Sea level changes along the Indian coast: Observations and projections

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Sea level changes can be of two types: (i) changes in the mean sea level and (ii) changes in the extreme sea level. The former is a global phenomenon while the latter is a regional phenomenon. Estimates of mean sea level rise made from past tide gauge data at selected stations along the coast of India indicate a rise of slightly less than 1 mm/year; however these estimates need to be corrected by including the rates of vertical land movements, whose measurements are not available at present. Simulation results of a regional climate model, HadRM2, were analysed for the northern Indian Ocean to provide the future scenarios of the occurrence of tropical cyclones in the Bay of Bengal for the period 2041–60. This model simulations consist of a control run with concentration of CO_2 kept constant at 1990 levels and a perturbed run with transient increase in the concentrations of CO_2 (GHG) according to the IS92a scenario for the period 2041–2060. The simulation results show increase in frequencies of tropical cyclones in the Bay, particularly intense events during the post-monsoon period, for the increased GHG run. A storm surge model was used to compute the surges associated with the cyclones generated by the climate model. The storm surge model was forced by the wind field from HadRM2 over the model domain and tides prescribed along the open boundary from a global tidal model. The frequency of high surges is found to be higher in the model run forced by winds from increased GHG run than in the model run forced by winds from the control run.

Keywords: Future climate projection, regional climate model, sea level rise, storm surges, tide gauge data.

ANALYSIS[1] of past sea level measurements, recorded by tide gauges located at various ports in different parts of the world ocean indicates a mean sea level rise of 1 to 2 mm/year during the last century. These changes are generally attributed to global warming. Various consequences of global warming such as melting of sea ice, volume expansion due to temperature increase in the ocean, etc. can contribute to global sea level rise.

Besides causing a sea level rise, there is a concern that global warming may cause changes in the occurrence of extreme events such as cyclones. Extreme events in the coastal regions occur in the form of storm surges, apart from tsunamis. The occurrence of extreme events is more or less a regional phenomenon, caused by changes in regional climate. The occurrence of storm surges is common to the countries surrounding the Bay of Bengal, as the Bay is the hotbed of generation of tropical cyclones. Any increase in the frequency or intensity of tropical disturbances in future will cause increased damages to life and property in the coastal regions.

The present paper mainly deals with the occurrence of tropical cyclones in the Bay of Bengal and associated storm surges in a future climate scenario. Projections for the future are needed for decision making by planners and policy makers. Future projections are made for different scenarios[2] of green house gas emissions from simulations of Atmosphere Ocean General Circulation Model (AOGCM). The AOGCM provides information on a global scale. In recent years, regional climate models, which have a finer resolution than global models, are used for an analysis on a regional scale. The results of a regional climate model (HadRM2), developed by the Hadley Centre for Climate Research and Prediction, UK, for the northern Indian Ocean were used for the present analysis. The model parameters such as atmospheric pressure field at the surface and near surface wind field during a future climate scenario (2041–2060) were used to identify the occurrence of lows, depressions and cyclones to determine their frequency distribution in the Arabian Sea and in the Bay of Bengal during the 20-year period. Besides, a storm surge model for the Bay of Bengal, developed in the institute, was forced by wind fields from HadRM2 to simulate the surges in this period.

Recent studies[3,4] on the occurrence of cyclones in the Bay of Bengal have not shown any trends during the last century. However, studies[5] on intensification of cyclones in the Bay have shown that the frequency of intense cyclones in the Bay during November has shown an increasing trend. Numerical experiments[6] using atmospheric general circulation models (GCM) showed that essential features of tropical disturbances could be identified in a GCM with $2.5° \times 3.75°$ grid resolution. They found that the effect

