Tropical cyclones in the Bay of Bengal and extreme sea-level projections along the east coast of India in a future climate scenario

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The simulations from the regional climate model, PRECIS (Providing REgional Climates for Impacts Studies), were analysed for the occurrence of tropical cyclones in the Bay of Bengal in a baseline scenario (1961–1990) and a future climate scenario (2071–2100), A2. The analysis showed an increase in the frequency of cyclones in the Bay of Bengal during the late monsoon (August and September) season in the A2 scenario compared to the baseline scenario. However, composite ground-tracks of cyclones do not show any appreciable spatial difference between the two simulations. Extreme sea-level projections along the east coast of India were made using a storm surge model developed for the Bay of Bengal, driven by winds and surface atmospheric pressure obtained from PRECIS. For A2 simulations, a uniform sea-level rise of 4 mm/yr from 1990 was included from the present levels. This corresponds approximately to the average sea-level projections for 2100. The simulated extreme sea-level events were identified and an extreme value analysis was performed using Gumbel fit to determine the return levels. The 100-year return levels of extreme sea-level events are found to be higher by about 15–20% for the A2 scenario than those in the baseline scenario for locations north of Visakhapatnam. However, for the regions experiencing large tidal ranges (Sagar and Kolkata), increase in 100-year return levels for the future scenario are found to be less than 5%.

Keywords: Cyclones, future projections, regional climate model, storm surges.

Introduction

EXTREME sea-level events occur in the form of storm surges, driven by tropical or extra tropical cyclones and also in the form of tsunamis. The present article discusses climate-related events such as storm surges. The storm surges are waves of large wavelength of the order of about 1000 km, which are generated by tropical or extra tropical cyclones through an 'inverted barometric effect'. In the generating area, the amplitudes of surges are small. Wind stress effects become dominant in the coastal regions. While propagating towards the shore, their amplitudes increase due to shallow water processes and due to the action of wind stress. At the coast, surges often become catastrophic.

The various physical processes affecting the magnitude of an extreme sea-level event in a given place are shown schematically in Figure 1. Observed sea-level during an extreme event depends on the phase of the tide. Thus, an event occurring at high tide will have a bigger impact than an event of the same magnitude occurring at low tide. Variations in sea level do occur with the spring–neap cycle of tide. Various modes of climate variability, such as El Niño Southern Oscillation (ENSO) in the Pacific Ocean, the North Atlantic Oscillation (NAO) in the Atlantic Ocean, etc. are found to have an effect on the sea level during an extreme event occurring in the respective regions. Future sea-level rise can increase the sea level during an extreme event.

There have been various studies in the past on storm surges in the Bay of Bengal. Most of these were on

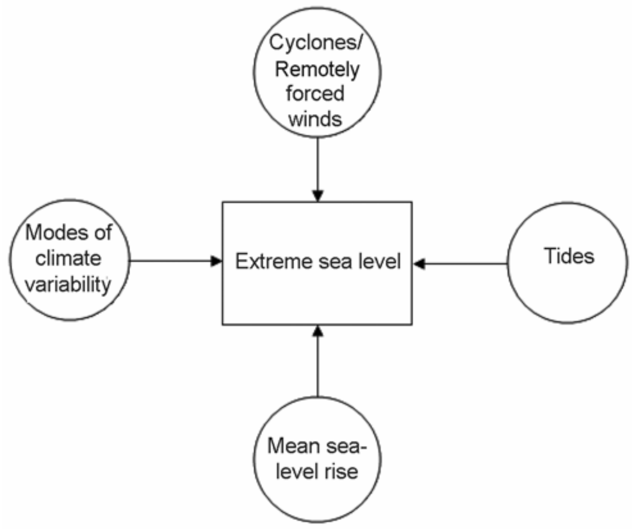

Figure 1. Various phenomena that determine the sea level during an extreme event.

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simulating past storm surge events using numerical models[1,2]. Unnikrishnan *et al.*[3] analysed historical tide-gauge data at hourly intervals to identify various storm surge events during a period of 15 years (1973–1988) and to determine their return periods.

