# Sea Level Rise due to Climate Change and Its Impact along the Coast of Mumbai

### **DECLARATION**

I hereby declare that the content embodied in the PhD thesis entitled "Sea Level Rise due to Climate Change and Its Impact along the Coast of Mumbai" is the result of research work carried out by me in the Department of Civil Engineering, The Assam Royal Global University, Guwahati, India under the supervision of Dr. Arnab Sarma. Dr. A.R. Kambekar of Civil Engineering Department of Sardar Patel College of Engineering under University of Mumbai was my Co-guide.

In keeping with the general practice of reporting research observations, due acknowledgements have been made wherever the work described is based on the findings of other researchers.

Further, I declare that this thesis as a whole or any part thereof has not been submitted to any University (or Institute) for the award of any degree / diploma.

(SUDIPTA CHAKRABORTY)
Registration No. 1190004

Roll No. 197021002 (2019-20)

Date: 28.03.2024 Place: Guwahati

#### Dedicated

To my heavenly

'Mom and Dad',

whose sacrifices only made me what I am today, from whom only I learnt how to tide over the ripple of my life.

# CERTIFICATE FROM THE SUPERVISORS

This is to certify that the work presented in the thesis entitled "Sea Level Rise due to Climate Change and Its Impact along the Coast of Mumbai" by Sudipta Chakraborty, submitted to the Assam Royal Global University for the award of the degree of Doctor of Philosophy in Civil Engineering, is a record of the results obtained from the research work carried under our supervision.

This thesis conforms to the template and stipulated guidelines of The Assam Royal Global University, has been checked for content plagiarism with the available literature, using the URKUND software. As per the report No. D127530736 dated 10-02-2022 generated through the software, the thesis conforms to the standard of plagiarism stipulated in the PhD guidelines of The Assam Royal Global University and has a plagiarism index of 1 %.excluding the bibliography. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Signature of the Supervisor

Royal School of Engineering & Technology

The Assam Royal Global University

Guwahati

Simplifier of the Co-Supervisor

ANDHERI S

Or A. Q. Kurblekr.



(Under Section 2(f) of UGC Act 1956)

#### **NOTIFICATION**

The under mentioned candidate is declared to have qualified for the award of the degree of *Doctor of Philosophy* (Ph.D) on 28<sup>th</sup> March, 2024 from The Assam Royal Global University for the thesis submitted by him on the title noted against his name. The award of degree of *Doctor of Philosophy* is subject to ratification by the Standing Committee of University Research Council and Academic Council of The Assam Royal Global University.

The degree will be conferred to him/her at the next convocation of the University. The particulars of the candidates are as follows: -

| Sl. | Name        | Department    | Ph.D         | Title of the Thesis       | Supervisor  | Co-supervisor |
|-----|-------------|---------------|--------------|---------------------------|-------------|---------------|
| No. |             |               | Registration |                           |             |               |
|     |             |               | No. & Date   | 1 200                     |             |               |
|     | Sudipta     | Department of |              | "Sea Level Rise Due to    |             |               |
|     | Chakraborty | Civil         | 22/08/2019   | Climate Change and Its    | Arnab Sarma | Kambekar      |
| 1   |             | Engineering   |              | Impact along the Coast of |             |               |
|     |             |               |              | Mumbai"                   |             |               |
|     |             |               |              |                           |             |               |

(Dr. Diganta Munshi) Registrar

Date: 30.03.2024

No. RGU/Ph.D/2024/07

Copy forwarded for information:

1. All Registrars of Indian Universities.

- 2. The Secretary, Ministry of Education, Govt. of India, New Delhi
- 3. The Secretary, University Grants Commission, Bahadurshah Zafar marg, New Delhi-110002
- 4. The Secretary General, Association of Indian Universities, AIU House, Kotla Marg, New Delhi
- 5. The Secretary to the Govt. of Assam, Department of Education, Assam
- 6. The DPI (Higher Education), Assam, Kahilipara, Guwahati- 781006
- 7. Deans of Schools, The Assam Royal Global University
- 8. Heads of Schools, The Assam Royal Global University
- 9. Controller of Examinations, The Assam Royal Global University
- 10. Director, IQAC, The Assam Royal Global University
- 11. Ph.D Cell, The Assam Royal Global University
- 12. Academic Section, The Assam Royal Global University
- 13. Personal Secretary to VC, The Assam Royal Global University, for VC's kind information
- 14. Concerned Supervisor and Co-Supervisor
- 15. Concerned candidate
- 16. The Librarian, The Assam Royal Global University
- 17. All India Radio/Doordarshan Kendra, Guwahati, with a request to broadcast the matter in local news bulletin.
- 18. Guard File

