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Climate change induced sea-level rise projections for the Pichavaram mangrove region of the Tamil Nadu coast, India: A way forward for framing time-based adaptation strategies

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Climate change induced sea-level rise poses serious threats to valuable coastal ecosystems like mangroves. However, projections of sea level rise at local level under different scenarios and for different time scale set forth greatest challenges to climate modelers. Further, information on location specific sea-level rise projections at local level are seldom available and rarely in the possession for the coastal managers and adaptation planners to frame suitable adaptation strategies to sea-level rise. In this context, this paper endeavors to provide local level sea-level rise projection for the Pichavaram mangrove region of the Tamil Nadu coast, India. A climate simulator model based on IPCC AR4 (Special Report on Emission Scenarios) has been used to project the sea-level rise at local level under different scenarios. The results revealed that the study area may experience sea-level rise ranging from 22.40 to 53.70 cm by 2100. Thus, the objective of this paper is to provide hands on information to facilitate coastal manager and adaptation planners to frame location specific and time based mangrove adaptation strategies to sea-level rise.

[**Keywords:** Climate change, Sea Level Rise, Projections, Mangroves, Adaptation, Policies]

Introduction

Global sea-level rise (SLR) is one of the more certain outcomes of global warming and about 10-20 cm rise occurred during the last century, and several climate models project an accelerated rate of SLR over coming decades[1,2,3,4,5]. In order to predict the climate (SLR) of the 21st century and beyond, it is necessary to estimate future changes[6]. Climate model simulations are commonly undertaken to estimate the magnitude and rate of sea-level change resulting from global warming related factors. In this context, to address the uncertainty associated with climate system dynamics and future green house gas (GHG) emissions, Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change – Assessment Report 4 (IPCC AR4) has developed a range of 'alternative' futures (scenarios) related to how varying socio-economic and technological factors may influence future emissions and climate change. They are classified broadly as A1, B1, A2 and B2 scenario families. The four scenario families describe future worlds that may be global economic (A1), [A1 family is further classified into three groups characterizing alternative developments of energy technologies, viz., A1FI (fossil intensive), A1T (predominantly non-fossil)]; A1B (balanced across energy sources)], global environmental (B1), regional economic (A2) and regional environmental (B2)[7,8].

IPCC AR4 projected a global SLR of 18 to 59 cm from 1990 to the 2090s[9].These ranges are narrower than in the IPCC- Third Assessment Report (TAR), mainly because of improved information about some uncertainties in the projected contributions[10].Whereas, IPCC AR5(Assessment Report 5) report following Representative Concentration Pathways (RCPs) states that the global mean SLR for 2081–2100 relative to 1986–2005 will likely be in the ranges of 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5[11].

On the other hand, scientists also predict that the rise of mean sea level has an immediate and direct effect on ecosystems of the intertidal zone with the decline in influence of the intertidal process at all locations, and increase in influence of marine processes[12]. Thus, stresses associated with a rise in the relative mean sea level, together with an increase in the frequency and level of extreme high water events, and other effects from climate change present threats to coastal ecosystems like mangrove ecosystem as well[13]. SLR poses a major threat to mangrove ecosystems through sediment erosion, inundation stress and increased salinity at landward zones. These problems will be exacerbated for mangrove stands that are subjected to 'coastal squeeze', i.e. where landward migration is restricted by topography or human developments[14]. However, adaptation measures can offset anticipated mangrove losses and improve resistance and resilience to climate change. In specific, coastal planning can adapt to facilitate mangrove migration with SLR[15]. But, coastal managers, adaptation planners and policy makers face major challenges to frame suitable coastal adaptation strategies to SLR without having reliable scientific information on the SLR projection on hand. Very importantly, modeling future projection of climate (SLR) will provide valuable input to climate change adaptation planning and implementation[16].

Although there is deepening in understanding of SLR trends, there still remains uncertainty around the rate and timing of SLR[17]. Coastal managers, adaptation planners and policy makers may require relevant scientific information on the SLR projection at local level viz., how much will the sea- level rise? when will it rise? . The answers to these questions will greatly help planners to frame location specific and time based adaptation strategies for coastal ecosystems, in particular mangrove ecosystem to rising sea level. In some cases sea level change scenarios are used as planning targets and the scenario chosen should be relevant to the time-scale of decisions being made[18]. Unfortunately, the comprehensive range of this type of information at local level typically required is seldom available and rarely in the possession of decision makers responsible for management within the coastal zon [19, 20]. In this context, the objective of the present study is to provide sea level changes at different SRES scenarios of IPCC (Intergovernmental Panel on Climate Change) for different time scale at local level for the chosen study area of high ecological importance i.e. the Pichavaram mangrove region of the Tamil Nadu coast, India.