Niyas *et al.*[4] analysed the observations of cyclones in the north Indian Ocean for the period 1891–2008 and showed that the frequency of cyclones in the Bay exhibits a slight negative trend. However, some of the earlier studies[5] have shown that there had been an increase in the intense cyclonic events in the Bay during the past century. Munikrishna[6] showed that the intensity of cyclones during the monsoon season has increased during the recent decades.

Changes in mean sea level are gradual and they occur at relatively long timescales. The mean sea-level rise trends along the north Indian Ocean coasts have been estimated to be about 1.30 mm/yr based on an analysis of past tide-gauge data[7]. Twenty-first century projections are available on global scales[8]. They vary depending on the climate scenario, but for a moderate scenario such as A1B, the 5% and 95% range for 2100 varies between 0.18 m and 0.48 m respectively. These projections are with respect to 1990.

Impacts at the coast occur mainly through extreme sea level. Bindoff *et al.*[9] reported an increase in the occurrence of extreme sea-level events based on various studies. Analysis of past tide-gauge records over the globe showed that there had been an increase in the occurrence of extreme events since 1970, caused primarily due to a mean sea-level rise[10]. Menéndez and Woodworth[11] reconfirmed this finding by analysing larger number of tide gauges[11]. Lowe *et al.*[12] reviewed the past changes in the occurrence of extreme sea level worldwide and on their regional future projections. A more recent review of changes in extremes may be found in Woodworth *et al.*[13].

The present study is an attempt to make future projections of extreme sea level along the east coast of India. In an earlier study[14], the wind fields from the regional climate model, HadRM2, were used to force a storm surge model developed for the Bay of Bengal. HadRM2 simulations were available for a control run, in which concentrations of CO_2 are kept constant at the 1990 levels and an IS92a scenario, in which 1% increase is made from the 1990 levels onwards. They found that higher storm surges occur along the east coast of India in the increased CO_2 scenario during 2040–2060.

Mitchell *et al.*[15] used HadRM2 projections to simulate storm surges for the northern part of the Bay and found that the changes in 50-year return levels between a control run and the increased CO_2 run in the IS92a scenario varied between 0.30 and 0.70 m, with a maximum of 0.70 m found in the northwestern part of the Bay. These simulations included a sea-level rise and accounted for vertical land movements.

Methodology

Regional climate model (PRECIS)

Simulations of the regional climate model, Providing REgional Climates for Impacts Studies (PRECIS), developed by the Hadley Center for Climate Prediction and Research, are available for a baseline scenario and future climate scenarios, A2, B2 and A1B[16]. The baseline scenario is for the period 1961–1990 and future scenarios are towards the end of the 21st century. The climate scenarios, based on emission and socio-economic factors are defined in the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change[17]. In the present analysis, we compared the simulations between the A2 scenario (2071–2100) and a baseline scenario (1961–1990). Even though the regional model domain covers the entire north Indian Ocean, the present analysis is carried out on the cyclones in the Bay of Bengal. For both the scenarios two simulations are available, one which included sulphur cycle and the other without the sulphur cycle. Since the two simulations do not show any significant differences in the surface air temperatures[16], we restricted our analysis to simulations without the sulphur cycle for the baseline and A2 scenarios. The parameters extracted from the model were the near surface (10 m) wind fields and surface atmospheric pressure fields at daily timescales.

An analysis of atmospheric pressure fields at sea level obtained from PRECIS simulations was made to determine the frequency distribution of cyclones in the Bay of Bengal in different climate scenarios[18]. The software, ‘TRACK’ (version 3.1.4) was used to identify groundtracks of cyclones[19]. Surface atmospheric pressure fields at daily timescale were used as the input and all the low pressure systems were identified. This information was used for determining the frequency distribution of cyclones in the baseline and A2 scenarios.

Storm surge model for the Bay of Bengal

A vertically integrated 2D model developed in our earlier studies[14,20] was used for developing a storm surge model for the Bay of Bengal. In the present model, we have used a modified bathymetry[21] for assigning depths to the grid points. The southern open boundary, shown in Figure 2, is along 6.25°N. The eastern, northern and western boundaries are closed. The grid spacing is 18.33 km in the x and y directions and the time step used was 24 s.

