Chesapeake Bay sustainability: Implications of changing climate and shifting management objectives

The intent of this workshop is to

1) Share the results of model simulations of natural system responses to climate change adaptation strategies

2) Discuss hypothesized consequences of climate change on linkages between the human and natural components of the system

3) Build interdisciplinary collaborations for sustainability research to be proposed to the Coastal SEES Program in 2015

The Coastal SEES program (CSEES) has a focus on the sustainability of coastal systems and proposed research is expected to further the understanding of the dynamics of this coupled human-natural system in order to inform societal decisions about the uses of coastal systems.

Our long-term research goals are to develop an advanced modeling framework that integrates the physical, biogeochemical, and human components needed to simulate and select climate change adaptation strategies that will support a sustainable system.

With funding from the Coastal SEES program, we used a hypothetical storm surge barrier at the Bay mouth and representative storm simulations to study the impacts on estuarine dynamics, fisheries production, and potential flooding risks, with emphasis on feedbacks to the human system.

Using fine resolution hydrodynamic models and a broader-scale whole-ecosystem model, estuarine responses to representative storms with a storm surge barrier in place were:

- An increase in stratification (less mixing)
- Increase in salinity intrusion due to weak tidal mixing
- Reduction in tide range by as much as 0.3 m
- Residence time will decrease (by ~ 5-10 days near the mouth)
- Significant increases in salinity near the mouth and middle Bay
- Increase in Vertical Transport Time (time to transport surface saturation dissolved oxygen water to the bottom) which could lead to increased hypoxia events
- Overall reduction in tidal wetlands

How will climate change and human adaptation to climate change modify fisheries, flooding, and other ecosystem services in a coupled human-natural system?
Sea level in Chesapeake Bay is affected by changes in three general factors. The result for coastal Chesapeake Bay has been a long-term, and recently accelerating, rise in the level of tidal waters.

1. **Volume of water in the ocean increasing due to 2 factors:** Glaciers, ice caps, and ice sheets in Greenland and Antarctica are melting, adding water that was stored on land surfaces to the ocean basins. At the same time, the water in the oceans is warming causing it to expand.

2. **Elevation of Chesapeake Bay’s coast is sinking:** The primary cause is the continuing adjustment of the earth’s crust to the melting of glaciers from the last ice age. Secondarily, groundwater withdrawal contributes to local subsidence.

3. **Changes in ocean circulation:** Changes in the location and rate of the Gulf current off the coast of Virginia affects water levels.

In Virginia, sea level is rising at the fastest rate of any of the Atlantic states, second only to the Gulf states. Analysis of historic data puts measured sea level rise rates on approximately the high (yellow) scenario below. We anticipate ~0.6m rise in sea level by 2050.

**This will significantly affect natural resources and increase human risk in the Chesapeake Bay.**

Sea level rise will increase the vulnerability of human infrastructure and natural resources to flooding.

Human infrastructure at risk includes: houses, businesses, roads, tunnels, airports, stormwater and sewer systems, and utilities.

Sea level rise is also predicted to increase coastal erosion. Many of our coastal resources are critical components of a natural system to reduce coastal flooding. Sea level rise and coastal erosion eat away at the extent of marshes, beaches and shallow water areas, reducing both their extent and their capacity to reduce flood impacts.
Climate change cascades: A cascade is defined as a process that occurs in successive stages, each of which is dependent on the preceding one, and often producing a cumulative effect.

Climate change cascades occur when a species or process not directly affected by changes in temperature or precipitation responds to climate change due to a change in a related species or process that is strongly affected by changes in temperature or precipitation. A cascade may be a linear relationship or a complex interconnected network. The diagram on the right illustrates some ways that a changing weather system can reverberate through natural systems and impact health and human safety as well as economic activities.