Study Area

All the mangrove formations in Tamil Nadu occur along the east coast, at the confluence points of major and minor rivers with the Bay of Bengal of Indian Ocean. The present study area i.e. the Pichavaram mangroves region lies between 79^0 45' to 79^0 50'E longitudes and 11^0 20' to 11^0 30' N latitudes at the Cuddalore District of Tamil Nadu, India (Fig.1). It is located between the Vellar river in the North and the Coleroon river in the South and Uppanar river in the west. The Vellar estuary is dominated by mud flats, while Coleroon estuary part is largely dominated by mangroves[21]. It communicates with the sea by a shallow passage, which is only opening in the sandy littoral sand[22]. The Pichavaram mangrove forest consists of three reserve forests (RFs), namely, Killai RF, Pichavaram RF and Pichavaram extension area. Thus, the total area of the Pichavaram Mangrove Forest is 1358 ha[23]. The tides of the study area are semi-diurnal and vary in amplitude from about 15-100 cm in different regions during different seasons, reaching a maximum during monsoon and post-monsoon and a minimum during the summer[24,25,26]. The Mean Sea Level (MSL) at Killai railway station of the study area is noted as 3.05 m concerning the revised local reference datum of tide gauge at Cuddalore port however this may not be applicable to entire study area[26].

Methodology

AR4 reports of IPCC climate change stated that the projection of future climate change including SLR is based on a hierarchy of models, ranging from Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth System Models of Intermediate Complexity (EMICs) to Simple Climate Models (SCMs). These models are forced with concentrations of GHG and other constituents derived from various emissions scenarios ranging from non-mitigation scenarios to idealized long-term scenarios[10]. The present study has used the climate modeling software called "Climate Simulator" from climsystems which is primarily based on pattern scaling method[27,28,29]. It involves the scaling of "standardized" (or normalized), spatial patterns of climate change from very complex, computationally demanding 3-D global climate models (GCMs) with the time dependent projections of global mean climate change from simpler models.

