Deliverable: MOEN/04/04/02/04b

Report on changes in storm surges from detailed model simulations for the Bay of Bengal

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Contract: RT/COM/4/5015

Version Number: 2

Number of Pages: 22 including cover pages

Table of Contents

Summary

A storm surge is a local exceptional water level that is driven by atmospheric conditions, typically a tropical cyclone. A storm surge can be particularly damaging when it coincides with the normal (and very predictable) gravitational high tide.

This report examines projected changes in storm surges and associated extreme high water levels in the Bay of Bengal under future climate change conditions. To examine these changes, this report details the effect of climate change on tropical cyclone activity in the Bay of Bengal, and discusses the associated changes in the frequency and location of storm surges both with and without the additional influence of tide and average sea level rise on extreme water levels in the north of the region. Further details of the methodology are provided in the following sections, and additional information on the impacts of sea level rise have been detailed in a previous report entitled 'Impacts of mean sea level rise based on current state-of-the-art modelling' (MOEN04/04/02/03).

Key results from this report are:

- The number of tropical cyclones is projected to increase in the Bay of Bengal region under future climate change.
- By the period 2071-2100, the maximum water heights for the extreme 1 in 100 year events are projected to increase by ~0.6 m in the north-east of the Bay of Bengal (location around the town of Cox's Bazaar), and ~1.3 m in the north-west of the Bay of Bengal (location around the town of Baleshwar). This assumes an average sea level rise of 0.5 m across the region.
- The largest changes in extreme water levels in the north-east of the Bay of Bengal are due to the rise in global average sea level. However, in the north-west part of the Bay of Bengal increases in extreme water levels are dominated by storm surges.
- Projections indicate that storm surges in the north-west of the bay may increase water levels by over double that of global average sea level rise, and therefore form an important component of coastal flooding projections in this region.
- Storm surge changes need to be considered in association with regional average sea level rise projections. A previous report under this project entitled 'Impacts of mean sea level rise based on current state-of-the-art modelling' (MOEN04/04/02/03) provides further details on future projected sea level rise and its spatial impacts.

Introduction

At tropical latitudes severe storms often cause significant loss of life and damage to property. At the coast, the detrimental effects of these powerful storms result from high winds and rainfall, and storm surges that are driven by the high winds and low atmospheric pressure. Storm surges are local exceptional water level events (either positive or negative) that are driven by atmospheric conditions, typically tropical cyclones. They are mainly caused by the combined effects of persistent strong wind, low atmospheric pressure and shallow coastal bathymetry. Storm surges interact with the normal (and very predictable) gravitational tidal cycles and are particularly damaging when they occur concomitantly with a tidal maximum.

The coastline of Bangladesh surrounding the shallow northern section of the Bay of Bengal is particularly vulnerable to damage by storm surges. In Bangladesh alone, approximately 30 million people live within 3 m of the current average sea level (Houghton, 1997), and during the past 40 years there have been a number of major storm surge disasters in this region.

To understand the impacts of climate change on coastal flood risk, particularly in regions that are prone to tropical cyclones, it is important to consider the spatial and temporal patterns of average sea level rise and the potential for changes in storm surges as a result of variations in storm activity. A previous report under the Defence and Security Implications of Climate Change project entitled ‘Impacts of mean sea level rise based on current state-of-the-art modelling’ (MOEN04/04/02/03) examines future projections of average sea level rise and the potential spatial impacts. This report focuses on the effects of climate change on tropical cyclone activity and associated storm surges around the Bay of Bengal under two future emission scenarios. It provides an overview of the methodology used to model storm surges from projections of tropical storm activity, and discusses the frequency and location of storm surge projections together with tidal and average sea level rise influences to examine potential changes in extreme water levels in the region.

1. Modelling Tropical Storms

1.1. Regional Climate Model description and scenarios

The PRECIS Regional Climate Model (RCM) is an atmospheric and land surface model of limited area and high resolution which is locatable over any part of the globe (The region used for this project is shown in figure 1, along with the surge model domain).

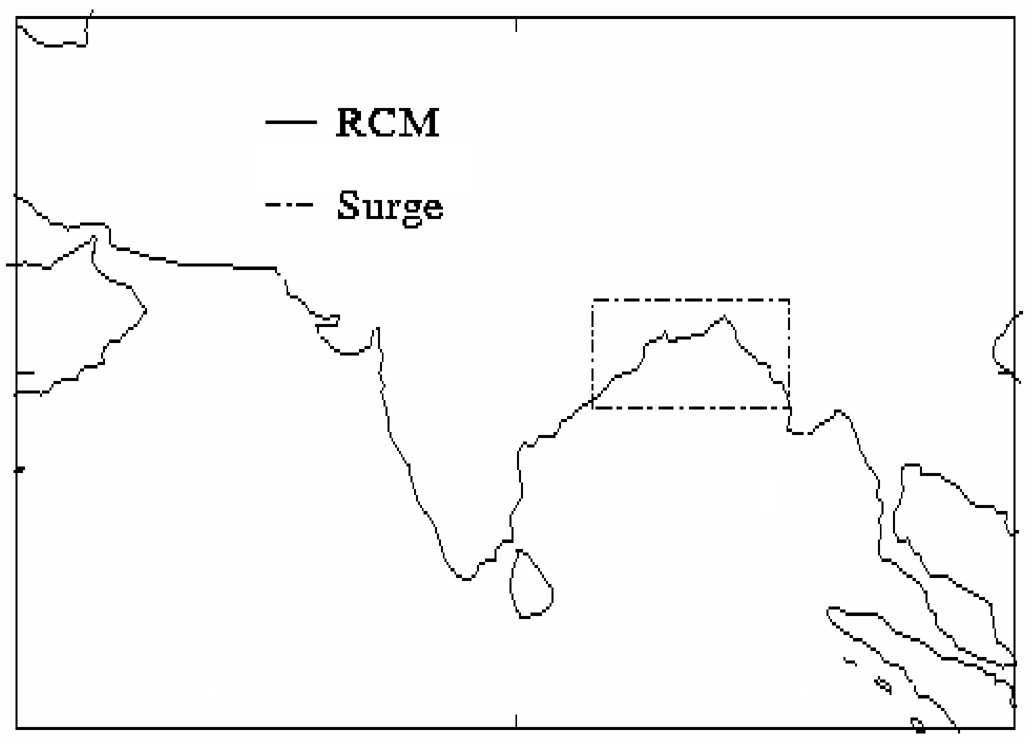

Figure 1. Model domains for the Regional Climate Model (RCM) and storm surge model (Surge) calculations.

