# Climate Change and Storm Surges: Assessing Impacts on Your Coastal City Through Mike Flood Modeling

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**Keywords**
Climate change, sea level rise, storm surge, urban flooding, Mike Flood.

**Abstract**
The effects of climate change on sea levels and coastal flooding are some of the most prevailing issues in the engineering industry today. In this study, a comprehensive procedure for detailed analysis of flooding from the sea under climate change conditions in a localized area was developed and applied. Through hydrodynamic and statistical modeling, detailed analysis of flooding from sea level rise and storm surges could be performed using general climate change information. Time series data for extreme sea level events for a climate scenario were derived through climate modeling and statistical analysis. Then, a Mike Flood model for the area made up of a Mike Urban model and Mike 21 surface flow model was used to simulate flooding from the derived extreme sea level events. The statistical analysis considers both peak and duration of the extreme events, and the flood modeling considers both terrain relief and presence of underground pipes in flow computations. The procedure has strong scientific bases in its use of hydrodynamic computations to simulate flow over surfaces and through pipes. It gives distributed, time-varying flooding information in all parts of the model area for the duration of the event and it shows the role of drainage networks in conveying flooding further inland. The procedure provides useful flooding information for the development of specific adaptation measures that are also easily used for generating flood maps such as those required by the EU Flood Directive.

## INTRODUCTION

Coastal areas are put under greater risk from flooding due to climate change. The occurrence and intensity of extreme events are likely to increase under climate change conditions in the future (Beniston et al., 2007; IPCC, 2007). The assessment of climate change and its effects by the Intergovernmental Panel for Climate Change (IPCC) shows that mean sea levels will rise between 28-43 cm by 2090-2099 depending on future emissions scenarios, and that the incidence of extreme high sea levels will increase (IPCC, 2007). A study by Grinsted, et al. (2010) indicates that sea level rise will be nearer to 70-160 cm, or about three times the projections by the IPCC. There is widespread growing concern about sea level rise because of the recognized seriousness of its potential additional impacts on coastal communities in terms of flooding (Michael, 2007; Nicholls, 2002). Problems relating to climate change are widely recognized and there is currently great interest in performing impact and adaptation studies. Impact studies generally begin with the estimation of changes to the environmental drivers such as sea water levels, temperatures, etc. due to changes in climate. Lowe and Gregory (2005) investigated the effect of increased greenhouse gas concentrations on storminess and storm surges using physical models, while in Denmark, regional climate modeling and statistical analysis were used by Madsen (2008) to estimate future extreme sea levels in Køge Bay under climate change conditions. The impacts of changed atmospheric storminess on coasts in terms of flood risks are then determined for the next stage of the impact study. Past analyses, like those summarized by Storch and Woth (2008), have used dynamical or empirical modeling to determine impacts to harbors and near-shore regions. However, they have mainly been regional analyses covering relatively large areas and having low resolutions, as in Woth, et al. (2006).

This study presents a comprehensive technique for high-resolution modeling of flooding in a coastal area due to storm surges under climate change conditions. The technique combines climate modeling, statistical analysis and hydrodynamic modeling to estimate climate change effects on storm surges and to simulate the resulting flooding. Climate change effects on mean and high sea levels are quantified for a selected emissions scenario and then translated into time series data that can be used in flood modeling. This study also aims to illustrate the advantages of the new technique in terms of producing physics-based flood information detailed enough to be useful for local decision-making in coastal communities. To test the new technique, it was compared to the Terrain Analysis method of flood calculation, and then applied for the coastal area of Greve in Eastern Denmark.

## METHODOLOGY

The technique for high-resolution climate change flood modeling comprises of two main parts as shown in *Figure 1*. The first part is derivation of extreme sea level event time series under climate change conditions. Then, the design time series are used as input for hydrodynamic flood modeling with Mike Flood in the second part.

