations	47
Table 3.2: Power generated (GW) by the wind farms. Wind farm efficiencies are given in parentheses.....	51
Table 3.3: Percentage occurrence of different stability conditions.....	53
Table 4.1: Momentum loss rate ($\times 10^{-3}$), ms^{-2} , vertical recovery ($\times 10^{-3}$), ms^{-2} , and horizontal recovery ($\times 10^{-3}$), ms^{-2} averaged over the wind farm and the simulation period. The numbers in the parenthesis give the percentage recovery with respect to the corresponding momentum loss rate.....	70
Table 4.2: Approximate momentum loss rate ($\times 10^{-6}$, s^{-2}) calculations, $\sim N_t C_T V^2$ (N_t (m^{-2}), C_T , V (ms^{-1})).....	71
Table 4.3: Change (TKE advection ‘off’ – TKE advection ‘on’) in vertical recovery ($\times 10^{-3}$), ms^{-2} and horizontal recovery ($\times 10^{-3}$), ms^{-2} , averaged over the 50 km x 50 km wind farm, the 48 hr simulation period and case A, B & C. The numbers in the parenthesis give the percentage change in recovery with respect to the corresponding momentum loss rate. * denotes that the numbers are significant at $p < 0.01$	78
Table 5.1: Physics settings used in WRF simulations	86
Table 5.2: Wind farm layout characteristics	90
Table 5.3: Power generation (MW) and efficiency (%) in wind farm for different cases. Power and efficiency are averaged over 5 sea-breeze days for 1230 to 1730 IST.	93
Table 5.4: Momentum loss rate ($\times 10^{-3}$), ms^{-2} , vertical recovery ($\times 10^{-3}$), ms^{-2} , and horizontal recovery ($\times 10^{-3}$), ms^{-2} averaged over the wind farm and sea breeze hours. The numbers in the parenthesis give the percentage recovery with respect to the corresponding momentum loss rate.....	104

List of Abbreviations

ABL	Atmospheric Boundary Layer
AEP	Annual Energy Production
ASCAT	Advanced Scatterometer
BEM	Blade-Element Momentum
CASES-99	Cooperative Atmosphere-Surface Exchange Study 1999
CTRL	Control
EWP	Explicit Wake Parameterization
FINO	Forschungsplattformen in Nord- und Ostsee (German) / Research platforms in the North and Baltic Seas (English)
GWEC	Global Wind Energy Council
HAWT	Horizontal Axis Wind Turbine
INCOIS	Indian National Centre for Ocean Information Services
IRENA	International Renewable Energy Agency
KE	Kinetic Energy
LES	Large Eddy Simulations
LLJ	Low-Level Jet
MATLAB	Matrix Laboratory
METAR	Meteorological Terminal Aviation Routine Weather Report
MKE	Mean Kinetic Energy
MYNN	Mellor–Yamada–Nakanishi–Niino
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
PDE	Partial Differential Equations
RAMS	Regional Atmospheric Modeling System
RANS	Reynolds Averaged Navier-Stokes'
RKE	Resolved Kinetic Energy
RRTMG	Rapid Radiative Transfer Model for General Circulations
SST	Sea Surface Temperature

TKE	Turbulent Kinetic Energy
WF	Wind Farm
WRF	Weather, Research and Forecasting
WS	Wind Speed