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Reducing the Uncertainty of Sea-Level Rise Future Projections using Ensemble of Global Circulation Models Along the Egyptian Red Sea Coastal Zones

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Abstract Sea-level rise is one of the most critical issues facing the world as a result of global warming. Finding robust projections for coastal flooding estimates is consequently essential for the effective management of coastal regions. The future impacts of climate change remain in the realm of uncertainty. According to Inter-Governmental Panel of Climate Change (IPCC) reports, the sea level rise imposes the ultimate challenge facing most of the coastal areas, so studying the inundation of low-lying lands along the coastal zones is a very important and vital issue, especially for countries like Egypt which is exposed to climate changes in terms of sea level rise (SLR), increase in temperature and reduction of precipitations. According to the Fifth Assessment IPCC Reports, the Sea Level Rise will be around 78 cm, and by 2100 may be around 100 cm (AR5,2014); but their magnitude remains uncertain. This study provides bounds on the uncertainty of sea-level rise variability arising from future-projection sensitivity analyzes of Twenty-Eight (28) Global Circulation Models (GCMs) on an annual basis along the Egyptian Red Sea coastal zones (from Suez to Hurghada). Values are examined under the conditions of four different scenarios of representative concentration pathways (RCPs) belonging to the Fifth Assessment IPCC Reports (IPCC, AR5). The results show that there is a wide range of possible sea-level rise scenarios, with some models projecting a rise of just a few centimeters and others projecting a rise of more than a meter. Using the ensembles of the optimum GCM the uncertainty of SLR values are reduced. such results revealed that the increase in the sea level due to the ensemble of the optimum Global Circulation Models (GCMs) under each scenario; RCPs 2.6, 4.5, 6, 8.5 will be 60.5, 71, 77.7, 104.6 cm, respectively.

Keywords GCMs, RCPs, uncertainty, SLR, Red Sea

1. Introduction

The global response to the climate change phenomena has grown more concerned during the last fifty years (IPCC,2018). The fundamentals of this phenomenon have been studied by a sizable number of organizations, regional research centers, and international research institutions with the aim of figuring out how to deal with it and how to reduce its related hazards. Some countries were classified as more vulnerable to climate change and more prone to the damage it may cause, both in the short and long term. This ultimately helped raise the alarm, and exposed the approaching risks and imminent events. However, reality was different. Indeed, the world was traumatized by the antagonistic nature of the climatic conditions that hit many locations, which had never been classified as more vulnerable and threatened such costal zones, island and Deltas (IPCC, 2018). A division was therefore made between climate change as a part of natural climatic events, and climate change caused by emissions of greenhouse gases such as nitrogen oxide, carbon dioxide, chlorofluorocarbons (CFCs) and methane resulting from human activities and the unreasonable use of fossil fuel in transportation and industry (Egypt's National Strategy, 2011). according to (IPCC 2001) as the sea level rise imposes the ultimate challenge facing most of coastal areas (Johnston et al. 2014). The Sea level was fairly steady for the past 3000 years; while, during the 20th century, the sea level started rising at a global average rate of 1.7 mm/year (Williams 2013). The sea level is predictable to continue rising even if the global climate stabilizes in the next few decades (Nicholls 2002). Global warming and consequent melting of ice in the main glaciers are the direct reasons for the sea level rise (Meehl et al. 2005). However, there are two other causes, including: (1) tectonic changes either by coastal subsidence/uplifting or by sediment compaction, and (2) changes either by loading/unloading of ice sheets or by changes in the ocean circulation and wind patterns (Arnott 2010) Recent and contemporary sea-level rise in our warming world is the result of a combination of a number of factors. The most important are: thermal expansion of seawater, the decay of mountain glaciers and small ice caps, melting of the Greenland Ice Sheet, and melting of the Antarctic Ice Sheet. Thermal expansion of seawater is based upon the simple premise that as seawater warms its density decreases and therefore it occupies more volume. For a given average ocean warming, sea-level rise depends upon where warming occurs. Because the expansion coefficient increases with water temperature, the greatest rise in sea-level will occur if warming is concentrated in regions where the ocean waters are already the warmest, in other words the upper few hundred meters of the sea at low latitudes (Mcguire B., 2008).