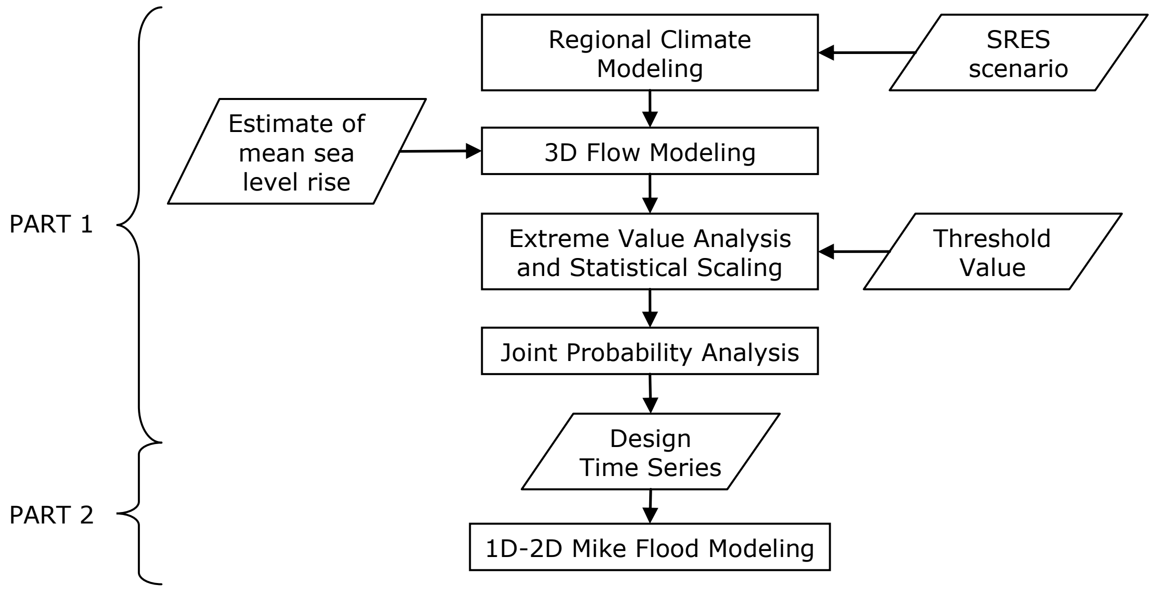


*Figure 1: Schematic diagram of the climate change flood assessment technique.*

## Derivation of extreme sea level event time series

Regional climate modeling had been performed by the Danish Meteorological Institute (DMI) under the ENSEMBLES project (van der Linden and Mitchell, 2009), which was about the development of a collective prediction system of climate change based on European tools and data. They used the regional HIRHAM model (Christensen, et al., 2007) for a transient simulation covering the period 1951-2100. The model had a grid resolution of about 12 km and it was forced with the SRES A1B Scenario (Nakićenović, et al., 2000). Wind and air pressure data were obtained from results of the HIRHAM model simulations.

3D flow modeling of the seas around the study area was performed in order to obtain corresponding sea levels to earlier-simulated climate conditions. Mike 3–a 3D modeling system for estuaries, coastal waters and open seas (DHI, 2009), was used to build the model which covered the North Sea, Baltic Sea and the inner Danish waters. Air pressure and wind data obtained from the climate modeling were used to drive the Mike 3 model.

Mean sea level and its variation over the simulation period needed to be considered in the 3D flow modeling. In the study, it was assumed that the mean sea level is +1 m higher in the Future Scenario based on findings of Grinsted, et al. (2010), which indicate that IPCC 2007 projections of sea level rise for 2090–2099 are underestimated by roughly a factor of 3.