Winds, clouds and precipitation, radiative processes, the atmospheric sulphur cycle, the land surface and the deep soil are all treated within PRECIS. It requires prescribed surface (over water only) and lateral boundary conditions. Surface conditions over land are calculated directly by PRECIS. Lateral boundary conditions provide information at the latitudinal and longitudinal edges of the model domain. The boundary conditions in this study are sourced from global climate model experiments.

PRECIS has been run at the Hadley Centre and Centre for Ecology and Hydrology, Wallingford (run by Fai Fung and Frank Farquharson) for a number of 30-year ‘time slices’. These cover the near present day control (1961-1990) and future (2071-2100) for the Special Report on Emissions Scenarios ‘A2’ and ‘B2’ scenarios (see previous report for details).

1.2. Climate change effects on storm number and location – results

The increase in regional mean atmospheric surface temperature between the first decade of the control and future SRES A2 simulation is 3.8ºC over land. As expected, the land warms more than the sea, which is a consequence of the large thermal inertia of the ocean and differences in surface and atmospheric feedbacks over the ocean and land. This latter cause means that even in stabilisation simulations the eventual warming is likely to exhibit a land/sea contrast. The regional mean surface warming in the SRES B2 scenario was 2.5ºC. Changes in surface and atmospheric temperature are likely to occur concomitantly with changes in surface pressure.

Figure 2 shows the pressure at mean sea level during the evolution and transit of a typical tropical cyclone in the control simulation. As the simulations progressed, the winds at 10m above the surface and the pressure at mean sea level were archived at the high temporal resolution needed to simulate storm surges.

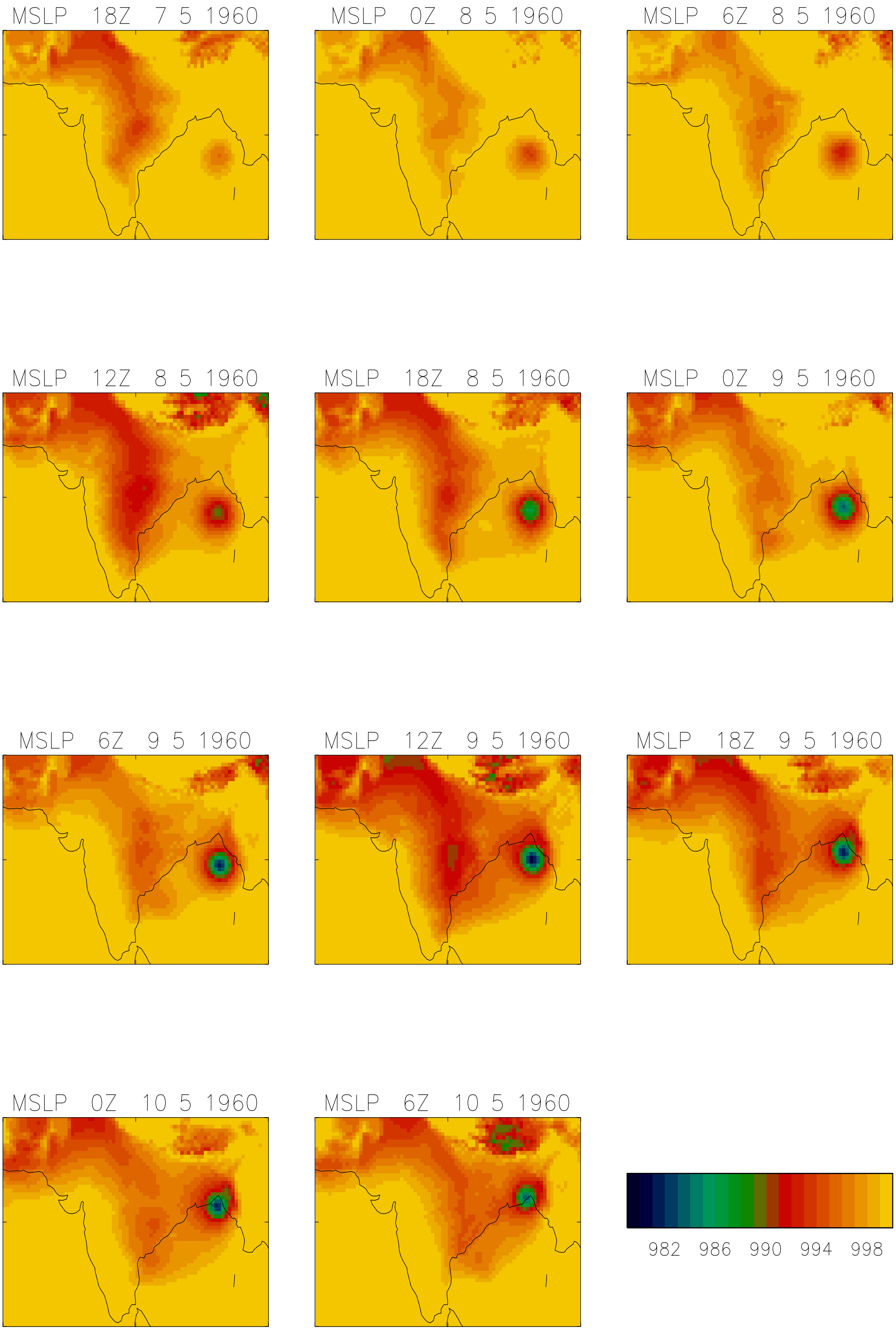

Figure 2. A typical RCM simulated cyclone in the new control simulation. Frames show the evolution at 6 hour intervals. Pressure at mean sea level is in millibars (SI units hPa).

The software package ‘TRACK’, developed at the Centre for Global Atmospheric Modelling, Reading University, was used to track minima in mean sea level pressure in the regional climate model output, which we take as indicating the location of the centre of each modelled tropical storm.