From the (IPCC, 2007) report, the global Sea level raised about seven inches over the last century due to global melting of land-based ice and thermal expansion owed to water warming. Coastal zones will also suffer from indirect impacts such as salt-water intrusion and contamination of ground water resources, exacerbating soil salinity and affecting food security. several studies have considered the generation of future beach flooding projections, but knowledge is still lacking on some aspects of these projection. First, the uncertainties involved to the modelling of these projections are not yet understood. Second, regional scale projections often rely on assumptions that may compromise the quality of the results (Agulles Gámez, M.,2023).

Sea level rise is considered a serious threat, and allocating financial resources efficiently becomes challenging due to the uncertain nature of SLR (Montijn, M. 2023). To deal with the uncertainties related to climate change, the IPCC, CMIP6, sixth assessment report (AR6) explores possible futures. The different scenarios present potential shifts in the climate throughout the 21st century as a function of GHG emissions, (Montijn, M.2023).

The purpose of these scenarios is to present the uncertainty linked to future human behavior and not necessarily to predict the future, as no probabilities are linked to the different scenarios. The scenarios cover a large range of plausible futures for GHG emissions. Starting off with a scenario in which CO2 emissions rapidly decrease to carbon neutrality by 2050 and become negative before the end of the 21st century, to a scenario in which the CO2 emissions as shown in figure (1) continue to climb sharply to double present emissions levels in 2050 (Pörtner et al., 2022).

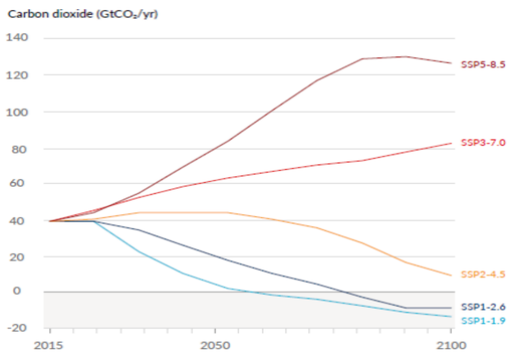

Figure 1: Future CO2 emissions in the five illustrative scenarios

Tier 1 experiments involve four scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). (SSPs) are Shared Socioeconomic Pathways that are scenarios of projected greenhouse gas emissions scenarios with different climate policies (Rogelj, et.al , 2022).The SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios provide continuity with Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathways (RCPs) by similar radiative forcing. The SSP3-7.0 scenario includes "gap scenarios" that include new unmitigated SSP baseline scenarios. Tier 1 experiments provide key future projections and give a wide variety of uncertainty with future forcing pathways. Furthermore, Tier 1 experiments are suitable for comparing data with those obtained in previous studies (Sung et.al 2021).

Depending on which model is chosen and which climate scenario acting on, (Edwards et al., 2021) can arrive at predictions of both less than and (DeConto et al., 2021) more than 1 m of sea level rise during this Century from all sources. (Siegert, M., & Pearson, P.2021). The latest Working Group I IPCC Assessment (AR6) of the physical science acquired these potential results, addressed in the Summary for Policymakers that with very high emissions, global mean sea level up to 2 m by 2100 and 5 m by 2150 "cannot be ruled out due to deep uncertainty in ice sheet processes" (IPCC, 2021). A reasonable description of the problem might be to consider the rise of the sea-level of around 1 m by the end of this Century, but higher assumptions cannot be ruled out given uncertainties in the models and the warming that will happen in the coming decades. Given the benefit of reduced uncertainty in expected 21st Century sea level rise to hundreds of millions of livelihoods, and Millions of dollars of capital locked into coastal towns and cities, (Siegert, M., & Pearson, P.2021).

On the other hand, many areas along the Egyptian coasts are at risk from natural and man-made impacts, created by geological (land subsidence) and meteorological disturbances of sea surface and human interventions to the coasts. These risks are of two categories (i) short term risks related to storms, swells, reclamation pollution and (ii) long-term risks related to climate change, sea level rise, coastal protection measures. The coastal zones of Egypt are classified according to their vulnerability and the potential harm resulting from rising sea level and extreme events. The criteria or standards used to classify the coastal zones can be summarized in: the surface elevation, the subsidence rate and relative sea level rise, the presence of natural coastal protection, whether natural or manmade, (Tourenq,et ,al 2011).In this regards, the present study aims to identify the upper bound of uncertainty of sea levels rising fluctuation resulting from the sensitivity analysis of future projection of 28 Global circulation models(GCMs) on annual basis at the end of this century, the values investigated were under the conditions of four different Representative Concentration Pathways (RCPs) scenarios, Additionally, the study explains and discusses the certainty of why and how sea-level based (GCMs) under (RCPs) scenarios are developed and supported the sustainable development in the study area by defining the impact of the rise in the sea level on the coastal conditions that allow the decision makers to identify problems coming from the climate changes which could threaten the sustainable development in the study area.