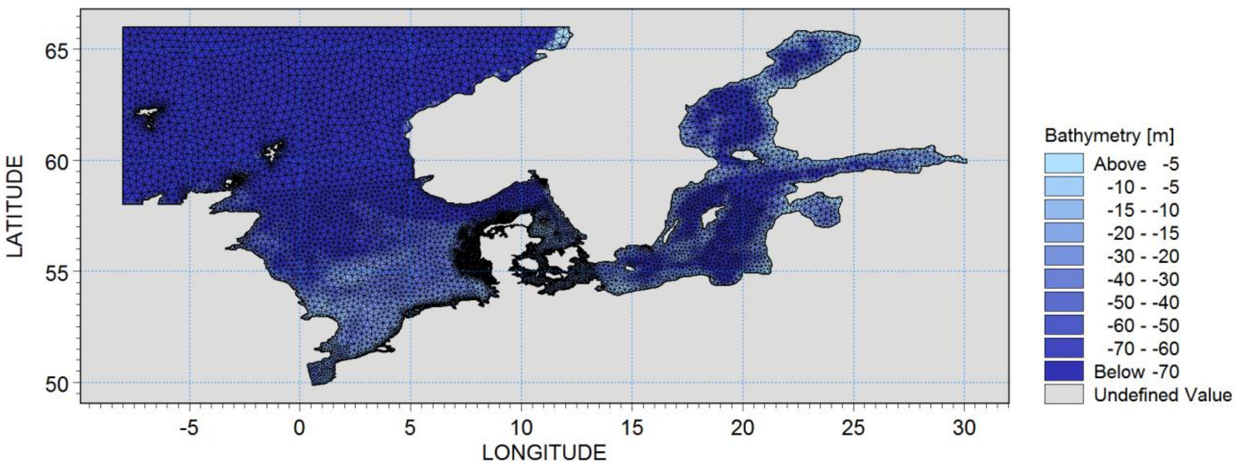


*Figure 2: Mike 3 FM flow model of the North Sea, Baltic Sea and inner Danish waters.*

Water level values were obtained from the 3D flow model in the areas of Køge and Drogden near the study area. They were statistically analyzed to determine appropriate change factors used for scaling actual extreme sea level statistics into Future Scenario estimates. Observed sea level statistics available in the study were sea levels in Køge and Drogden, and event durations in Drogden.

Subtracting mean levels from simulated sea levels in the extreme value analysis ensured that only storm surge statistics were considered. A threshold of 0.85 m above Mean Sea Level (MSL) was set to identify extreme sea level events, and the analysis was carried out for 1960-1990 corresponding to the Present period, and 2070-2100 for the Future period.

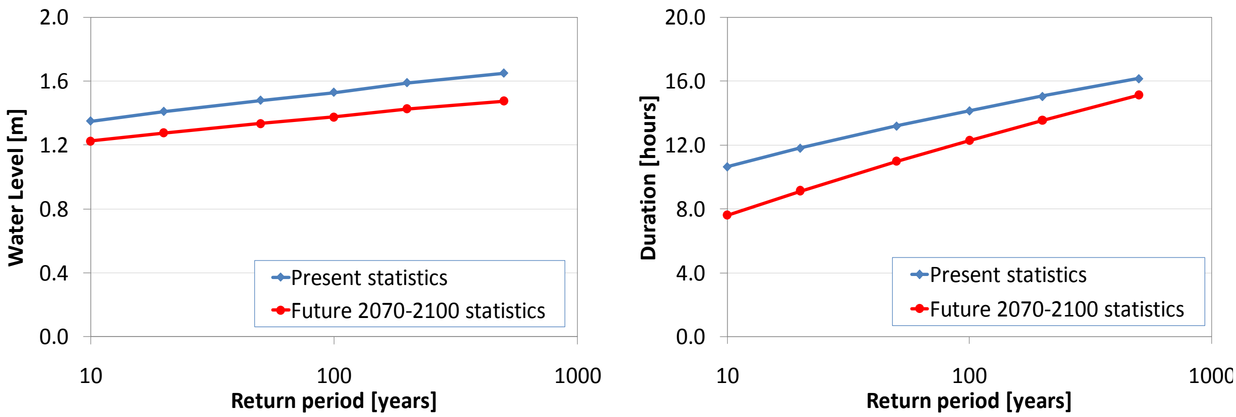


*Figure 3: Extreme value statistics for simulated Water Levels (Left) and Durations (Right) for Present (1960-1990) and Future (2070-2100) periods.*

*Figure 3* compares projected downscaled water level and duration statistics for the Future period to those of the Present period. The analysis found projected Future extreme water level statistics to be lower than Present statistics (by 12-17 cm for return periods between 10 and 500 years). Similarly, projected extreme duration statistics were found to be less than Present statistics (by 1-3 hours). The lesser extreme value statistics for the Future period are consistent with the higher mean sea level, which reduces the wind setup in the coastal region.

After obtaining marginal distributions of extreme water levels and durations for the Present and Future periods, the Joint Probability Method was applied in order to determine water level-duration combinations for different events of particular return periods. The method uses Copula functions to define the correlation between peak and duration of extreme sea level events. Detailed description is given by Pinya, et al. (2009).

The last step in deriving extreme sea level event time series is designing the variation pattern based on past observed extreme sea level events. Time series values were derived using patterns identified from observed events in Drogden, and the resulting time series are shown in *Figure 4*.