#### Acknowledgements

It is indeed my pleasant duty to express my deep sense of gratitude and hearty thanks to my supervisor, Prof. (Dr.) Arnab Sarma, Head, Department of Civil Engineering, Royal School of Engineering and Technology, The Assam Royal Global University, Guwahati for sowing the seed of the quest on the contemporary subject of research to my mind which triggered the neurons of my brain. I am grateful for his constant support and encouragement with all-out help throughout the process of my research work since inception.

I would also like to express my hearty thanks and sense of gratitude to Prof. (Dr.) A.R. Kambekar, Associate Professor, Civil Engineering Department, Sardar Patel College of Engineering, Mumbai University, my Co-Guide, who in spite of his busy academic schedule, suggested me the technical clues and reference literature, which helped me to reach my goal and complete my research. Their continuous help and kind suggestions were key sources of motivation for me.

I also convey my sincere gratitude to Danish Hydraulic Institute authorities at Copenhagen, Denmark including to their Technical Director Dr. Tirumaleswara Reddy Nemalidinne at New Delhi, who granted a student license free of charges for a period of one year allowing to use MIKE 21 HD FM SW, the world renowned most versatile state of the art tool for coastal modelling, without which my research work would not have been completed. I also thank Mr. James Ebenezer Samuel, Assistant Manager, DHI, Guwahati who coordinated with their Principal Office at Copenhagen, Denmark regarding the entire process of installation of the software and helped me whenever required.

During the process of research, I interacted with a number of scientists in the professional field to address my doubts and queries for understanding the complex subject of Climate Change and resulting Sea Level Rise. I am grateful to all of them for their support. To mention a few names here, the list includes (i) Dr. Rajasree BharathanRadhamma, Project Research Scientist, Ocean Engineering Department, Indian Institute of Technology Bombay, (ii) Dr. Ruchi Kalra, Principal Numerical Modeler, Hatch Marine Consultants, Thiruvananthapuram, (iii) Dr. Karan Gupta,

Department of Civil Engineering, Indian Institute of Technology, Delhi, (iv)

Dr.(Smt.) Swapna Panickal, Scientist, Indian Institute of Tropical Meteorology,

Pune, (vi) Dr. Roxy Mathew Koll, Scientist, Indian Institute of Tropical Meteorology,

Pune and (vii) Ms. Prativa Singh, Alumnus of Sardar Patel College of Engineering,

Mumbai et. al. were truly supportive towards my Work and I remain grateful to all of

them. My special thanks go to Dr. Vikrant Vishal, a Young Scientist from Danish

Hydraulic Institute, Guwahati who helped me to run the MIKE 21 tool.

I also owe to all my friends and colleagues, who have directly or indirectly

encouraged me continuously and appreciated my keenness to arrive at the goal and

one of them Mr. Arun Chakraborty, my ex-colleague from Haldia Port deserves

special mention for encouraging me for the research. These encouragements have

facilitated me to sustain my academic motivation unimpeded.

Also, I acknowledge with profound regards, the encouragement received

from my first boss in service life, Mr. Madan Gopal Bhowmik, former Chief

Engineer, National Highways wing of PWD, Govt. Of WB.

Last but not the least; I should be failing in my duties if I do not mention

about the co-operation with stimulus and inspiration, I received from my spouse

Mahuya and daughter Ananya, during the period of my research work.

Above all I am sure that my parents from their heavenly abode must have

been showering their affectionate blessings without which I would have never been

able to come to this juncture of life and carry out the research on a topic of Global

Concern.