The surface atmospheric pressure fields and wind velocity components at 10 m height obtained from PRECIS model simulations were used to force the storm surge model. Along the open boundary, tides were prescribed from the output of the global tidal model[22], FES2004 and a radiation boundary condition was defined. Two simulations were made. In the first, the model was forced by winds and tides, and in the second, forcing was done by the tides alone. The difference between the two simulations provides surge fields, assuming that the interaction between tides and surges is zero. Surge fields were used to identify extreme events and the maximum sea-level value for each event was identified. This was done by defining a window of 60 h before and after the time of occurrence of the peak surge. The number of maximum values identified for each extreme event in a year varied between 2 and 5. The simulations were carried out for the baseline (1961–1990) and future scenario, A2 (2071–2100). For simulations of the A2 scenario, a sea-level rise of 4 mm/yr, which corresponds to an average projected trend from the envelope of sea-level rise projection scenarios for the 21st century described in fourth assessment of the IPCC, was added to the levels from 1990.

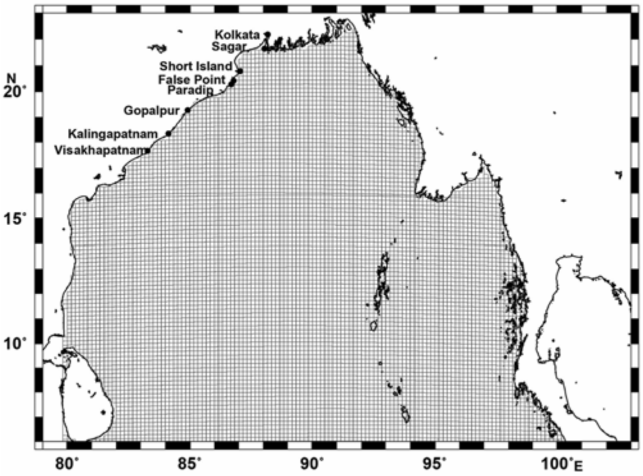

Figure 2. Storm surge model domain for the Bay of Bengal. Return levels of extreme sea level were calculated for stations shown along the coast.

Results

Occurrence of tropical cyclones in the Bay

The composite tracks of the cyclones (Figures 3 and 4) for the baseline (without sulphur cycle) and A2 (without sulphur cycle) scenarios respectively, do not show any significant difference between them. However, the frequency of cyclones (Figure 5) during the late monsoon season during the future (2071–2100) scenario is found to be much higher than that during the baseline scenario (1961–1990). Maximum wind speed associated with each cyclone during the entire period is plotted in Figure 6, which indicates higher number of intense cyclones in the A2 scenario than that in the baseline scenario.

Simulation of storm surges in present and future climate scenarios

Extreme sea-level values associated with storm surge events were fitted with the Gumbel extreme value distribution and return levels at different locations were determined. The methodology is described in our earlier work[3]. Since most of the cyclones in the simulations (Figures 3 and 4) cross the northern part of the coast, peak surges occur mainly in the northern and northeastern regions. We present the estimated return period curves for selected stations (see Figure 7), located north of Visakhapatnam. The 100-year return levels and standard errors associated with the Gumbel fit are shown in Table 1.

It is found that for all locations north of Visakhapatnam, except Sagar and Kolkata, the increase in 100-year return levels (Table 1) is about 15–20% in the future scenario, compared to those in the baseline scenario. For the two stations considered in the head of the Bay, namely

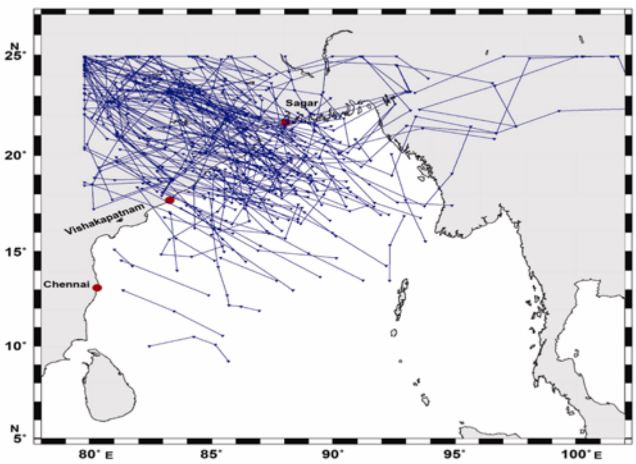

Figure 3. Composite track of cyclones during baseline (without sulphur cycle) scenario (1961–1990) from PRECIS simulation.