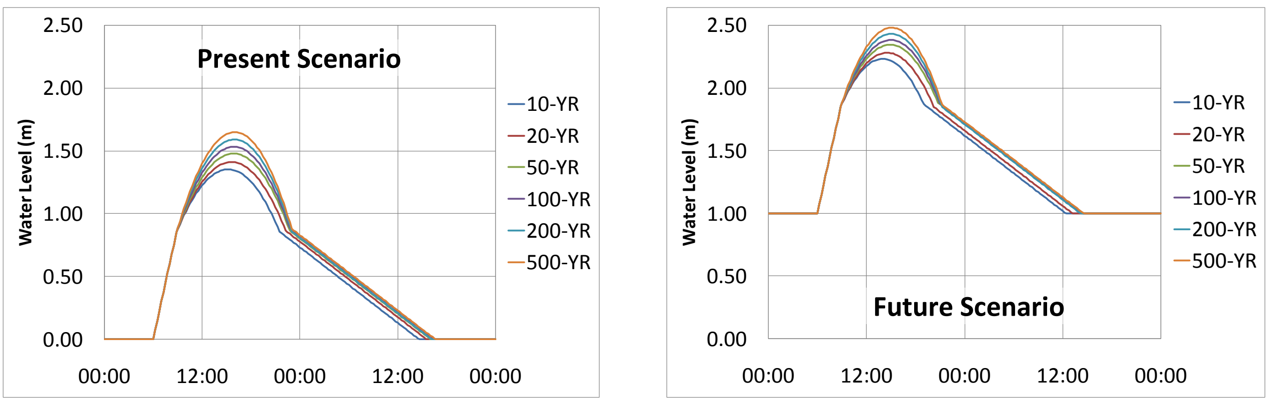


*Figure 4: Derived time series for extreme water level design events for Present (Left) and Future (Right) periods.*

## Hydrodynamic flood modeling with Mike Flood

A hydrodynamic model is used to calculate possible flooding from storm surges in the coastal zone. Mike Flood, a modeling system that integrates one-dimensional and two-dimensional hydrodynamic models into a single, dynamically coupled system (DHI, 2009b) is used. In the Mike Flood model, a 2D surface flow model of the coast is linked to a 1D model of the drainage system to simulate flooding in the coastal zone.

The 2D surface flow model of the coast is built with Mike 21, a modeling system for 2D free-surface flows used in simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas and seas (Mark, et al., 2008; Rungø and Olesen, 2003). Unsteady two-dimensional flows are numerically solved over a grid of equally spaced cells. The grid represents the terrain and is an important component of the model. Surface features such as dikes and waterways must be described in enough detail to consider their influence in overland flow calculations. The Mike 21 model of the test area in this study covered a 1.2 km x 9 km strip of the coast in Greve (*Figure 5*). In order to be able to consider flow along roads but still optimize computation time, a grid resolution of 5 m x 5 m was used in this study.

The 1D drainage system is included in the modeling in order to consider the influence of drainage pipes and channels in flood propagation. It is built with Mike Urban, a system for modeling and design of water distribution networks and collection systems for wastewater and stormwater. Its hydrodynamic pipe flow model numerically solves the complete St. Venant equations throughout the drainage network using an implicit, finite-difference computational scheme (DHI, 2009c). It is important to include drainage structures that sit below the maximum estimated sea level, especially along the coast, to ensure that all possible routes of flooding from the sea are considered. In this study, the drainage model of the test area used was relatively detailed consisting of around 7000 nodes, 6500 links and 9 sea outlets (*Figure 5*).