Figures 3 and 4 show the locations of diagnosed tracks from model baseline and A2 runs, respectively, over 30 year periods. Figure 5 shows 28 years of observed tracks taken from the Joint Typhoon Warning Centre (JTWC) database. The main purpose of the colour scheme is to distinguish between tracks: the first storm each year is shown in red, the second in green, the third in blue.

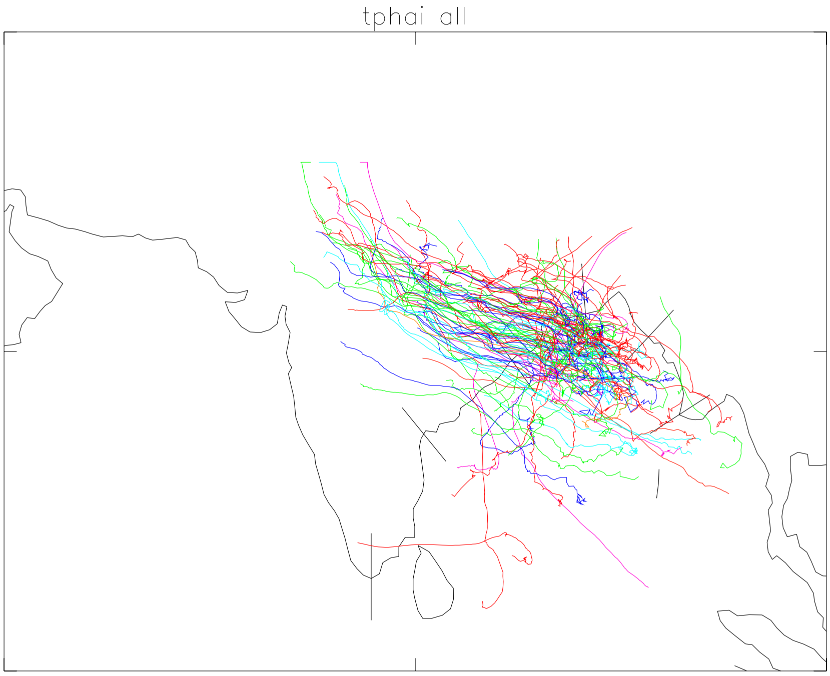

Figure 3. 30 years of modelled cyclone tracks from the Baseline/Control run.

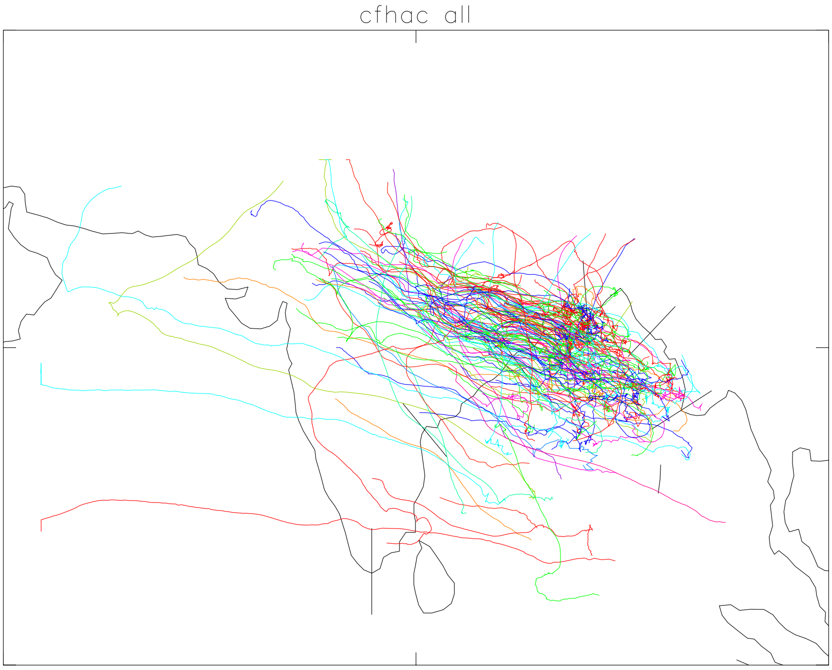

Figure 4. 30 years of modelled cyclone tracks from the A2 run.

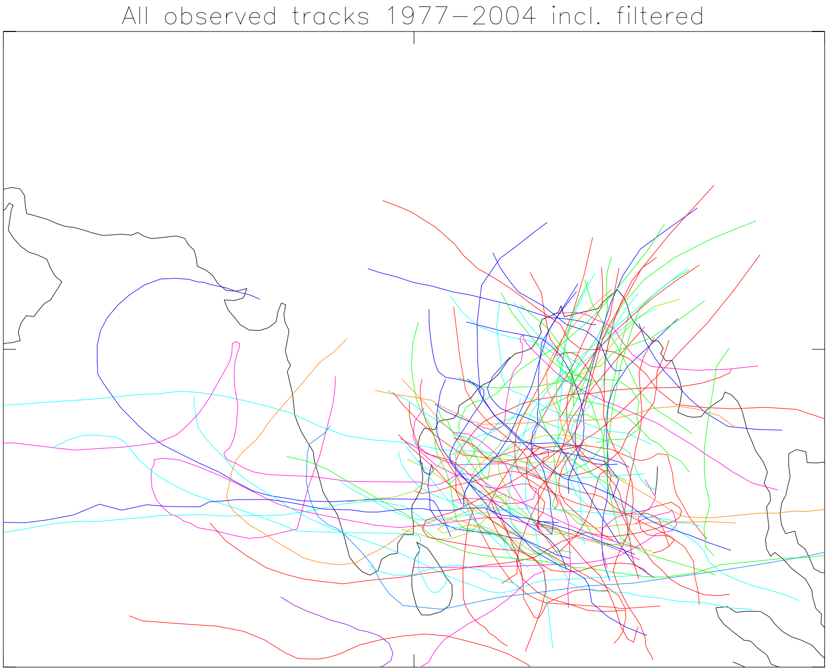

Figure 5. 28 years of observed cyclone tracks from the JTWC database.

The depth of a minimum in MSLP relative to some representative average is known as the central pressure deficit. The largest value of this over the lifetime of a storm is the maximum central pressure deficit. In order to make meaningful comparisons with observations, we tuned our maximum central pressure deficit threshold to give the same mean number of storms per year in our baseline run as in the JTWC database of observations. This was necessary because the “cut off” value of maximum central pressure deficit was not clear for all of the observed storms.