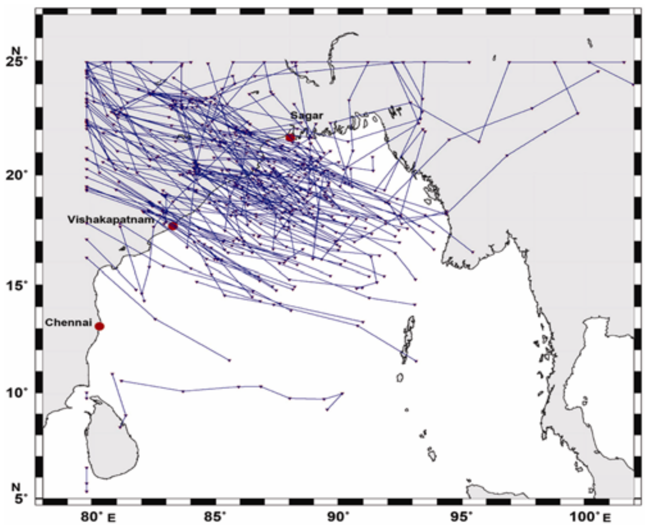

Figure 4. Composite track of cyclones during A2 (without sulphur cycle) scenario (2071–2100) from PRECIS simulation.

Table 1. Hundred-year return levels and standard errors associated with the Gumbel fit at stations shown in Figure 2, estimated from the storm surge model simulations

Station	Hundred-year return level (1961–1990) (m) relative to the chart datum	Hundred-year return level (2071–2100) (m) relative to the chart datum
Visakhapatnam	2.53 ± 0.08	2.94 ± 0.08
Kalingapatnam	2.47 ± 0.06	2.99 ± 0.07
Gopalpur	3.17 ± 0.10	3.70 ± 0.11
Paradip	3.63 ± 0.09	4.36 ± 0.11
False Point	3.77 ± 0.11	4.19 ± 0.11
Short Island	4.32 ± 0.11	4.99 ± 0.13
Sagar	7.98 ± 0.26	7.96 ± 0.20
Kolkata	7.14 ± 0.18	7.34 ± 0.17

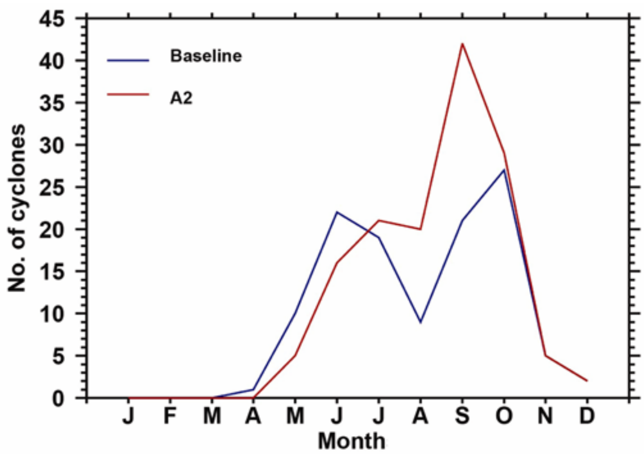

Figure 5. Frequency distribution of cyclones in the Bay of Bengal. Blue (red) indicates the baseline (A2) scenario.

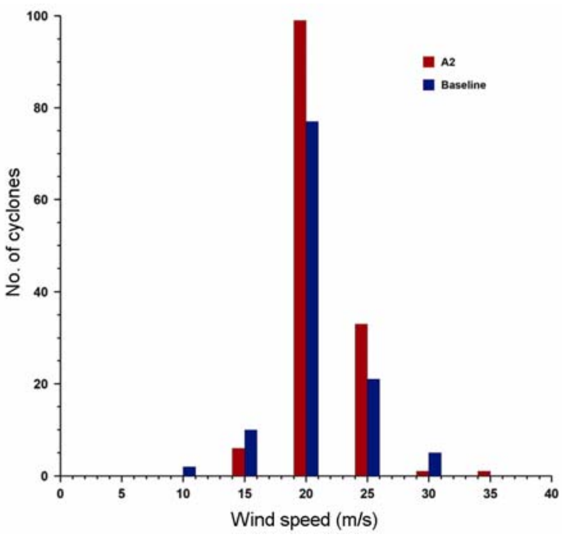

Figure 6. Maximum wind speeds associated with cyclones during the entire period. Blue (red) indicates the baseline (A2) scenario.