SUDIPTA CHAKRABORTY

Research Scholar

Department of Civil Engineering,

Roll No. 197021002 (2019-20)

#### **Plagiarism Checking Report**





#### **Document Information**

Analyzed document PhDCivilRGU.docx (D127530736)

**Submitted** 2022-02-10T10:06:00.0000000

**Submitted by** Royal Global University

Submitter email centrallibrary@rgu.ac

Similarity 1%

Analysis address centrallibrary.rgu@analysis.urkund.com

## **List Of Figures**

| Figure No. Chapter II |   | Page No |  |
|-----------------------|---|---------|--|
| Figure 2.1            | Sea level reconstruction from past 150,000 years till present time                              | 12      |  |
| Figure 2.2            | Global mean sea level (1870-2006)   | 13      |  |
| Figure 2.3 a          | Oxygen-18 isotope signals   | 15      |  |
| Figure 2.3 b          | Oxygen-18 isotope record  | 15      |  |
| Figure 2. 4           | Flood extent map for the 2005 event   | 21      |  |
| Figure 2. 5           | Ranking of coastal cities as per FVI for different scenarios                                    | 22      |  |
| Figure 2.6            | Island and coastal regions vulnerable to coastal flooding                                       | 23      |  |
| Figure 2.7            | Shifting of shoreline inside the coast  | 24      |  |
| Figure 2. 8           | Waves Diverted & Refracted from Sri Lanka   | 26      |  |
| Figure 2. 9           | Coast of Karnataka  | 27      |  |
| Figure 2.10           | Shoreline positions (during 1910-2008), Transects and littoral cells                            | 28      |  |
| Figure 2.11           | Area Inundation Map for 1M & 2M Sea Level Rise  | 29      |  |
| Figure2.12            | Geographical Locations of Tide<br>Gauges  | 30      |  |
| Figure 2. 13          | Annual mean sea-level anomalies at (a)Mumbai, (b)Kochi, (c)Visakhapatnam and d) DiamondHarbour. | 31      |  |
| Figure 2. 14          | Study Area at Surat, Navsari and Valsad   | 32      |  |

| Figure 2. 15 | Changes in Shoreline from (i)1990-<br>2001 (ii) 2001-2014 and (iii) 1990–<br>2014      | 32 |
|--------------|--|----|
| Figure 16    | Location Map   | 33 |
| Figure 2. 17 | Annual rates in change future shoreline - output from the numerical and ANN, compared  | 34 |
| Figure 2. 18 | The study locations (AS; BOB; EEIO; WEIO; SOUTHIO; THERMO)                             | 35 |
| Figure 2.19  | The Site-1 and Site-2 of the study   | 36 |
| Figure 2. 20 | Area of Inundation Map for SLR of 1 m, 2 m and 3 m                                     | 36 |
| Figure 2.21  | Locations of study   | 37 |
| Figure 2.22  | Shoreline changes along Udipi, New Mangalore Port and Gangavali River                  | 40 |
| Figure 2. 23 | Location Map – Maharashtra   | 42 |
| Figure 2. 24 | Location of tide gauges at Indian Ocean  | 42 |
| Figure 2. 25 | Exposed Rebar in Deck Slab, Piers and RC Fenders                                       | 44 |
| Figure 2.26  | CVI Ranks for (a) Gangavali estuary; (b)<br>Udupi coast; and (c) New Mangalore<br>Port | 45 |
| Figure 2.27  | Mass balance of the polar ice sheets—<br>Copernicus Climate Change Service             | 48 |
| Figure 2. 28 | Summary characteristics of the four SRES storylines IPCC                               | 54 |
| Figure 2. 29 | Global GHG Emissions Scenario  | 55 |
| Figure 2.30  | RCPs at IPCC Climate Change<br>Scenario  | 58 |
| Figure 2.31  | Warming Situation in differentRCPs   | 60 |
| Figure 2.32  | Comparison of SRES & RCP / AR4 vs<br>AR5 SRES  | 62 |
| Figure 2.33  | Changes in mean temperature CMIP5 model ensemble                                       | 63 |