To test the ability of the model to reproduce realistically the year-on-year variability in the number of storms we compared the variance of our 30 year baseline distribution with the 28 year observed distribution using an f-test. The difference was not statistically significant (68% probability that the two samples were drawn from populations with identical variances).

We then used a T-test to compare the mean number of storms in the A2 simulation with that of the baseline and found a statistically significant increase under the future climate (only 1.6% probability that the samples were drawn from populations with identical means). We did a similar test on the B2 model results and found the smaller increase to be still significant (approx 6% probability that the samples come from the same distribution) over the baseline. However the mean numbers of storms in the A2 and B2 results were not statistically separable from each other by this test. Similar results were also found when non parametric tests were used on the data.

Next we examined the spatial distribution of the storm land fall points. First the coastline of the bay was divided into five segments (labelled 0,1,2,3,4 and shown in figure 6) and significance tests performed on the mean number of storms per year crossing the coastline in each segment. These results are shown in the two bar charts (figure 7). It could be argued that this test was unnecessary in the case of baseline versus observations because the differences are so gross that they are immediately apparent from the track plots, but they are included here for completeness. The probability that model and observations agree are largest for segment 1 on the West of the bay. For all other segments it appears highly unlikely that the storm counts in the model and observations were drawn from identical populations. Thus, there are clear limitations on PRECIS’ ability to replicate the precise detail of storm tracks in this region. The reasons for this are the subject of further work.

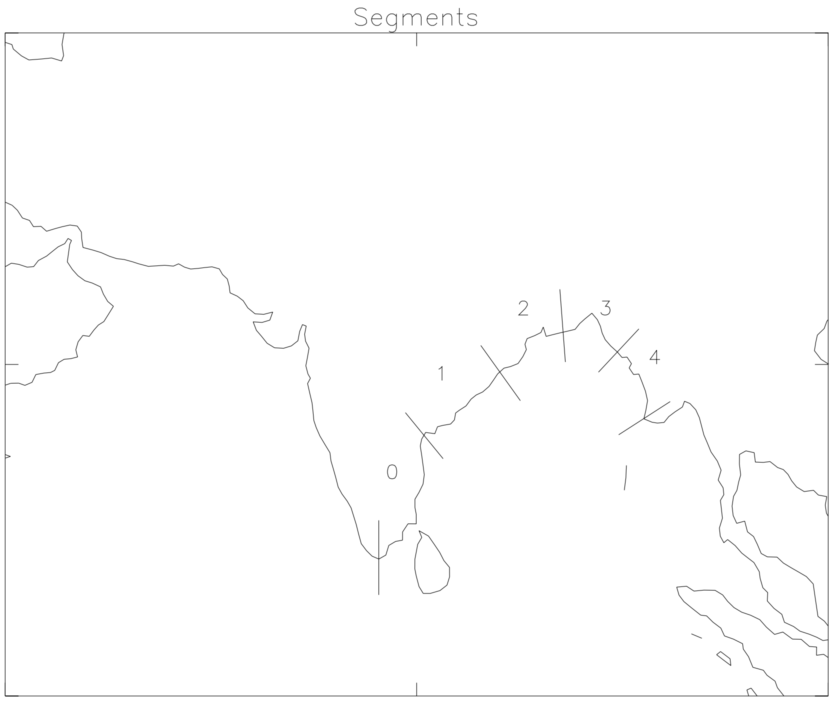

Figure 6. Division of the Bay of Bengal coastline into segments.

While there are clear differences between the A2 scenario and the baseline, it is statistically quite difficult to isolate the spatial detail of the signal at the 90% level (Figure 7b).

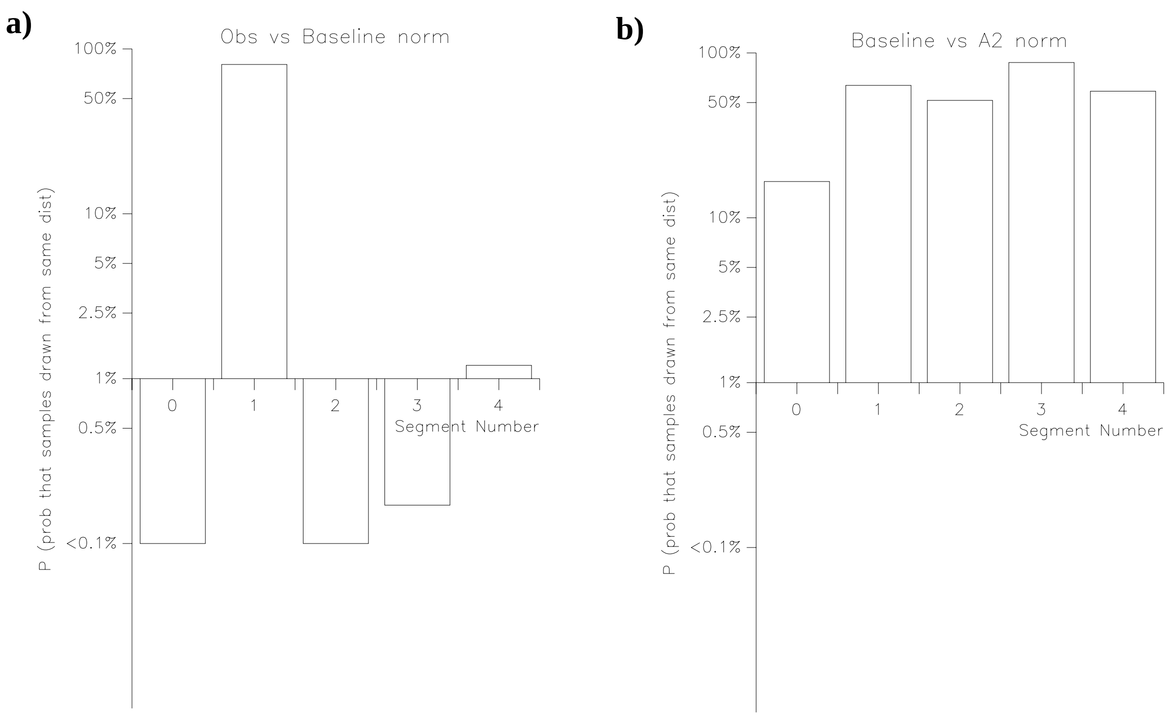

Figure 7. Spatial distribution of storms under changed climate, separating storms with a) significant model bias in the spatial distribution, and b) no significant change in the spatial distribution.