Sagar and Kolkata, the increase in 100-year return levels for the future scenario was found to be less than 5%. Figure 7 also indicates a reduction in 1000-year return periods at different stations. In the future scenario with

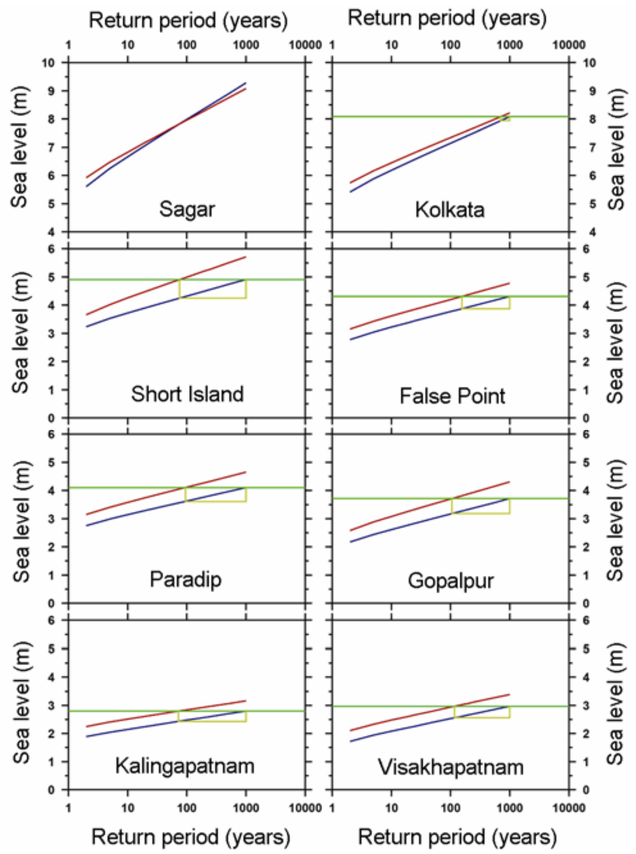

Figure 7. Estimated return levels from 30-year storm surge model runs. Blue (red) line indicates the baseline (A2). Mean sea-level rise of 4 mm/yr is added from 1990 from the current sea level for the model runs for the A2 (2071–2100) scenario. The green line indicates the changes in return period of the future scenario (red) from the 1000-yr return period of the baseline scenario (blue).

increased sea level, 1000-year return period reduces to about 100-year period. However, in regions of large tidal ranges, such as Sagar and Kolkata, the difference in return levels due to sea-level rise is relatively small.

Discussion

The present study analyses changes in the frequency and intensity of cyclones in the future A2 climate scenario compared to a baseline scenario using PRECIS. Uncertainties associated with the PRECIS results for the Indian region are not quantified fully; however, representation of orography and using a fine-grid resolution have helped in obtaining better simulations of rainfall than those from GCMs[16].

Previous studies have not shown any significant trends in the frequency distribution of tropical cyclones in the Bay in the past century. However, many studies point out that intense cyclones have increased in the last century. Regional climate model simulations show an increase in the frequency of cyclones in the later part of the monsoon (August and September) in the future A2 climate scenario, compared to the baseline scenario. Moreover, assessing from the maximum wind speeds associated with cyclones, it is found that the number of intense cyclones also increases in the A2 scenario.

Storm surge simulations were performed for the Bay of Bengal using the wind fields and surface atmospheric pressure from PRECIS. A projected sea-level rise was included for the A2 simulations. The results show that 100-year return levels of extreme sea-level events will increase by 15–20% for locations north of Visakhapatnam in the A2 scenario (2071–2100) compared to the baseline scenario (1961–1990). However, in the head of the Bay, where the tidal ranges are large, increase in return levels is found to be as low as about 5%. Further studies are required to assess the relative roles of mean sea-level rise and changes in the intensity and frequency of cyclones on the projected changes in return levels of extreme events along the east coast of India.

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