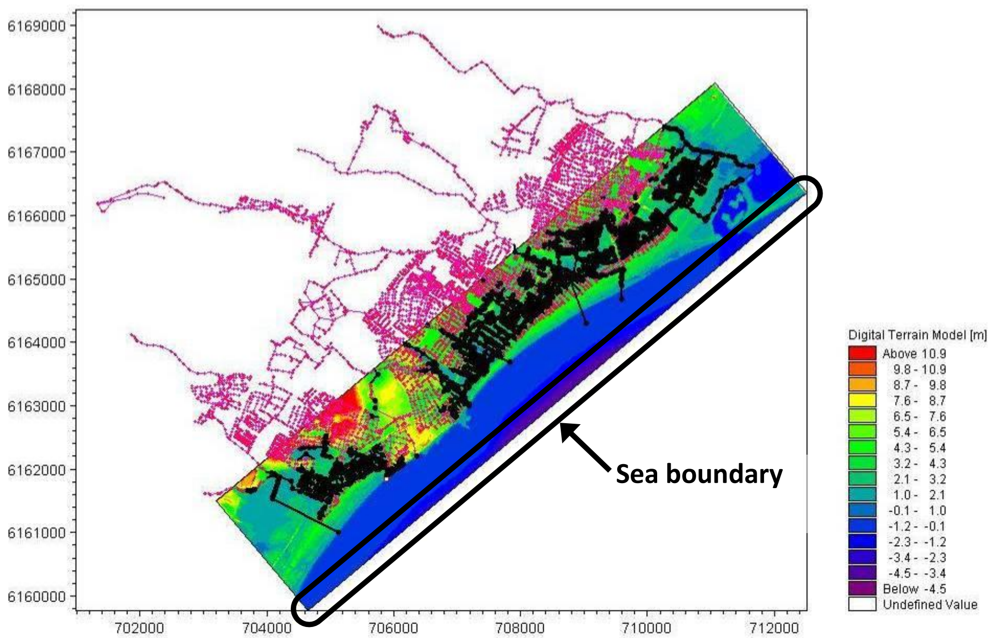


*Figure 5: The Mike Flood model for the test area showing the integrated 2D surface and 1D drainage network models and showing the location of the open sea boundary.*

The 2D surface flow model and the 1D drainage model are dynamically linked with Mike Flood at identified points of flow exchange between the two systems, such as at drainage outlets, unsealed manholes, and open channels. Flow exchange can be in both directions—from the surface into a manhole or inlet, or from a surcharged manhole onto the surface. The weir equation is used to describe most of the computational links, wherein flow is determined based on calculated head differences in the linked network node and terrain grid cell(s) (Mark and Djordjević, 2006). Links to sea outlets are described with the orifice equation since they are expected to be mostly submerged. In this study, the terrain model was linked at node points where the ground level was less than 3.7 m—the highest sea level recorded in Køge Bay in the last 1000 years (Madsen, 2008).

The Mike Flood model is driven by varying sea water levels at the open sea boundary. Extreme sea level time series derived as described in the first part of this paper are used as boundary conditions for the Mike Flood model. Initial water levels in drainage outlets are set according to the estimated mean sea level for the scenario of interest. For example, in this study, Present Scenario simulations used 0 m MSL while Future Scenario simulations used 1 m MSL. Initial sea levels are also specified in the 2D model using distributed grids for MSL values. Land cells with elevations lower than MSL and having overland connections from the sea were initialized as wet cells in the modeling. This study assumed extreme sea level events occur independent of extreme rainfall. Nevertheless, rainfall may be easily applied to the modeling system if extreme scenarios with high water levels occurring at the same time as significant rainfall should be simulated.

To calibrate this type of linked 1D-2D model, the 1D drainage model is first calibrated on its own by comparing its results against observed data such as flows and water levels at key points in the system. The full 1D-2D model is then evaluated against measured flows and water depths in both systems. The parameters of both the drainage and surface flow models may be adjusted within the bounds of rational values representing reality. For this study, attaining models that fit reality would presumably only be relevant for simulating Present scenarios. It should however be noted that the flexible, physically-based and distributed description of parameters in the models allow for their easy adjustment for simulation of other various hypothetical scenarios.

## METHOD ASSESSMENT

The new technique for storm surge flood modeling was assessed by comparing it to traditional Terrain Analysis. Terrain Analysis is performed by subtracting terrain elevation from water level to compute for flood depth. It calculates flooding in all areas below the given water level including areas behind dikes. Maximum water depths were extracted from Mike Flood results and compared to Terrain Analysis results. Terrain Analysis was performed on the same area as the 1D-2D model domain.

The comparison used scenario results for 100-YR extreme water level under the Present Period in the test area. The peak sea level was 1.53 m. The comparison showed that more flooding is calculated by traditional Terrain Analysis than by Mike

Flood.  There was around 0.8 MCM flood volume over 1.8 $km^2$ of area from Terrain Analysis—twice that in Mike Flood, which computed only around 0.47 MCM of water over 0.9 $km^2$ of area.  Flooding was calculated by Terrain Analysis in some areas just because of land elevations that were lower than the peak water level.  Over common flooded areas, Terrain Analysis computed higher depths than the 1D-2D model, with a mean difference of around 14 cm and a standard deviation of 0.15.  This is because Mike Flood considers the dynamics of wave propagation and friction losses through underground pipes and over land surface in calculating flow and flood depths. Traditional Terrain Analysis, where all areas below a certain water level are flooded, can give irrational results of flooding in areas without any connection to the sea.  To avoid this, the technique can be modified by assuming that flooding will stop at dikes and high terrain and not flow to low lying areas behind them.