In conclusion, we note that in the baseline scenario we are able to reproduce some observed features of tropical cyclones but there is a bias in the coastal distribution of landfall. We also note that the spatial distribution of tracks and the accompanying track counts clearly show increases in the predicted number of storms under both the A2 and B2 SRES future emissions scenarios.

2. Extreme Water Level Modelling

2.1. Description of storm surge model & relative sea level rise

The storm surge model of the northern Bay of Bengal was developed at the Proudman Oceanographic Laboratory (POL), Liverpool. It has been set up and validated for tidal simulation and against idealised cyclones. The model is based on that of Flather (1994), which was used in a previous study of the devastating storm surge that struck Bangladesh in April 1991.

The depth mean storm surge model used in the current study remains similar to that of Flather (1994). The height of the water surface above mean sea level and the depth mean currents are determined using a continuity equation and a momentum conservation equation. The surge model equations were solved using a finite difference method on a regular latitude-longitude grid of approximately 10 km resolution. The region represented by the model was approximately 20^{o}N to 23^{o}N by 86^{o}E to 93^{o}E. Changes in sea surface elevation were applied at the open boundary to represent the effect of tides. At the coastal boundaries, the normal component of the depth mean current was set to zero. We would like to acknowledge the work of Kevin Horsburgh at POL towards the setting up and running of the storm surge model for this study.

The meteorological forcing from the regional climate model was linearly interpolated in space onto the surge model grid and linearly interpolated in time at every surge model time step between the hourly results of the regional climate model. Two separate surge model runs were carried out for each future climate scenario. The first run was driven by both tidal and meteorological forcings. The second run was driven by tidal forcing alone. Surge heights were determined by subtracting the tide only results from the tide plus meteorological forcing results. This approach made it possible to include non-linear interactions between the tide and surge components.

Analysis software has been developed to extract the upper extreme percentiles of total water level and the surge residual. These are shown in section 2.2 for the baseline (1961-1990) and future projections (2071-2100). At point locations, annual maxima have been fitted to a ‘Gumbel’ extreme value distribution. This enables the extreme water level results to be extrapolated to longer return periods. The results of this are shown in section 2.3.

The effect of having large channels in the current study is mainly to reduce the potential height of positive surges along the coast line by providing an additional reservoir for coastal water. However, the channel treatment is too simplistic for the simulated surge heights within any particular channel to be considered realistic. It is for this reason that the locations chosen for the results in section 2.3 are all on the ‘open sea’ coastline of the model, and not on channels.

It is important to note that the changes in extreme water level analysed here are only one component of water level changes in a particular region. To consider potential regional changes in the total water level, extreme changes need to be added to changes in local relative sea level, which is affected by changes in global average sea level and by regionally-specific vertical land movements. Further details on the spatial distribution, uncertainties and impacts of sea level rise projections are detailed in a previous report for this Defence and Security Implications of Climate Change (DSICC) project, entitled ‘Impacts of mean sea level rise based on current state-of-the-art modelling’ (MOEN04/04/02/03).

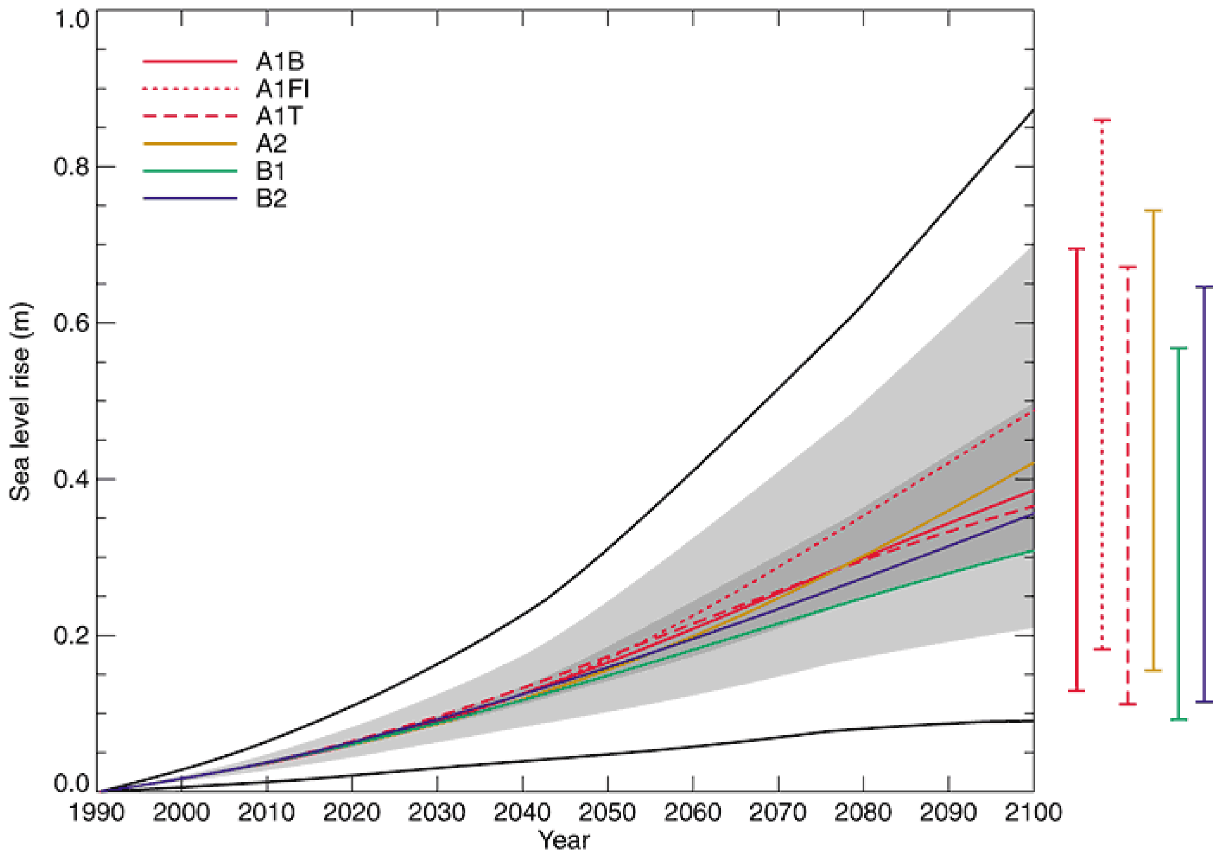

Figure 8. Global average sea level rise 1990 to 2100 for the SRES scenarios. (Reproduced from IPCC TAR Figure 11.12; see this reference and DSICC report MOEN04/04/02/03 for full details).