2. Material and Methods

2.1 Site description

This research is going to be applied on the Red Sea Coastal Strip from Suez to Hurghada as shown in figure (2). This area is significant from the economic, industrial, social and cultural points of view. In addition to increased tourism activities, a substantial move towards building new industrial complexes is currently under development.

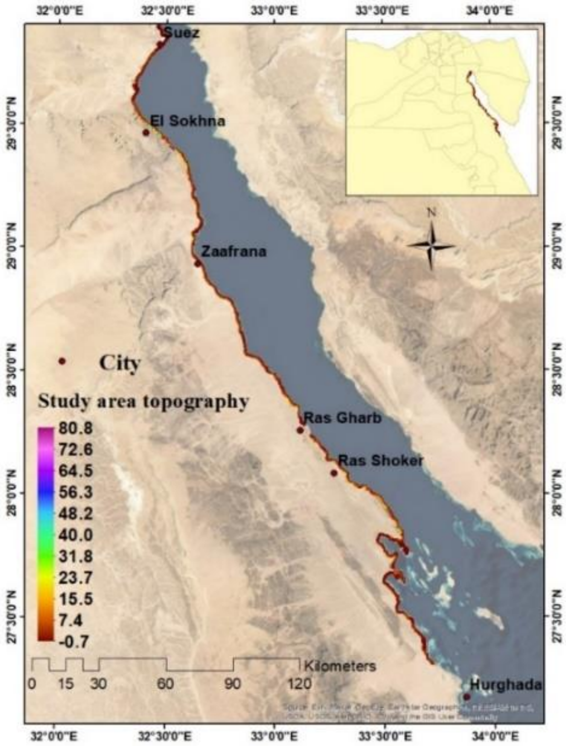

Figure 2: Location of the Study area along the Red Sea

For better understanding of climate change impacts over the study area in terms of rising of the Sea Level and because of the high level of vulnerability of coastal areas to climate change, also an urgent need to understand the threats from climate change that helping in policies formulation which will lessen the risks and helps in taking actions towards the drowning areas, which is a very important and vital issue for Egypt that also expose to increase in temperature and reduction of precipitation, excerption of extremes event in additions to fluctuations of sea level rise. Studies at the Egyptian Red Sea which handled the impact of the SLR on coastal areas specially from (Suez to Hurghada) are still limited although that has a high economic sound for sustainability, however, capital and private investments are the nation’s most rapidly growing, particularly in the field of coastal tourism in addition to the major settlement centers in Hurghada, Safaga, Al-Quseer and Marsa Allam besides the four main harbors at Suez, Ain Sokhna, Safaga and Abu Ghosoun.

2.2 The sensitivity of the GCMs

It is very likely that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971– 2010 for all Representative Concentration Pathway (RCP) scenarios due to increases in ocean warming and loss of mass from glaciers and ice sheets. Projections of sea level rise are larger than in the AR4, primarily because of improved modeling of land-ice contributions. For the period 2081–2100, compared to 1986–2005 (IPCC 2007), it can be resolved that there are three major processes are thought to influence global SLR, which are melting of glaciers and ice-sheets, thermal expansion of ocean water, and varying water storage on land (Simclim essentials 4x Manual, 2018), So, Studying the sensitivity of the Global Circulation Models in terms of sea level rise (SLR) will be by simulating and displaying the annually future sea levels data for 28 global circulation models as shown in table (1), data were processed for these global models by a pattern scaling method, Pattern scaling provides a great way to release these issues. To an extent, pattern-scaling is more akin to a data compression technique while other downscaling methods do not have such a role, it can be described as follows: climate variable V, for a particular grid cell (i), month (j) and year or period (y) under a representative concentration pathway (RCP) 4.5,

$$\Delta V^{*}_{yij} = \Delta T.\ \Delta V_{ij}{}^{`}$$

ΔT being the annual global mean temperature change

$\Delta V_{ij}{}^{`}$ The local change pattern value was calculated from the GCM simulation anomaly

ΔV_{yij} using linear least squares regression:

$$\Delta V'_{ij} = \frac{\sum_{y=1}^{m} \Delta T_y \cdot \Delta V_{yij}}{\sum_{y=1}^{m} (\Delta T_y)^2}$$

then were re-gridded to a common resolution (0.25°*0.25°) using a bilinear interpolation method which is a resampling method that uses the distance weighted average of the four nearest pixel values to estimate a new pixel value. The four cell centers from the input raster are closest to the cell center for the output processing cell will be weighted and based on distance and then averaged. It was applied due to its highly efficient computing ability (SimClim essentials 4X Manual, 2018) under the four scenarios following IPCC guidelines (2.6, 4.5, 6 and 8.5) RCP respectively.