Modified Terrain Analysis was also applied in the test area and the results compared to those of Mike Flood.  It was found, however, that inflow through underground pipes occurred and could not be considered by the modified Terrain Analysis technique. Mike Flood model results indicated that there was flow of water inland through the drainage network, especially since the area is relatively flat and is well-connected to the sea through a dense drainage network.  Mike Flood results showing inland flooding brought through the drainage network in one part of the study area is shown in *Figure 6*.

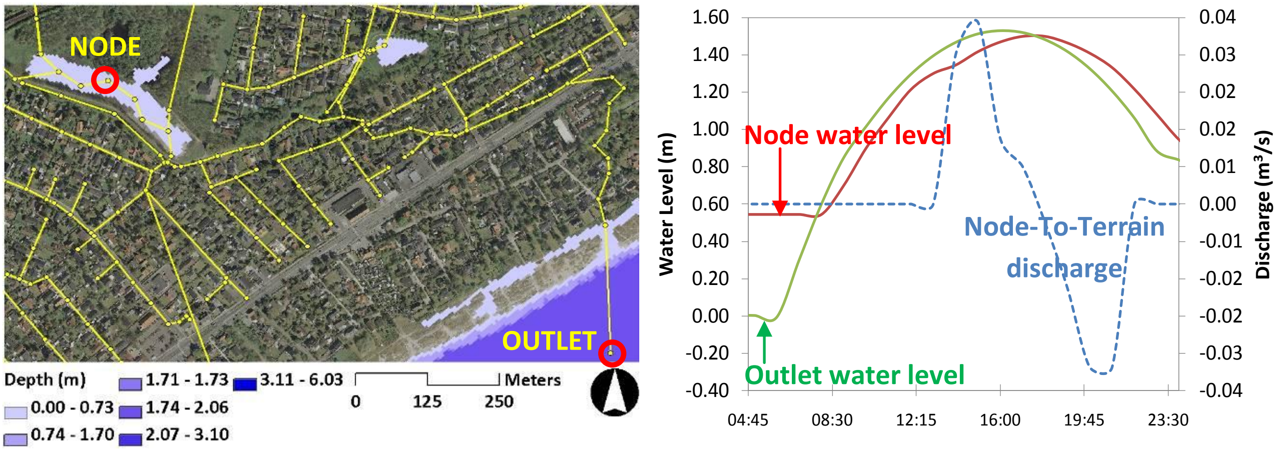

*Figure 6: Inland flooding calculated from Mike Flood showing locations of an outlet to the sea and a drainage node in the flooded area (Left).  On the right are plots of computed water level in the flooded node and sea level at the outlet shown against discharge from the node to the terrain.*

In *Figure 6*, the plot on the left shows flooding in an area inland (northwest corner) about 700 m from the coast.  Pipe network modeling results indicate that water from the sea travelled through the drainage system by entering the outlet (shown in *Figure 6*) and emerging through several nodes in a low-lying area inland, one of which is encircled in *Figure 6*.  The plot on the right in *Figure 6* shows water level variations in the sea outlet and in the selected node inland where flooding occurred.  The plot also shows flow exchange between the node and the terrain above it.  It shows that water flowed out from the drainage system onto the ground surface as can be seen from the positive values for "node-to-terrain" discharge.   The negative values for "node-to-terrain" discharge indicate that eventually, space was freed in the pipes and the water re-entered the drainage network when the sea surge subsided. Comparing the plots of node water level and outlet water level, peak water levels were reached about 1 hr apart in the sea and inland. The lag in node water level response shows that the flood wave took some time to propagate—a phenomenon that could not be reflected by Terrain Analysis.

## ASSESSING CLIMATE CHANGE EFFECTS ON FLOODING

Distributed and time-varying flood information in the entire model area can be obtained through application of this new technique for storm surge flood modeling. When applied for assessment of climate change impacts, comparison flood maps are readily generated from distributed computations of water depths and velocities. For example, *Figure 7* shows a comparison of calculated flood extents for 100-YR Present and Future SRES A1B Scenario events in a part of the test area.