| Figure 3.3   | Map showing Topography in the study area  | 84      |
|--------------|---|---------|
| Figure No.   | Chapter III   | Page No |
| Figure 3.2   | Gateway of India (Between Pali<br>to Sasane)  | 79      |
| Figure 3.1   | Indian Coast  | 77      |
| Figure No.   | Chapter III   | Page No |
| Figure2.42   | Brun's rule regarding shore shifting for SLR  | 75      |
| Figure2. 41  | Sea Level Rise Trend in Indian<br>Ocean   | 74      |
| Figure 2.40  | RSLR rate at different places in India  | 74      |
| Figure2.39   | Rising Trend in Mumbai<br>as per NOAA   | 72      |
| Figure 2.38  | Rising Trend at India vs. Global<br>Trend as per NOAA   | 70      |
| Figure 2.37  | Projected global temperature rise<br>by 2100 as per Paris Agreement                                     | 67      |
| Figure 2. 36 | SLR at Mumbai in different RCPs   | 67      |
| Figure 2. 35 | Temperature and precipitation<br>for the period 1971-2000,<br>Compared through CMIP5 model<br>for India | 65      |
| Figure 2. 34 | change distribution under different RCPs at India 2070-2099 relative to 1861-1900                       | 04      |

| Figure 3.4  | Map showing bathymetry in the study area                        | 85      |
|-------------|---|---------|
| Figure 3.5  | Combined map of topography and bathymetry data                  | 86      |
| Figure 3.6  | Map showing the coastline of the study area                     | 87      |
| Figure 3.7  | Mesh generated in MIKE Zero with detail of the study area       | 88      |
| Figure 3.8  | Mesh with model boundaries highlighted in red                   | 89      |
| Figure 3.9  | Flood Hazard Classification                                     | 90      |
| Figure No.  | CHAPTER IV  | Page No |
| Figure 4.1  | Point of study (Gateway of India)                               | 99      |
| Figure 4.2  | Tidal water level variation in lowest<br>Tide from 2020 to 2050 | 100     |
| Figure 4.3  | Tidal water level variation in HWL from 2020 to 2050            | 100     |
| Figure.4.4: | Maximum water depth (m) inundation in 2020                      | 101     |
| Figure 4.5  | Maximum water depth (m) inundation in 2050                      | 101     |
| Figure 4.6: | SLR Data- Scenario vis-a-vis<br>Methods                         | 103     |
| Figure 4.7  | Base Sea Water Level at Gateway of India (base model) 2020      | 104     |
| Figure 4.8  | Raised Sea Water Level at<br>Gateway of India 2050              | 105     |

| Figure No.           | CHAPTER IV   | Page No |
|----------------------|--|---------|
| Figure 4.9           | Sea Water level at the Gateway of India in 2050                        | 105     |
| Figure 4.10 (a to f) | Sea level inundation maps from Mike 2020-2050                          | 106     |
| Figure 4.10 g        | Sea level inundation maps from Mike 2050                               | 107     |
| Figure 4.11          | Relation between SLR and Sinking of Land Mass in Coastal Cities        | 110     |
| Figure 4.12          | Displacement analysis over Mumbai city                                 | 111     |
| Figure 4.13          | Original configuration of Mumbai                                       | 94      |
| Figure 4.14          | Relative SLR in 2050 (Climate central)                                 | 120     |
| Figure 4.15          | Probable intrusion of Sea Level inside Shore against Rise in Sea Level | 123     |
| Figure 4.16          | CO <sub>2</sub> concentrations in different<br>SSPs across the century | 126     |
| Figure 4.17          | Projection from NASA Sea Level<br>Tool                                 | 127     |
| Figure 4.18          | Projection from CoFu Tool  | 128     |
| Figure 4.19          | Impressive Inundation MAP<br>Due to Climate Change<br>Only (2050)      | 132     |
| Figure No.           | APPENDIX -I  | Page No |
| Figure 1             | Maximum water depth (m) inundation in 2021                             | 2       |
| Figure 2             | : Maximum water depth (m)<br>inundation in 2022                        | 2       |
| Figure 3             | : Maximum water depth (m)<br>inundation in 2023                        | 2       |
| Figure 4             | : Maximum water depth (m)  | 2       |