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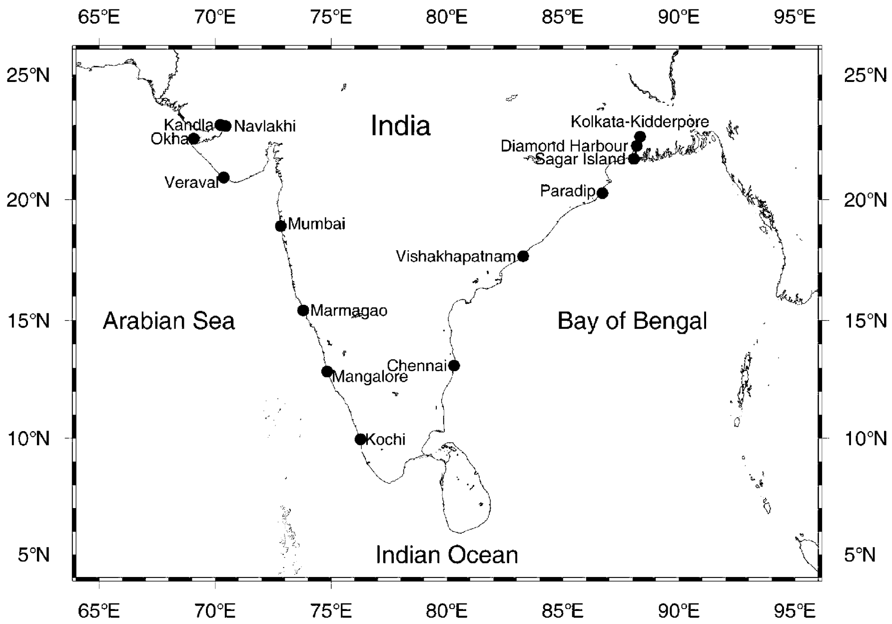

Figure 1. The location map. Filled circles indicate tide gauge stations.

of doubling of CO_2 in numerical simulations produces an increase in the number of tropical disturbances, particularly intense events. A regional model, by virtue of its finer grid resolution, can resolve the features of a cyclone in a better way than a global model. In the present work, we studied the frequency distribution of cyclones in the Bay of Bengal in a future climate scenario by analysing the results of HadRM2.

Methodology

Long-term changes in mean sea level along the Indian coasts

Mean sea level changes were estimated by analysing past tide gauge data at different ports along the Indian coasts. Measurements of sea level by tide gauges at various ports are usually available at hourly interval. These measurements contain tides, which are deterministic and can be predicted. Tides are filtered from the observed sea level for the study of long term changes in mean sea level. Usually, monthly mean values of sea level are used for estimating sea level rise. These data are available with the Permanent Service for Mean Sea Level (PSMSL), at the Proudman Oceanographic Laboratory, UK. In an earlier study[7], the monthly mean sea data up to the year 1982 were used to determine the sea level rise along the Indian coasts. In the present study, the monthly mean sea level data up to 1994 were included for the analysis. Mean sea level changes obtained by an analysis of trends could be either caused by global warming or due to vertical movements of the land, where the instrument is located. In order to get the net sea level rise at a place, rates of vertical land movements need to be included. The location of tide gauge stations along the Indian coast is shown in Figure 1. Mumbai is one of the few stations in the world, which has a record of more than 100 years of sea level data. However, for Mangalore, only relatively short duration of data (18.4 years) is available. Therefore, the station Mangalore was not considered for the present analysis. The stations along the northeast coast were not considered for the present analysis, since signals of storm surges are often present in the monthly mean sea level data and perhaps these stations are not suitable for estimating mean sea level rise. Therefore, only selected stations were considered for the present analysis. A five-point moving average was applied to the data and a least square fit was made. The results are shown only for some selected stations, namely, Mumbai, Kochi, Chennai and Vishakhapatnam (Figure 2).

Analysis of regional climate model (HadRM2) data

In the present study, the results of the regional climate model (HadRM2) of the Hadley Centre for Climate Prediction and Research, UK, were analysed to study the effects of climate change on the frequency distribution and intensities of tropical disturbances in the northern Indian Ocean. These simulations are available for a control case (CTRL) with fixed green house forcing and a future scenario[2] called IS92a involving transient increases in greenhouse gas forcing (GHG). In the CTRL run, the concentration of CO_2 is kept constant at the 1990 levels and in the increased GHG run, 1% of CO_2 is increased every year from 1990 in a compounded manner. The future simulation covers the period 2041–2060. The domain of HadRM2 for the northern Indian Ocean extends from 58.54°E to 101.4625°E and 3.273°N to 36.018°N with a grid resolution of 0.4425 × 0.4425°. The lateral boundary conditions for HadRM2 were taken from the simulations of global model[8] HadCM2. The computed parameters include atmospheric pressure at sea level, precipitation, temperature and wind fields at different atmospheric levels, etc. Among these, sea level pressure fields can provide the signatures of atmospheric disturbances varying from lows, depressions to cyclones. Thus, sea level pressure fields, at least, on a daily time scale are needed to identify the evolution of atmospheric disturbances. A given disturbance is characterized by two parameters, namely, the maximum wind speed in the system and the pressure drop (ΔP), which is the difference between the minimum pressure found in the cyclone and the normal atmospheric pressure.