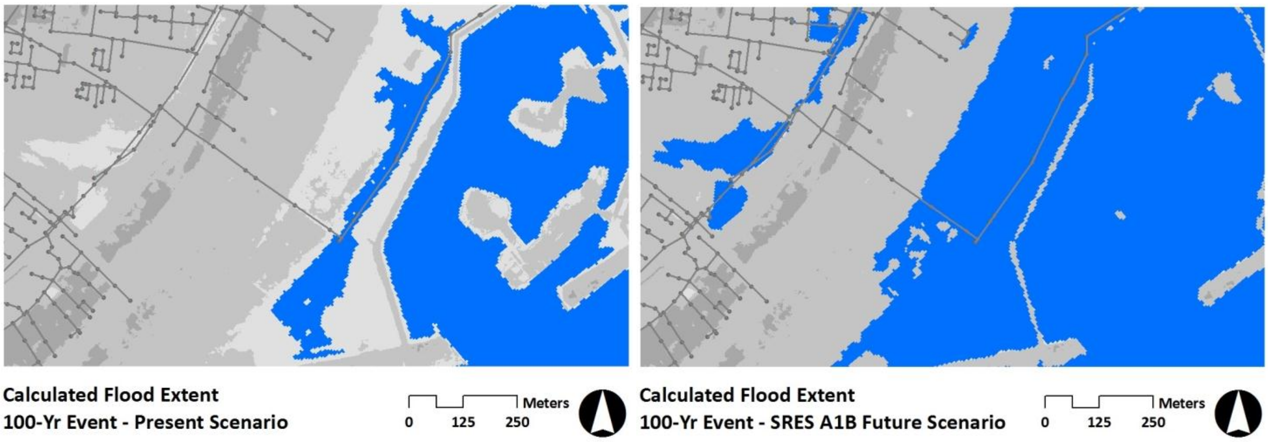


*Figure 7: Comparison of simulated flood extents for Present (Left) and Future SRES A1B Scenario (Right) 100-YR extreme sea level events in part of the test area.*

The technique was applied in the area of Greve in order test its performance in assessing climate change impacts on storm surge flooding in an area. Storm surge time series for Future and Present Periods were obtained as presented in *Figure 4*, showing values for peak levels as well as event durations. In this case, results show that peak and duration values in the Future Period are lower than in the Present Period. Present scenario 100-YR storm surge has a peak of 1.53 m and a duration of 14 hrs, while Future SRES A1B scenario storm surges has a peak water level of 1.38 m above future MSL and a duration of 12 hrs. Nevertheless, it must be noted that since future mean sea level is estimated to be 1 m higher than it is at present, the total sea level heights in the Future Period would still be higher than for the Present Period.

Applying the second part of the technique, Mike Flood simulations showed climate change significantly increased flood extents due to storm surges in the test area. For a 100-YR extreme event, flood extent increased from 0.9 $km^2$ in the Present Scenario to 3 $km^2$ in the Future Scenario. Flood depths also increased, such that in one common flooding point for both scenarios, maximum flood depth increased from 0.3 m (Present) to 1 m (Future). Model results showed water reaching as far as 1.6 km inland in the northeast end of the test area near a stream, wherein water flowed through the channel and emerged at the calculated farthest point around 1 hr after peak water levels were reached in the bay. So, aside from distributed and time-varying flood information, other information that could be obtained from the technique include: fluxes and flood velocities showing flow direction; discharge and water depths in pipes and channels; and flow exchange at all linking points between the drainage system and the terrain. These can be very useful for local communities and decision-makers in developing specific adaptation measures like emergency response procedures for an area. They can also be easily used for preparing flood maps that fulfill technical mapping requirements such as those of the EU Floods Directive.

## CONCLUSIONS

A new comprehensive technique for detailed assessment of climate change impacts on storm surges and flooding in urban coasts has been presented in this study. It is a two-part technique involving: (1) climate modeling, 3D flow modeling, and statistical analysis for deriving extreme sea level event time series from climate change projections; and (2) 1D-2D hydrodynamic storm surge modeling with Mike Flood that combines 1D pipe flow and 2D surface flow computations for detailed modeling of coastal flooding that can simulate water movement not only over the land surface but also through underground pipes. The first part used 3D flow modeling and statistical analysis to derive extreme event time series that could be used in hydrodynamic modeling. A strong point of the procedure is it recognizes and rightly considers the relevance of both peak water level and duration of extreme events, and takes the correlation of both parameters into account in the analysis through use of the Copula Method. Then, application of 1D-2D Mike Flood modeling showed its advantages over other methods like Terrain Analysis in simulating and mapping flooding from the sea. It is physics-based and uses hydrodynamic computations to simulate flow over surfaces and through underground pipes, and it is able to provide time-varying and distributed flooding information in all parts of the model area for the whole duration of the event being simulated. Finally, it considers the role of underground pipes in conveying flood waters from the sea to various low-lying areas inland. The new technique for detailed analysis of flooding from the sea that has been presented in this paper provides comprehensive information on the calculated flooding giving data on extents, peak, peak time, duration, depth, and velocity everywhere in the area. These can be very useful for local decision-makers and communities in their development of specific adaptation measures for their area, as well as for preparing flood maps that easily fulfill technical mapping requirements such as those of the EU Floods Directive.