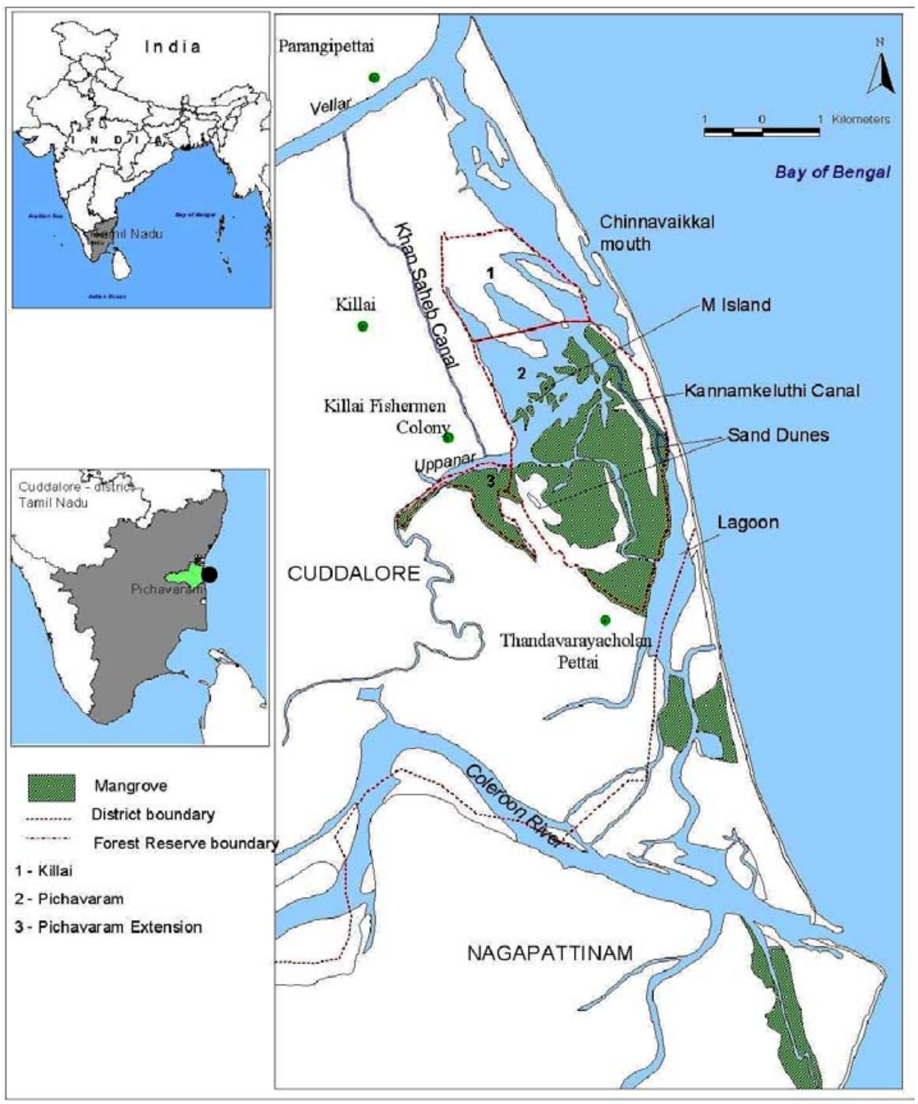

Fig. 1-Study area-Pichavaram mangrove region, Cuddalore District, Tamil Nadu Coast, India.

The global SLR projection is processed from "scenario generator" of climate simulator as forced by the six key SRES (Special Report on Emission Scenarios) GHG emission scenarios used by IPCC AR4. However, local SLR projections for the selected study area i.e. the Pichavaram mangrove location of the Tamil Nadu coast corresponding to the Bay of Bengal region of the Indian Ocean (Long $80^{0}50$ E'; Lat $11^{0}50$' N) is obtained by using multi-model ensemble based on different global circulation model constructed within the climate simulator. The mean sea level trend of the nearest Chennai tide gauge station has been noted as 0.27 mm yr^{-1} and used as a reference datum to project future sea level change for the chosen study area. Sea level changes are projected as high, medium (mid) and low projections for the six SRES scenarios (A1B, A1FI, A1T, A2, B1, B2) which are consistent with the values given in IPCC AR4[30] to meet the uncertainties of different GCM used. Total trend (i.e. the total observed, the undifferentiated trend of observed relative sea level change, which includes GHG-related effects) is selected for the simulation of SLR projection for the given study area convenience of this study the SLR projection of the Pichavaram mangrove region has been projected for 2025, 2050, 2075, 2100. Vertical land movement (VLM) component (subsidence or uplift) together with a variety of other local factors are not taken into consideration owing to objective of this paper to project only climate change induced SLR. However, including vertical land movement component together with projected climate change induced SLR may further accelerate the projection of SLR.

Results

The future projections of total trend of SLR for both global and local level for different SRES scenarios viz., A1B, A1FI, A1T, A2, B1, B2 for the present study together with low, mid and high projections are given in Table 1 and Table 2. For the convenience of understanding and to give an overview of SLR projection for the chosen study area, only three major scenarios namely: *B1 Scenario (Global environmental)*, *A1B Scenario (Balanced across energy sources*) and *A1FI Scenario (Fossil Intensive*), are discussed below.

Global SLR Projections:

For *B1 Scenario (Global environmental):* The global projection of total SLR for the year 2100 is estimated as 18.74cm (low), 29.33cm (medium) and 39.92 (high). Similarly, for *AIB Scenario* (*Balanced across energy sources*): the global projection of total SLR for the year 2100 is estimated as 22.05 cm (low); 36.53 cm (medium) and 51cm (high), respectively. Likewise, for *A1FI Scenario (Fossil Intensive)* : the global projection of total SLR for the year 2100 is estimated as 27.51 cm (low), 45.73 cm (medium) and 63.95 (high), respectively. Whereas, global projections of total SLR for the year 2025, 2050, 2075 and 2100 with respect to all scenarios (SRES) are given in the Table 1.

Local SLR Projections (Pichavaram Mangrove Region):

For *B1 Scenario (Global environmental):* The local projection of total SLR for the year 2100 is estimated as 2.33 cm (low), 12.65 cm (medium) and 25.16 cm (high) (Fig.2) . Similarly, for AIB Scenario (*Balanced across energy* sources): the local projection of total SLR for the year 2100 is estimated as 5.41 cm (low);

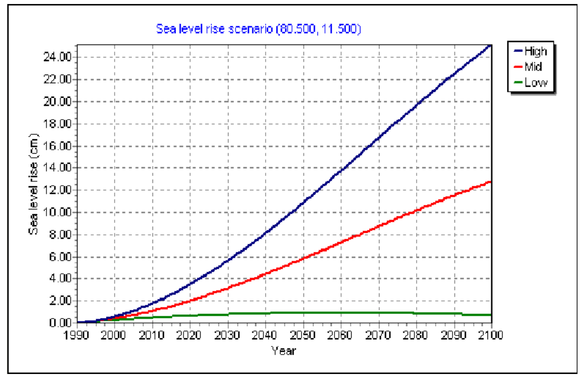

Fig. 2-IPCC AR4-B1 scenario based SLR projection for Long $80^0 50'$ E; Lat $11^0 50'$ N.