The distribution of surface pressure for each day was viewed using Ferret (http://ferret.wrc.noaa.gov) and the frequencies of tropical disturbances were identified and tabulated for the entire period 2041–2060 for both the CTRL run and the increased GHG runs. The disturbances identified are classified into lows, depressions, cyclones, etc. based on the classification norms of the India Meteorological Department. The frequency distribution of all the tropical disturbances is plotted in Figure 3 *a b*, while that of intense events such as cyclones is plotted in Figure 3 *c d* in the Arabian Sea and the Bay of Bengal respectively. During the period of the evolution of each storm, the maximum wind speed associated with each storm was noted and their frequency distribution during the 20-year period is shown in Figure 4. The tracks of cyclones over a period of 5 years in the beginning of the CTRL and increased GHG runs are depicted in Figure 5 *a* and 5 *b* respectively.

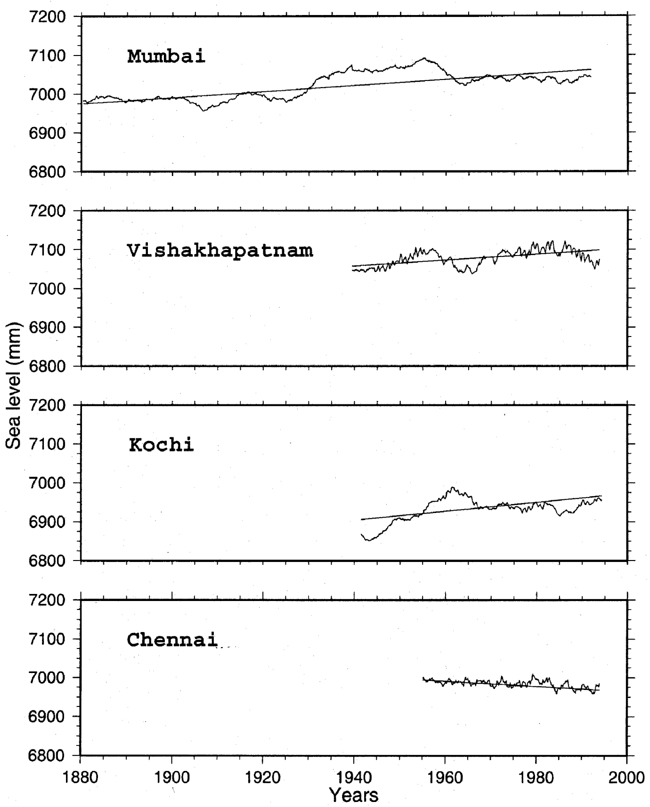

Figure 2. Estimates of sea level rise for selected stations. Monthly mean tide gauge data from the past sea level records measured by tide gauges are used to estimate the trends.

Simulation of storm surges using winds from regional climate model HadRM2

One of the greatest impacts in the coastal regions by the tropical cyclones is due to storm surges. Storm surges are generated by tropical cyclones by inverse barometric effect in the open ocean region. Surges are barotropic in nature, i.e. they are vertically homogeneous. They propagate towards the shore along with astronomical tides, which are also barotropic. While approaching the shore, they amplify due to the bottom topographic effects and cause damages while striking the coast.

In coastal regions, wind stress plays an important role than the inverse barometric effects. The bathymetry of the coastal region plays an important role in the amplification of the surges. In India, most of the earlier studies[9,10] on storm surges were based on numerical modelling on particular events based on the track of the cyclone and pressure drop in the cyclone as input. The wind fields computed using the cyclone parameters, are used to drive the storm surge model.