## ACKNOWLEDGEMENTS

The modeling procedure that has been presented in the study was developed in collaboration with the Municipality of Greve in Denmark.

## REFERENCES

Christensen, O.B., Drews, M., Christensen, J.H., Dethloff, K., Ketelsen, K., Hebestadt, I., Rinke, A., and Poulsen, J.W. (2007). The HIRHAM Regional Climate Model Version 5 (β) H. Technical Report 06-17, Danish Meteorological Institute.

DHI (2009). MIKE 3 Flow Model FM, Hydrodynamic Module, User Guide. DHI, Denmark, 116 pp.

DHI (2009b). MIKE FLOOD User Manual. DHI, Denmark, 114 pp.

DHI (2009c). MIKE URBAN - Model Manager. DHI, Denmark, 388 pp.

DHI (2009d). MIKE 21 Flow Model, Hydrodynamic Module, User Guide. DHI, Denmark, 118 pp.

Greve Kommune (2007). Oversvømmelserne i Greve Kommune: Juli 2007. http://www.greve.dk/~/media/migration%20folder/upload/oversvommelserne_i_greve_kommune_juli_2007.pdf.ashx (accessed 15 August 2008).

Grinsted, A., Moore, J.C. and Jevrejeva, S. (2010). Reconstructing sea level from paleo- and projected temperatures 200 to 2100 AD. Climate Dynamics, 34 (4), 461-472.

IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

van der Linden, P. and Mitchell, J.F.B. (eds.) (2009). ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

Lowe, J.A. and Gregory, J.M. (2005). The effects of climate change on storm surges around the United Kingdom. Philosophical Transactions of the Royal Society A, 363, 1313-1328.

Madsen, H. (2008). Vandstandsstatistik i Køge Bugt under klimaændringer. Report by Danish Hydraulic Institute for Greve Kommune. http://www.greveforsyning.dk/dokumenter/Klima/Vandstandsstatistik %20i%20K%C3%B8ge%20Bugt%20under%20klima%C3%A6ndringer%20dec08.pdf (accessed 03 November 2008).

Mark, O. and Djordjević, S. (2006). While waiting for the next flood in your city…. In: 7th International Conference on Hydroinformatics, Nice, France.

Mark, O., Svensson, G., König, A., and Linde, J.J. (2008). Analyses and Adaptation of Climate Change Impacts on Urban Drainage Systems. In: 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

McInnes, K.L., Walsh K.J.E, Hubbert, D. and Beer, T. (2003). Impact of Sea-level Rise and Storm Surges on a Coastal Community. *Natural Hazards*, **30**(2), 187-207.

Michael, J.A. (2007). Episodic flooding and the cost of sea-level rise. Ecological Economics, 63, 149-159.

Nakićenović, N., Davidson,O., Davis, G., Grübler, A., Kram, T., La Rovere, E.L., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R. and Dadi, Z. (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K., 599 pp.

Nicholls, R.J. (2002). Analysis of global impacts of sea-level rise: a case study of flooding. Physics and Chemistry of the Earth, 27, 1455–1466.

Pinya, M.A.S., Madsen, H., Rosbjerg, D. (2009). Assessment of the risk of inland flooding in a tidal sluice regulated catchment using multi-variate statistical techniques. Physics and Chemistry of the Earth, 34 (10-12), 662-669.

Rungø, M. and Olesen, K.W. (2003). Combined 1- and 2- dimensional flood modeling. In: 4th Iranian Hydraulic Conference, 21-23 Oct, Shiraz, Iran.

von Storch, H. and Woth, K. (2008). Storm surges: perspectives and options. Sustainability Science, 3, 33-43.

Woth, K., Weisse, R., von Storch, H. (2006). Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. Ocean Dynamics, 56 (1), 3-15.