Table 1: Global Circulations Models (SimClim 4xessentials manual, 2018)

Model No	Model Name	Country	Spatial resolution for atmospheric variable (longitude*latitude)	Spatial resolution for ocean variable (longitude*latitude
1	ACCESS1-0	Australia	192*145	360*300
2	ACCESS1-3	Australia	192*145	360*300
3	BCC-CSM1-1	China	128*64	360*232
4	BCC-CSM1-1-M	China	320*160	360*232
5	CanESM2	Canada	128*64	256*192
6	CCSM4	USA	288*192	320*384
7	CMCC-CM	Italy	480*240	182*149
8	CMCC-CMS	Italy	192*96	182*149
9	CNRM-CM5	France	256*128	362*292
10	CSIRO-MK3-6-0	Australia	192*96	192*189
11	GFDL-CM3	USA	144*90	360*200
12	GFDL-ESM2G	USA	144*90	360*210
13	GFDL-ESM2M	USA	144*90	360*200
14	GISS-E2-R	USA	144*90	288*180
15	GISS-E2-R-CC	USA	144*90	288*180
16	HADGEM2-CC	UK	192*145	360*216
17	HADGEM2-ES	UK	192*145	360*216
18	INMCM4	Russia	180*120	360*340
19	IPSL-CM5A-LR	France	96*96	182*149
20	IPSL-CM5A-MR	France	96*96	182*149
21	MIROC-ESM	Japan	128*64	256*192
22	MIROC-ESM-CHEM	Japan	128*64	256*192
23	MIROC5	Japan	256*128	256*224
24	MPI-ESM-LR	Germany	192*96	256*220
25	MPI-ESM-MR	Norway	192*96	802*404
26	MRI-CGCM3	Japan	320*160	360*368
27	NorESM1-M	Norway	144*96	320*384
28	NorESM1-ME	Norway	144*96	320*384

3. Results and Discussions

3.1 Sensitivities of Predicting the SLR

The prediction of the SLR will be under the four Representative Concentration Pathways (RCPs) following the Intergovernmental Panel on Climate Change (IPCC), Fifth Assessment Report (AR5). The greenhouse gas concentration (not emissions) trajectories are RCP2.6, RCP4.5, RCP6.0, and RCP8.5, named after a possible range of radiative forcing values in the year 2100 (of 2.6, 4.5, 6.0, and 8.5 W/m2, respectively) as shown in Table (2).

Table 2: Radiative forcing values at the end of the century

	Description
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100
RCP 6	Stabilization without overshoot pathway to 6 W/m^2 at 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at 2100
RCP 2.6	Peak in radiative forcing at ≈ 3W/m^2 before 2100 and decline

The estimation of SLR will be according to the thermal expansion only and under three Climate Sensitivities (Different representations of the climate system) Low, Medium and High. Scientists have concluded that there is a nine in Ten chances that the true sensitivity is between 1.5°C and 6.0°C. Therefore, the medium sensitivity is centered on 3 C and low on 2 C and high on 4.5 C (Simclim manual 4x,2018) as shown in Figure (3) below.