The extreme sea level variability at the coast in a future climate can be studied using a storm surge model, driven by wind field simulated by a regional climate model. In the present work, we developed a storm surge model for the Bay of Bengal for simulating the surges forced by HadRM2 winds. A barotropic model, developed[11] for the propagation of tides in shallow water, was modified by incorporating the wind stress terms in the momentum equations and defining a radiation type of boundary condition[12] along the open boundary. A description of model equations and the numerical method used is elaborated in the earlier studies[11,13]. The model domain (Figure 6) consists of the entire Bay of Bengal with the open boundary lying along 6.58°N along the southern side. The bathymetry of the domain was defined using the global bathymetric data set (ETOPO5) available at every 5 min interval. The grid resolution is about 18 km and the time step used is 30 sec.

The wind field from HadRM2 was interpolated to the model grid using a two-dimensional linear interpolation method. In the storm surge model, the forcing of the wind field gets updated every 24 h and the model was run for a period of 20 years for the (i) CTRL run representing the 1990s and (ii) increased GHG run representing the 2050s. Along the open boundary, tides were prescribed at each

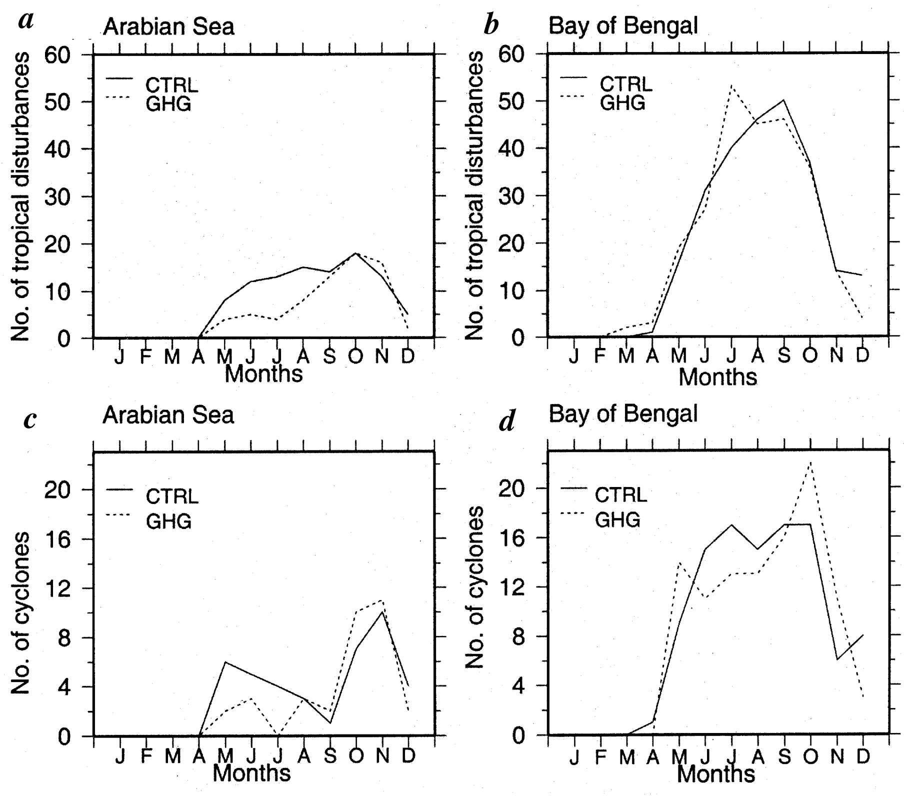

Figure 3. Frequency distribution of all tropical disturbances and that of intense events (cyclones) as simulated by the regional climate model HadRM2 in CTRL run (1990s) and in the increased GHG run (2050s; IS92a scenario) over the Arabian Sea and the Bay of Bengal.