2.2. Water levels and storm surges for different extreme events - Results

Extreme water levels were calculated for the 99th, 99.9th and 99.99th percentile water levels at each point in the surge model domain. Spatial distributions of these percentiles are shown in figure 9, and the specific storm surge component of these heights (the residual of water level heights with and without tidal forcing) are shown in figure 10.

In general, extreme water levels (figure 9) and the storm surge component of these levels (figure 10) increase under either of the future climate scenarios. For the most extreme water levels (99.99th percentile), the largest increases (~0.25m for A2 scenario and 0.35m for B2 scenario) occur to the west of the region, along the West Bengal and Orissa coastlines. Increases in the intensity and frequency of storm surges (without the tidal component) are the main reasons for these high water levels (figure 10). An exception to this general trend occurs along the north-eastern coast of the bay. Here both the extreme water levels and storm surges show a general decrease, but this is only noted under the B2 scenario, for the A2 scenario water levels and storm surges are generally increasing in this region. Furthermore, even though increases in the concentration of greenhouse gases and air temperatures are smaller in the B2 scenario extreme water levels in the north-west of the bay are larger. A full understanding of this apparent anomaly requires further research.

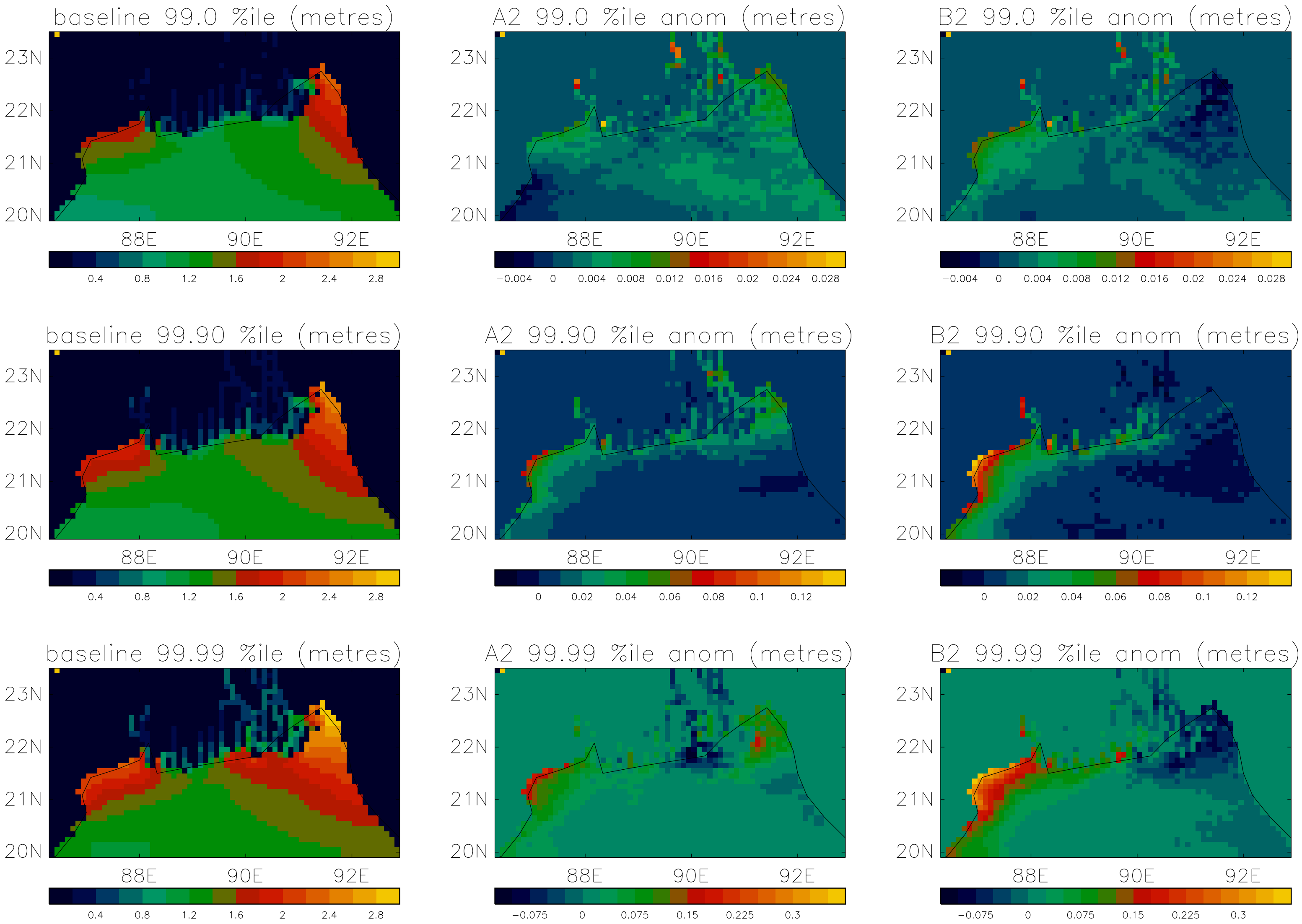

Figure 9. 99.0%, 99.9% and 99.99% percentiles of extreme water levels in the surge domain, showing values from the baseline time slice (1961-90) and changes arising under the A2 and B2 future scenarios (2071-2100 average minus baseline).