|          | inundation in 2024        |   |
|----------|---------------------------|---|
| Figure 5 | : Maximum water depth (m) | 3 |
|          | inundation in 2025        |   |

| Figure No. | APPENDIX -I                                  | Page No |
|------------|--|---------|
| Figure 6   | : Maximum water depth (m) inundation in 2026 | 3       |
| Figure 7   | : Maximum water depth (m) inundation in 2027 | 3       |
| Figure 8   | : Maximum water depth (m) inundation in 2028 | 3       |
| Figure 9   | : Maximum water depth (m) inundation in 2029 | 4       |
| Figure 10  | : Maximum water depth (m) inundation in 2030 | 4       |
| Figure 11  | : Maximum water depth (m) inundation in 2031 | 4       |
| Figure 12  | : Maximum water depth (m) inundation in 2032 | 4       |
| Figure 13  | : Maximum water depth (m) inundation in 2033 | 5       |
| Figure 14  | : Maximum water depth (m) inundation in 2034 | 5       |
| Figure 15  | : Maximum water depth (m) inundation in 2035 | 5       |
| Figure 16  | : Maximum water depth (m) inundation in 2036 | 5       |
| Figure 17  | Maximum water depth (m) inundation in 2037   | 6       |
| Figure18   | Maximum water depth (m)inundation in 2038    | 6       |
| Figure19   | Maximum water depth (m)inundation in 2039    | 6       |
| Figure 20  | Maximum water depth (m)inundation in 2040    | 6       |
| Figure 21  | Maximum water depth (m)inundation in 2041    | 7       |
| Figure 22  | Maximum water depth (m)inundation in 2042    | 7       |
| Figure 23  | Maximum water depth (m)inundation in 2043    | 7       |
| Figure 24  | Maximum water depth (m)inundation in 2044    | 7       |

| Figure 25 | Maximum water depth (m)inundation in 2045 | 8 |
|-----------|---|---|
| Figure 26 | Maximum water depth (m)inundation in 2046 | 8 |
| Figure 27 | Maximum water depth (m)inundation in 2047 | 8 |
| Figure 28 | Maximum water depth (m)inundation in 2048 | 8 |
| Figure 28 | Maximum water depth (m)inundation in 2049 | 9 |
| Figure 28 | Maximum water depth (m)inundation in 2050 | 9 |

#### III RELATED SCREENSHOTS FROM MIKE OUTPUT...... 9

| METHODS             | Page No |
|---------------------|---------|
| IPCC AR4 SRA1B      | 10      |
| IPCC AR4 SRA2       | 10      |
| IPCC AR4 SRB1       | 11      |
| GRINSTED 2009 SRA1B | 11      |
| GRINSTED 2009 SRA2  | 12      |
| GRINSTED 2009 SRB1  | 12      |
| HORTON 2008 SRA1B   | 13      |
| HORTON 2008 SRA2    | 13      |
| HORTON 2008 SRB1    | 14      |
| VERMEER 2009 SRA1B  | 14      |
| VERMEER 2009 SRA2   | 15      |
| VERMEER 2009 SRB1   | 15      |

#### **List Of Tables**

| Table No. | Chapter II   | Page No |
|-----------|--|---------|
| Table 2.1 | Summary of literature cited by this author for the present study | 17      |
| Table 2.2 | Radiative forcing and CO2 as per RCPs of IPCC AR5                | 56      |
| Table 2.3 | RCP scenarios  | 56      |
| Table 2.4 | Warming vs SLR in different RCPs                                 | 59      |
| Table 2.5 | Scenario-wise Global Mean Warming [Present & Future]             | 69      |
| Table No. | Chapter III  | Page No |
| Table 3.1 | Climate change scenarios   | 92      |
| Table No. | Chapter IV   | Page No |
| Table 4.1 | Prediction of Rise in Sea Water Level by 2050 (From Software)    | 102     |
| Table 4.2 | Maximum water level at the Gateway of India                      | 105     |
| Table 4.3 | Effective Sea Level Rise from 2020 to 2050                       | 107     |
| Table 4.4 | Chart Datum vs. Mean Sea Level                                   | 115     |
| Table 4.5 | SSP x- y. z  | 125     |