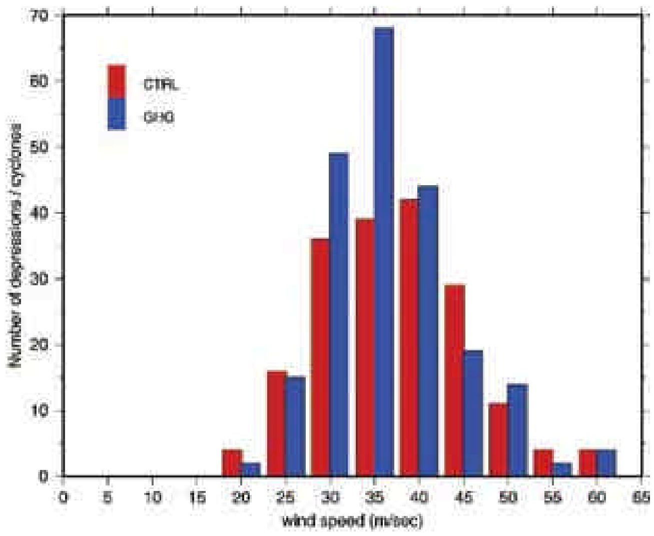

Figure 4. Frequency distribution of maximum wind speeds associated with cyclones in HadRM2 for CTRL (199s, red columns) and increased GHG (2050s, blue columns)

time step from the global tidal model[14] output and a radiation type boundary condition[12] was applied.

The information on storm surge during the period of model simulation for each grid point along the coastline was compiled by taking the maximum value of sea level found during each event. These values were picked up by defining a window width of 96 h consisting of 48 h before and 48 h after the crossing of the cyclone over the land. Thus for each storm, one highest value of simulated sea level was chosen and a frequency distribution of this information was built over the period of 20 years (Figure 7) for each grid point at the coast. Occurrence of higher sea levels is found to be more in the storm surge simulations forced by winds from increased GHG run than in the simulation forced by winds from the CTRL run.

Results and discussion

Long-term variability of mean sea level along the Indian coast

Table 1 shows the estimates of mean sea level rise at selected stations along the Indian coast. Among these stations, the estimates for Mumbai, Kochi and Vishakhapatnam showed a sea level rise of 0.78, 1.14 and 0.75 mm/year respectively, whereas the estimate for Chennai showed a decrease in sea level (– 0.65 mm/year). The present estimates do not significantly differ from those in the earlier study[7], except for Chennai. The decreasing trend found at Chennai in the present study can be partly explained by examining the monthly mean sea level curve for Chennai (see Figure 2), which shows a decreasing trend since about 1980. In the earlier study[7], data since 1982 were not present. The estimates of sea level rise obtained for the Indian coasts need to be corrected by including the rates of vertical land movements, which are not available at present, in order to get the net sea level rise.

Tropical cyclones in the Bay of Bengal in a future climate scenario

The simulation results of HadRM2 for the CTRL run (the 1990s) and for the increased GHG run (2050s; IS92a scenario) were analysed. The total number of disturbances identified during the entire period for each month is used to make the frequency distribution diagrams. Figure 3 *a*, *b* indicates the frequency distribution of all disturbances, whereas Figure 3 *c*,*d* indicates the frequency distribution of intense events (cyclones). It can be noticed that even though there is no significant change in the number of total tropical disturbances in the increased GHG simulation from that in the control run, there is an increase in the number of intense events (cyclones) in the Bay of Bengal, particularly during the post-monsoon period (Figure 3 *d*).

Maximum wind speeds associated with each storm during the 20-year period is shown in Figure 4. The frequency of cyclones having maximum wind speed, particularly in the range of 30–35 m/sec, is much higher in the increased GHG run than in the control run. This indicates that the intense cyclones may be more frequent in the increased GHG scenario than in the control scenario, consistent with the finding[5] based on the trends from past observations. A visual examination of the composite tracks of the cyclones for the initial five-year period each in the CTRL and the increased GHG simulations (Figure 5 *a*, *b*) does not indicate major changes.

Table 1. Estimates of sea level rise for selected stations along the Indian coast (positive sign indicates rise)

Station	Period of analysis (years)	Sea level rise (mm/year)
Mumbai	1878–1994	0.78
Kochi	1939–1997	1.14
Chennai	1955–1994	–0.65
Vishakhapatnam	1939–1994	0.75