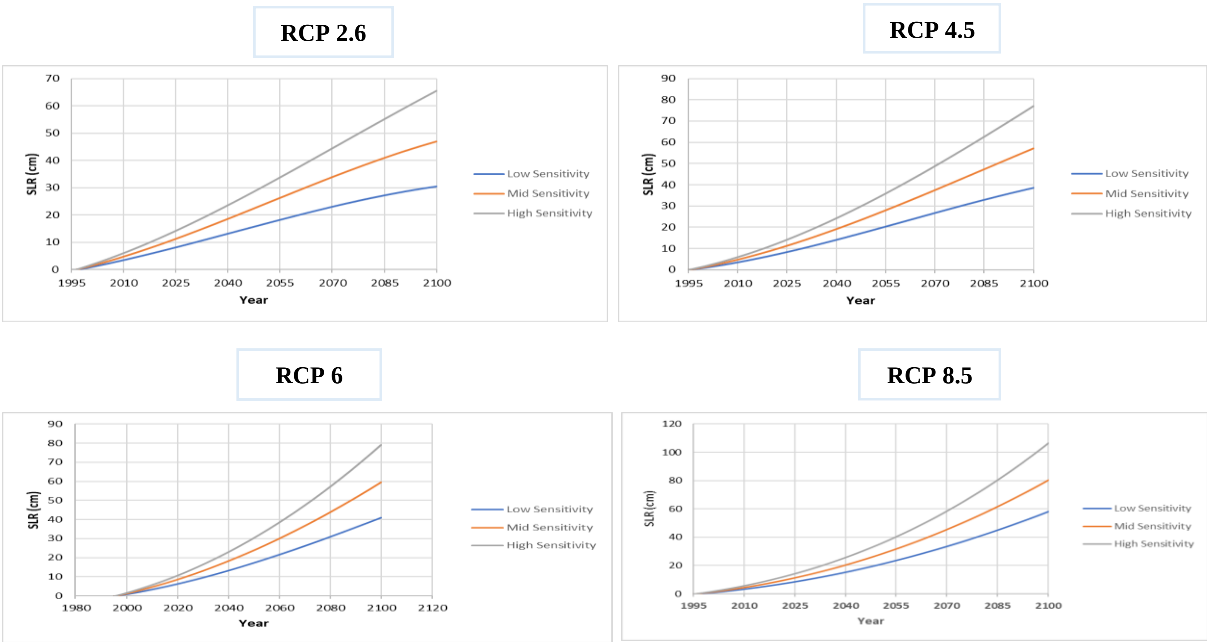

Figure 3: SLR under Climate Sensitivities for different RCPs

In this research, the increase in the sea level along the study area is going to be detected at the end of the century using the values from 28 Global Circulation Models (GCMs). The values of SLR at high sensitivity for example are shown in figures (4,5,6,7).