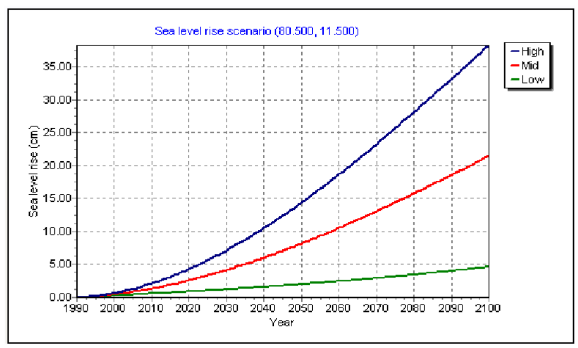

Fig. 3-IPCC AR4-A1B scenario based SLR projection for Long $80^0 50'$ E; Lat $11^0 50'$ N.

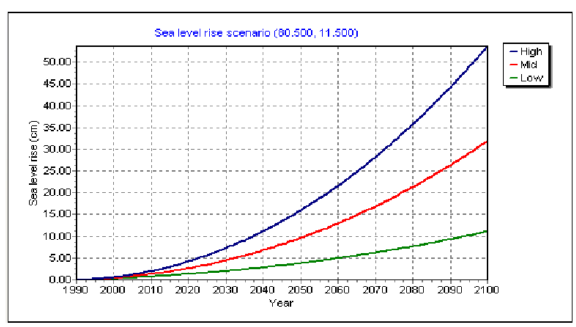

Fig. 4-IPCC AR4-A1FI scenario based SLR projection for Long $80^0 50'$ E; Lat $11^0 50'$ N.

Table 1 - Global SLR estimate (cm) based on IPCC AR4 and 1990 as a baseline.

	A1B			A1FI			A1T			A2			B1			B2		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
2025	6.61	8.59	10.58	7.21	8.88	10.55	6.66	8.74	10.81	6.43	7.92	9.41	6.30	7.96	9.62	6.35	7.97	9.59
2050	11.63	16.95	22.28	13.34	18.43	23.51	11.61	16.99	22.37	11.52	15.97	20.42	10.70	15.00	19.30	11.03	15.43	19.83
2075	16.81	26.47	36.13	20.15	30.69	41.24	16.43	25.77	35.12	17.44	26.50	35.57	14.88	22.36	29.83	15.90	24.02	32.13
2100	22.05	36.53	51.00	27.51	45.73	63.95	20.84	34.07	47.31	24.53	39.94	55.35	18.74	29.33	39.92	21.06	33.44	45.82

Table 2 - Local SLR estimate (cm) based on IPCC AR4 and 1990 as a baseline for the Pichavaram mangrove region.

	A1B			A1FI			A1T			A2			B1			B2		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
2025	1.32	3.29	5.66	1.92	3.52	5.68	1.37	3.46	5.95	1.19	2.53	4.27	1.03	2.59	4.53	1.07	2.61	4.47
2050	2.60	7.98	14.42	4.27	9.45	16.00	2.58	8.03	14.57	2.56	6.87	12.23	1.72	5.83	10.89	2.03	6.32	11.47
2075	4.01	13.94	25.71	7.20	18.35	31.91	3.66	13.19	24.56	4.68	13.93	25.11	2.21	9.42	18.23	3.15	11.26	20.92
2100	5.41	20.56	38.30	10.53	30.37	53.70	4.29	17.88	33.97	7.79	24.28	43.62	2.33	12.65	25.16	4.49	17.19	32.16

20.56 cm (medium) and 38.30 (high) (Fig.3), respectively. *A1FI Scenario (Fossil Intensive)* : the local projection of total SLR for the year 2100 is estimated as 10.53 cm (low), 30.37 cm (medium) and 53.70 (high) (Fig.4), respectively. Whereas, local projections of total SLR for the year 2025, 2050, 2075 and 2100 with respect to all scenarios (SRES) are given in the Table 2.

Validation:

To meet the uncertainty of model estimates with different extreme estimates i.e. low and high projections, only the medium projection alone is taken into consideration. The validation of the medium projected estimates is done based on the performance of the multi-model ensemble of different GCMs, arranged hierarchically according to the normalized GCMs values by pattern scaling method. It has been observed that the medium estimated projections of all SRES scenarios are based on the ukm_hadcm3 model (United Kingdom Met Office_Hadley centre coupled model version 3) from Hadley Centre for Climate Prediction and Research, Met Office, U.K, and it best suits for the chosen study area viz. the Pichavaram mangrove region.