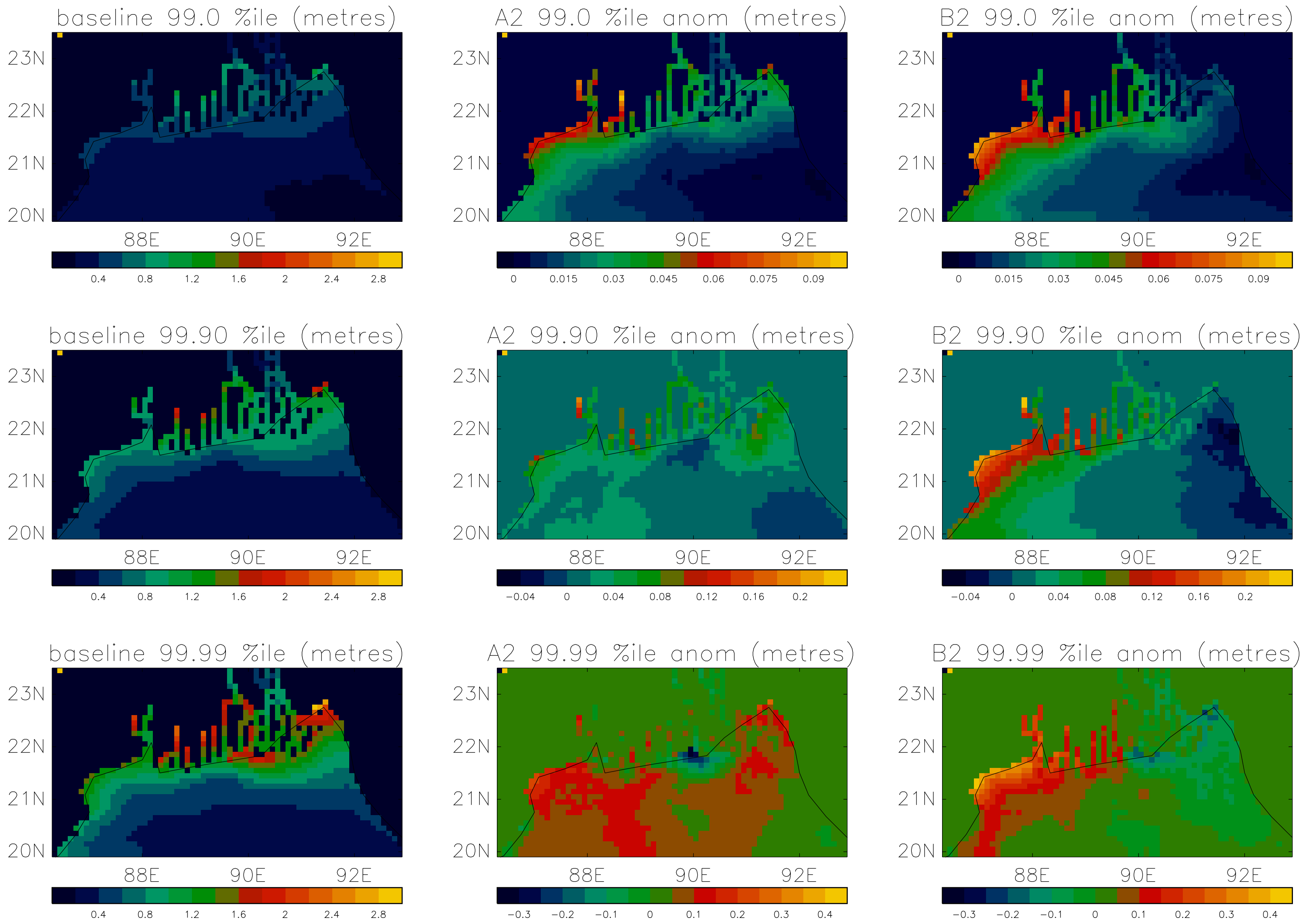

Figure 10. As in figure 9 but for residual storm surge elevation (i.e. after removal of the tide component).

2.3. Extreme water levels and storm surges at specific locations - Results

Model pixels were selected from around the bay. For reference, the name of a nearby place is used to identify each pixel. The place names, and the corresponding pixel centres, are:

Baleshwar	87.05ºE	21.45ºN
Cox's Bazaar	91.85ºE	21.65ºN
Chittagong	91.75ºE	22.35ºN
Noakhali	91.05ºE	22.55ºN

For each pixel, the annual average maximum water level (surge plus tide relative to mean sea level) and storm surge residual (relative to mean sea level) were analysed.

For the surge plus tide results on the north-east of the bay, at Cox's Bazaar, the most extreme water levels are higher in the A2 simulation than in the present day simulation (baseline/control). Conversely, for B2 they are lower than in the present day. Without a change in average sea level neither future water level is statistically separable from the present day simulation at the 90% level (using a t-test), and they are also not separable from each other. However, adding in a change in average sea level of 0.5 m does make the future periods separable from the present day. We draw a similar conclusion from the storm surge residuals, but the significance levels of the t-test are lower. Using this technique and experimental design, it appears that the change in storminess (as manifested in the change seen in local water levels) is too small at this site to be isolated from the natural variability.

On the north-west of the bay, at Baleshwar, there is a statistically significant increase (t-test significance of 90%) in the water levels of both the A2 and B2 from the present day levels. However, they are not statistically separable from each other. Both the A2 and B2 extreme water levels are significantly higher than the present day extremes (the sign of the change is similar on this side of the bay), but the magnitude of the B2 change is larger than the A2. Since they are not statistically separable, this again indicates that a sizeable part of the change is due to natural variability. The A2 and B2 extreme water levels are more difficult to separate from the present day levels in the residual storm surge minus tide results, although they are still statistically significant at a 90% level.

The final part of our analysis involves fitting ‘Gumbel’ distributions to the annual maximum water levels and residuals and examining the change in return period of particular events between the baseline and future simulations (figure 11).

Including average sea level changes of 0.5m, the maximum increases in water heights for the extreme 1 in 100 year events are ~0.6 m at the Cox’s Bazaar location (north-east of bay) under the A2 scenario, and ~1.3 m at the Baleshwar location (north-west of bay) under the B2 scenario. In the north-east part of the bay (Cox’s Bazaar location), the largest changes in extreme water levels and storm surges alone are due to the rise in the average sea level, represented by the difference between the coloured solid and dashed lines in figure 11b and d. However, in the north-west part of the bay (Baleshwar location), the largest increases in extreme water levels are dominated by the storm surge component, as shown by the difference between the black line and coloured lines in figure 11. These projections indicate that storm surges in the north-west of the bay may increase water levels by over double that of global average sea level rise, and storm surges therefore form an important component of coastal flooding projections in this region.