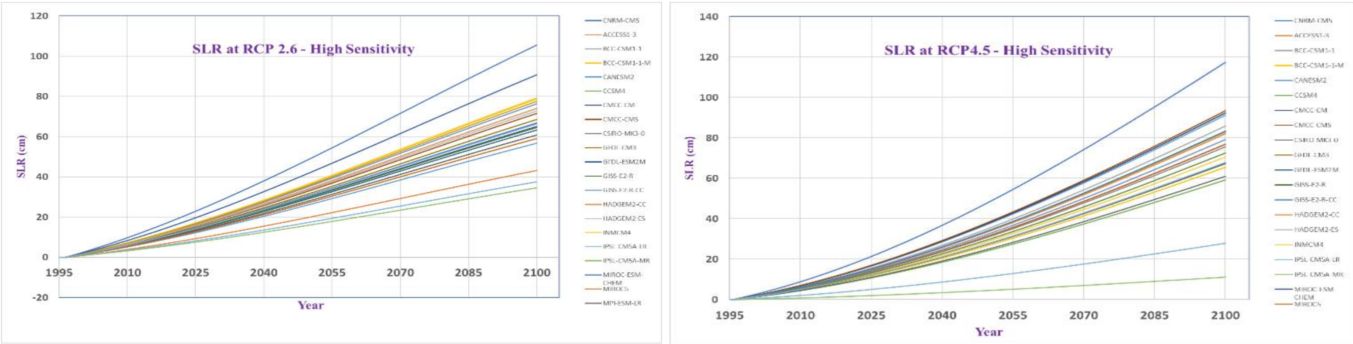

Figure 4,5: SLR values from 28 GCMs, RCP 2.6, 4.5 High Sensitivity

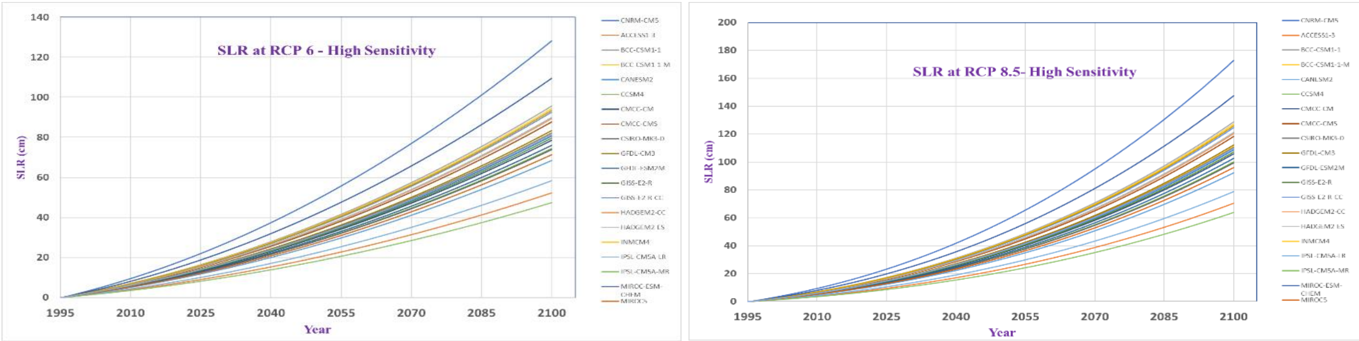

Figure 5,6: SLR values from 28 GCMs, RCP 6, 8.5 High Sensitivity

Referring to table (3) and according to IPCC, AR5; the optimum GCMs were selected which illuminate on the variation of the mean sea level rise, to be between (0.28 – 0.61), (0.36 – 0.71), (0.38 – 0.73), (0.52 – 0.98) m, under RCPs 2.6, 4.5, 6. 8.5 respectively.

Table 3: Ranges of sea level rise under IPCC , AR5 through different RCPs

Emission scenario	**Representative Concentration Pathway (RCP)**	**2100 CO2 Concentration (ppm)**	**Mean sea level rise(m)**		**Emission scenario**	**Mean sea level rise(m)**		
			2046-2065	**2100**				
Low	2.6	421	0.24 (0.17-0.32)	0.44 (0.28-0.61)	Low	2200	2300	2500
Medium Low	4.5	538	0.26 (0.19-0.33)	0.53 (0.36-0.71)	Medium	0.35-0.72	0.41-0.85	0.5-1.02
Medium High	6.0	670	0.25 (0.18-0.32)	0.55 (0.38-0.73)	High	0.26-1.09	0.27-1.51	0.18-2.32
High	8.5	936	0.29 (0.22-0.38)	0.74 (0.52-0.98)		0.58-2.03	0.92-3.59	1.51-6.63

3.2 Ensembles of Optimum GCMs

The optimum GCMs Models are selected out of 28 models based on their sensitivities. and was applied to decrease the uncertainty of the SLR results as recommended by Simclim 4x essentials 2018. As shown in figure (4), 28 GCMs under the high sensitivity are investigated to build the ensembles of the optimum models According to IPCC, AR5´s ranges for mean SLR values. It was found that, there are 7, 7, 5 and 5 optimum GCMs for RCPs 2.6, 4.5, 6, 8.5 respectively, furthermore, the increase in the sea level due to the ensemble of these models under each scenario will be 60.5, 71, 77.7, 104.6 cm, respectively as shown in table (4).