Discussion

In its AR4 report, the IPCC has projected a global SLR of 18 to 59 cm from 1990 to the 2090s, plus an unspecified amount that could come from changes in the large ice sheets covering Greenland and Antarctica[9], while, AR5 report estimated that the global SLR will likely be in the range of 26 to 82 cm following RCP[11]. The present study has outlined global SLR projection ranges from 18.74 to 63.95 cm for 2100 based on climate simulator modeling software. This projected range of SLR is primarily in the range of lower and upper estimates of the IPCC AR4.

Whereas, the local sea level generally differs from the global-mean, under the influence of ocean circulation together with regional variations in ocean density and atmospheric pressure. Climate model projections for the 21st century suggest that as well as global mean sea level changes, the large-scale spatial pattern are also liable to change, potentially having a significant effect on local SLR[31]. The present study has projected local SLR ranges from 2.33 to 53.70 cm for all IPCC-AR4 SRES scenarios with respect to the Pichavaram mangrove location of the Tamil Nadu coast corresponding to Bay of Bengal region of the Indian Ocean emphasizing the time period of 2025, 2050, 2075 and 2100. This is based on projections by an ensemble of current coupled climate models, run for a number of plausible BAU socio-economic scenarios, with simple climate model results used to scale to alternative scenarios[31].

Thus, the projected SLR will have a profound impact on the coastal ecosystem in general and mangrove ecosystem in particular. However, to reduce the risk of projected climate change (SLR), adaptation activities can be taken in an attempt to increase the resistance and resilience of ecosystems to climate change stressors[32,33,34,35]. Thus, it is persuasive to state that one of the effective ways to address climate change is creating adaptation mechanisms to boost resilience and the ability to cope with anticipated impacts[36,37]. However, the optimal approach to manage adaptation to mangrove responses to climate change effects will depend on the local context[13]. It is important to adapt mangrove to changing climate (SLR) at local context because, it is one of the nature's gift that stood bravely against tsunami other than then the humanitarian services in the coast[38], in particular for this study area i.e. the Pichavaram mangrove region of the Tamil coast, India. Thus, adaptation to SLR has specific relevance for local policy making because it is at the local level where the effects will play out. Nevertheless, adaptation will need to be tailored to the specific local vulnerabilities (e.g. SLR) and needs involved. Climate scientists, with a sense of urgency, have been calling for policy action on climate change adaptation, especially since the 1990s as it became clearer that impacts like SLR were unavoidable and could be significant in the coming decades[39].

Conclusion

Thus, this study is new of its kind in the Indian context, yet the need of the hour. The study has projected rise in sea level with a maximum of 53.70 cm for the Pichavaram mangrove region of the Tamil Nadu Coast based on IPCC-AR4 SRES scenarios. It urges coastal managers, adaptation planners and policy makers to frame coastal adaptation strategies in particular mangrove adaptation to SLR based on a different time scale of SLR projections till 2100. The possibility of a faster SLR needs to be considered when planning adaptation measures[40], however, incorporating sea level change in planning processes involves more than selecting a number[18]. That is why this paper advocates the scenario approach with different time scales. Unless advanced planning to deal with climate change induced SLR impacts-adaptation to climate change takes place as an ongoing and integral part of the planning process, the country is in danger of finding itself in extremely dire circumstances[41].

Limitations and Scope

The present study has only projected SLR projection for the study area. However, predicted impact of projected SLR and its vulnerability assessments are not addressed. Further, this study has emphasized the importance of time-based adaptation strategies by projecting SLR for different year till 2100 for the Pichavram mangrove location of the Bay Bengal region of Tamil Nadu coast. But, framing suitable place-based adaptation strategies of Pichavaram mangroves to changing sea level do not fit into the scope of this paper.

The present study is primarily based on IPCC-AR4 report. However, availability and easy accessibility of climate model data based on IPCC-AR5, particularly for developing countries like India in future, will open the windows of promising opportunities for modelers. This will make a new platform for climate modelers in general, SLR modelers in particular, to project SLR at local level. This will further enhance better understanding of model evolution and to provide more efficient information for coastal manager, adaptation planner and policy makers to frame time based and location specific adaptation strategies for mangroves to rising sea level. Very importantly, this paper throws a light for comparative study of local level SLR projection between IPCC AR4 and AR5.

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