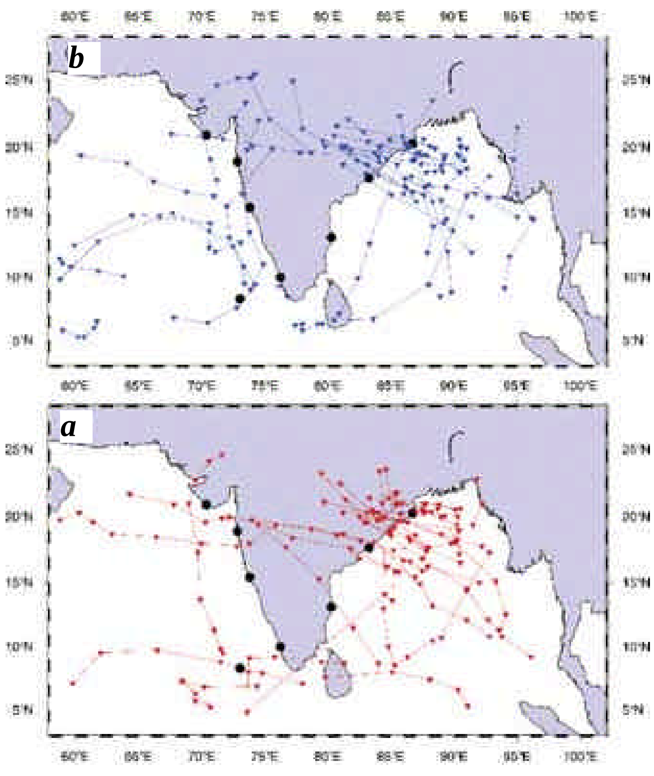

Figure 5. Tracks of cyclones from HadRM2 during the first five years of (***a***) CTRL run and (***b***) increased GHG run.

Storm surges in a future climate scenario

The occurrence of storm surges in the Bay of Bengal in the above future climate scenario was studied from the simulations of the storm surge model. The simulations were made by driving the model using winds (at 850 hPa) from HadRM2 on a daily time scale for the 20-year period for the CTRL run and the increased GHG run.

Storm surge events were identified from the simulated results of 20 years. The maximum value of simulated sea level during a storm surge event for each grid point along the coastline was compiled for all the events in the 20-year period. These values were picked up by defining a window, which consists of 48 h before and 48 h after the crossing of the cyclone over the land. Thus, for each storm, one highest value of sea level was chosen and this information was compiled for 20 years (Figure 7). While picking up the highest sea level during a storm surge event, care was taken not to include the highest spring tides, which could be mistaken as storm surges. Since the model results are over the mean sea level, the results presented in Figure 7 are with respect to the mean sea level. At a given port, the height of the chart datum, which is the reference level over which sea level measurements are made, has to be added to the simulated sea level to obtain the actual sea level in that location. However, this is not very critical as far as the interpretation of this result is concerned (Figure 7), as it is intended to make a comparison between the two model simulations. Occurrence of higher sea levels is found to be more in the storm surge simulations forced by winds from GHG run than in the simulation forced by winds from the control run. This is consistent with the frequency distribution of maximum wind speeds associated with cyclones shown in Figure 4 showing the greater