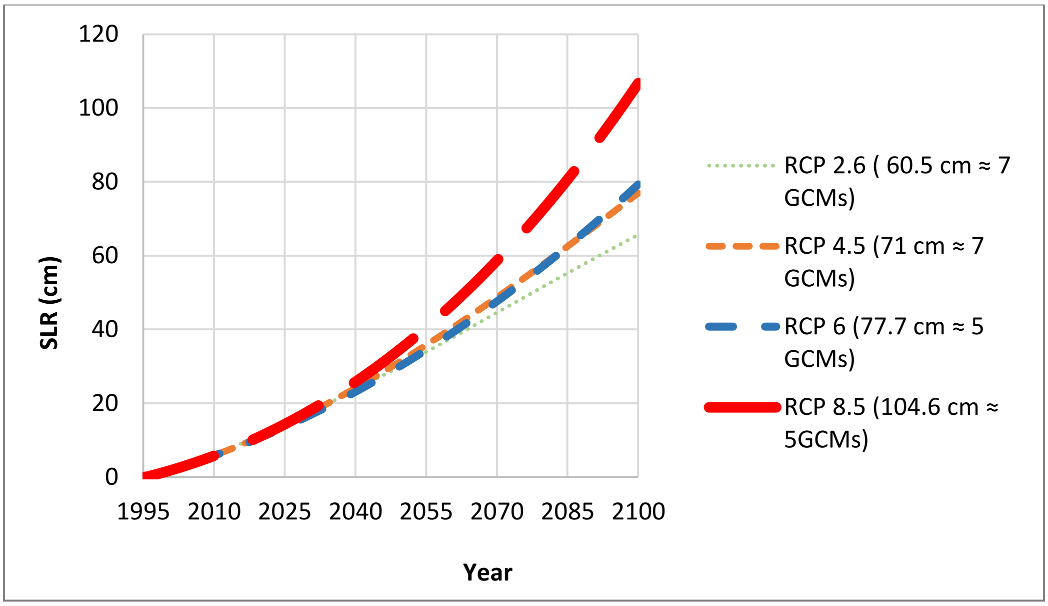

Figure 4: Ranges of sea level rise under different RCPs due to high sensitivity

Table 4: Ranges of sea level rise and ensembles' values of the optimum models under RCPs from suez to Hurghada at Red Sea coastal zone

Emission scenario	Representative Concentration Pathway (RCP)	2100 CO2 Concentration (ppm)	Mean sea level rise (cm) 2100	Sensitivity	Name of Optimum Models
Low	2.6	421	60.5 * (37-61)**	Low	ACCESS1-3, CanESM2, CCSM4, CSIRO-MK3-0, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
				Medium	ACCESS1-3, CanESM2, CCSM4, CSIRO-MK3-0, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
				High	ACCESS1-3, CanESM2, CCSM4, CSIRO-MK3-0, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
Medium Low	4.5	538	71 * (59 -70)**	Low	CCSM4, CSIRO-MK3-0, BCC-CSM1-1-M, GFDL-ESM2G, GISS-E2-R, INMCM4, NorESM1-ME
				Medium	CCSM4, CSIRO-MK3-0, BCC-CSM1-1-M, GFDL-ESM2G, GISS-E2-R, INMCM4, NorESM1-ME
				High	CCSM4, CSIRO-MK3-0, BCC-CSM1-1-M, GFDL-

					ESM2G, GISS-E2-R, INMCM4, NorESM1-ME
Medium High	6.0	670	77.7 * (52 -71)**	Low	ACCESS1-3 , CanESM2, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
				Medium	ACCESS1-3 , CanESM2, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
				High	ACCESS1-3 , CanESM2, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
High	8.5	936	104.6 * (64 -96)**	Low	ACCESS1-3 , CanESM2, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
				Medium	ACCESS1-3 , CanESM2, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5
				High	ACCESS1-3 , CanESM2, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5

* Ensemble values for optimum models in high sensitivity, ** Range of optimum models in high sensitivity
2 C° for low sensetivity,3 C°for medium and 4.5 C° for high

Table (5) illustrates the range of sea level rise and their ensembles' values of the optimum models under RCPs from Suez to Hurghada at Red sea coastal zone. It could be noted that the range of sea level rise values diverstate from low to medium and high sensitivities. Meanwhile, applying the ensembles of the optimum GCMs models will limit these variabilities to be consider in saving adaptive strategies for further development and investment at coastal zone.

4. Conclusions and Recommendations

the uncertainty of sea levels improvement along the Red Sea coastal zones under the four Representative Concentration Pathways (RCPs) 2.6, 4.5, 6.0, and 8.5, was investigated by following the Intergovernmental Panel of Climate Change, Fifth Assessment Report (AR5). Twenty - eight of GCMs are used to evaluate the sensitivity of increasing the SLR. The optimum GCMs followed the recommended procedures in high sensitivity were found to be seven GCMs out of twenty-eight for RCP 2.6, seven GCMs for RCP 4.5, five for RCP 6 and also five models for RCP 8.5. The ensembles of the optimum GCMs for each scenario were conducted to reduce the uncertainty and predict the projected values of SLR at study area. wherever, the fluctuations of sea levels along the Egyptian coastal zone from Suez to Hurghada due to the ensemble of these optimum global circulation models in high sensitivity and under each emission scenario will be projected as 60.5, 71, 77.7, 104.6 cm, respectively. So, using the ensemble of the optimum GCMs will limit the variabilities of SLR to be consider in saving adaptive strategies for further developments and investments at coastal zone. Meanwhile, and due to the SLR the integrated coastal zone management should be drawn with monitoring system for early warning and actions.

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