Considering these results, it is suggested that future work should focus on better understanding of the driving storms and their changes within RCMs, and combining storm surge changes with regional uncertainties in average sea level. Improvements in the baseline (present day) return period curves using higher resolution surge models will also be useful.

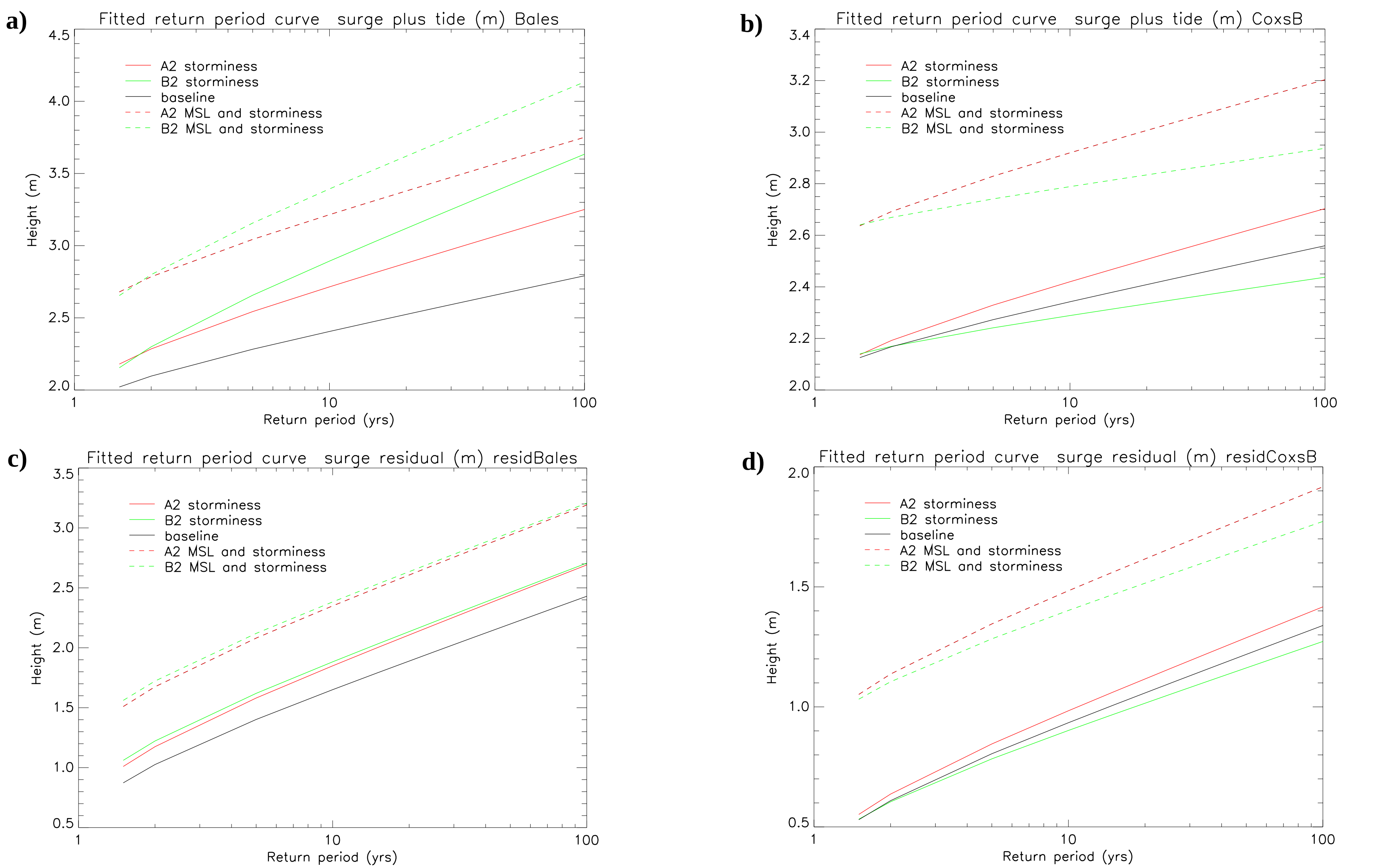

Figure 11. Return period curves for baseline and future changes in storminess and in time average sea level (neglecting non linear depth effects of mean sea level on surges) under A2 and B2 scenarios. Figures a and b are surge plus tide results and c and d show surge residuals only, for the Baleswar (north-west of bay) and Cox's Bazaar (north-east of bay) locations, respectively.

Conclusions

We report on changes in storm surges in the Bay of Bengal under two different SRES scenarios, A2 and B2. Projections were made using a RCM, storm tracking software, and a barotropic storm surge model driven by surface wind and pressure from the RCM.

Results indicate that the large-scale surface features of tropical cyclones in the Bay of Bengal are credibly simulated with the regional climate model. The observed year-on-year variability of tropical cyclones is also captured reasonably well by the regional climate model and storm tracking software. However, it is noted that the spatial distribution of simulated cyclones is biased in comparison to the observations.

Results also show a statistically significant increase in the number of tropical cyclones per year for either of the changed climate scenarios but the difference between the two is not detectable in these simulations.

Combining the climate model simulations of tropical storms with projections of global average sea level rise, results indicate that the largest increases in extreme high water levels at the north-eastern part of the Bay of Bengal (Cox's Bazaar location) are dominated by the rise in average sea level across the area. However, in the north-western part of the bay (Baleshwar location), the largest increases in extreme water levels are dominated by the storm surge component.

The heights of the extreme 1 in 100 year storm events are projected to rise by ~0.6 m at the Cox's Bazaar location (north-east of bay) under the A2 scenario, and ~1.3 m at the Baleshwar location (north-west of bay) under the B2 scenario. Projections therefore indicate that storm surges in the north-west of the bay may increase water levels by over double that of the global average sea level rise. As such, they are an important consideration for future coastal flooding risk in this region.

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Flather R.A. 1994. A storm surge prediction model for the northern Bay of Bengal with application to the cyclone disaster in April 1991. Journal of Physical Oceanography, 24, 172-190.

Houghton J.T. 1997. Global Warming the complete briefing. 2nd Edition. Cambridge University Press.