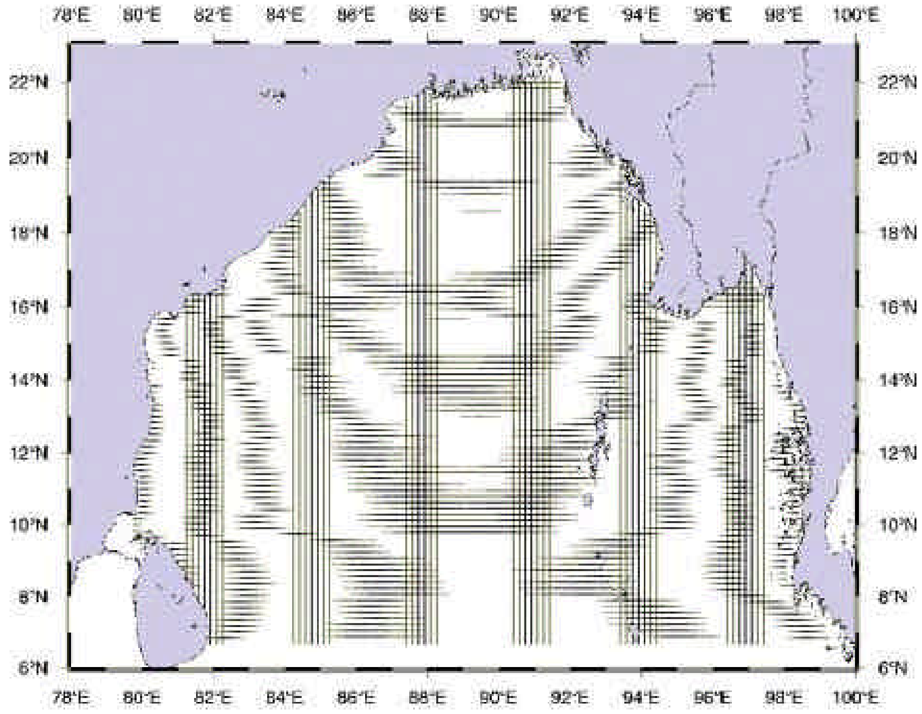

Figure 6. Domain of the storm surge model for the Bay of Bengal. The wind field (daily time scale) from HadRM2 was interpolated to each model grid point. Along the open boundary, tides were prescribed from a global tidal model.

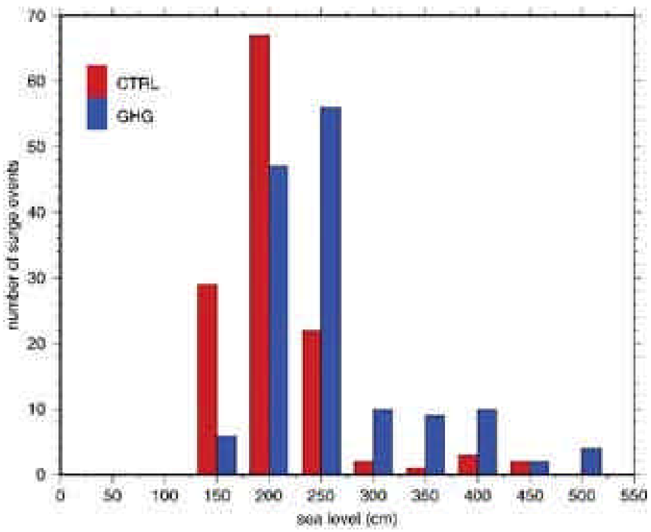

Figure 7. Frequency distribution of maximum surges generated by all cyclones, as simulated by the storm surge model forced by the winds from the CTRL run (1990s; red columns) as well as the increased GHG run (2050s; blue columns) of the regional climate model HadRM2.

occurrence of extreme events in increased GHG run than in the CTRL run.

Conclusion

The estimates of sea level rise along the coast of India were made by analysing the past tide gauge data. Among the stations considered for the analysis, Mumbai, Vishakhapatnam and Kochi showed a sea level rise of slightly less than 1 mm/year; however, the analysis for Chennai showed a rate of decrease. The present estimates are consistent with the global mean sea level rise estimates[1], though lower in magnitudes. These estimates need to be corrected by subtracting the measurements on vertical land movements, which are not available at present, in order to get the net sea level rise.

The analysis of regional climate model of the Hadley Centre, HadRM2 provided indications of the possible changes that could occur in future due to an increase in greenhouse gases, even though recent studies[3,4] on the occurrence of cyclones in the Bay of Bengal have not shown any trends in the last century. A comparison between the results of two simulations, namely, the control run (CTRL) and a run with increased green house gas (GHG) in the IS92a scenario, showed an increase in occurrence of cyclones in the Bay of Bengal in the increased GHG scenario, particularly in the post-monsoon period. The increased maximum wind speeds associated with cyclones (Figure 4) found in the increased GHG run when compared to the CTRL run, also indicate the occurrence of more intense events in the increased GHG scenario. However, the composite tracks of the cyclones do not show any significant difference between the two simulations. Corresponding changes are found in the storm surge simulations, forced by HadRM2 winds. High surges occur more frequently in the increased GHG run than in the CTRL run.

The results obtained on surface atmospheric parameters from HadRM2 and the storm surge simulations suggest that global warming due to increase in CO_2 may cause changes in the regional climate of the Bay Bengal and can cause increases in the occurrence of intense tropical cyclones and high surges. This finding is consistent with the study on trend analysis[5], which shows intensification of cyclones in the Bay, particularly in November, during the last century. However, the present study deals with only one future climate scenario. It is necessary to examine simulations from more scenarios for obtaining better regional climate projections for the future. Increases in high surges can also occur due to an increase in mean sea level. This aspect needs to be taken into account for future numerical modelling experiments. Also, the socio-economic implications associated with increased flood risks caused by storm surges and increases in mean sea level need to be studied.

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