For example:
- Sea level rise
  - change in salinity distribution
  - change in Estuarine turbidity maximum location
  - location of phytoplankton bloom
  - availability of food for zooplankton population
  - availability of food for jellyfish and ctenophore populations

Adapting to climate change:
Shifting climatic conditions, such as sea level rise and changes in the frequency or intensity of storms, are predicted to increase flood damage. Predicting the impact of these changes allows localities to target adaptation strategies which will mitigate both current and future flooding. Practically, only sea level rise changes can be predicted with any level of confidence. Although some research has been done on changes in storm patterns, Chesapeake Bay receives heavy precipitation from both tropical systems (tropical storms and hurricanes) and Nor’easters, which respond to different climatic forces. This makes changes in precipitation patterns difficult to predict.

Most sea level rise adaptations are aimed at reducing flood losses and are particularly focused on reducing storm surge impacts, since storm surge impacts will increase with sea level rise, causing damage in currently unaffected areas.
Pore (1965) studied hurricane-generated storm surges in the Chesapeake Bay. The hurricanes in the Bay can be grouped into two categories, namely Type A and Type B storms. The Type A storms are those storms that approach the Bay from the east and pass to the north of the Bay. Type B storms are the storms that approach the Bay from the south quadrant and passes over south of the Bay. The representative hurricanes are Hurricane Isabel (2003) and Hurricane Floyd (1999), respectively. Besides hurricanes, the northeaster (or nor’easter) is another kind of storm that is less intense but more frequent, lasts longer, and impacts larger areas within the Chesapeake Bay.

The hurricane Isabel approached the Bay from the east and moved towards the northwest. It generated storm surge in both the lower Bay and upper Bay, which caused the largest damage in the Bay region.

The hurricane Floyd approached Bay from the south and moved toward the northeast. The hurricane generated a strong northeasterly wind, which caused set-down in the upper Bay region and storm surge in the lower Bay. A local high of surge occurred near Hampton Roads due to the local southerly wind and the Ekman transport that transported a large amount of water from outside of the Bay into the Bay (Shen et al., 2006).

Prepared by the Coastal SEES Research team.

References:
This study investigated the response of the Bay hydrodynamics to different types of storm surge barriers near the mouth. The typical storms we selected for the investigation are:

- Isabel (1993)
- Floyd (1999)
- Ernesto (2006)

Hurricane Isabel caused the largest damage in the Bay. Ernesto was a tropical storm that was similar to a Nor'easter in that it generated a strong northeasterly wind and caused large surge in the lower Bay region.

Wind from different directions can have different impacts on the Bay. The surge will be generated resulting from combined effects of local and remote winds. In general, southerly winds generate surge in the upper Bay and northerly winds generate surge in the lower Bay; Northeasterly winds generate surge in the lower Bay, while westerly winds generate set-down inside the Bay.

An example of typical surge generated by northerly, southerly, northeasterly, easterly, and northwesterly winds of 15m/s over a three-day period (Shen and Gong, 2009)
Influence of Storm Surge Barrier on Vertical Transport Time and Hypoxia

The vertical transport time (VTT) is a timescale used to measure the required time for transporting surface saturation dissolved oxygen (DO) water to the bottom. Its variability in summer indicates the influences of external physical forcings on summer DO in the Bay. The interannual variations of the VTT depend on freshwater discharge, tide, and wind. A short VTT indicates a fast DO aeration, which reduces hypoxia volume in the Bay (Shen et al., 2013). We used the VTT to quantify the influences of storm surge barriers on the bottom water DO in the Bay for this study.

- Closing the Bay mouth with a storm surge barrier only during hurricane events has a minor influence on the vertical transport time.
- Building a permanent storm surge barrier will result in an increase of VTT (ranges from 5-8 days) that will degrade DO conditions in the Bay.

The distributions of long-term averaged (a) summer vertical transport time (days) and (b) DO (mg/l) have very similar patterns along the mainstem of the Bay. High VTT corresponds to low DO in the middle and upper Bay regions. VTT and the bottom DO are highly correlated.

Distribution of VTT (days) along the mainstem of the Bay. A larger VTT is located in the middle-upper Bay with persistent low DO

- a: Existing condition in 2003
- b: Permanent partial closure of the Bay mouth
- c: Permanent closure of a large section of the Bay mouth except two large deep channels.

Construction of a permanent storm surge barrier will affect the VTT. The magnitude of influence depends on barrier size. With closure of a large portion of the Bay mouth, the VTT will increase by more than 5 days in summer resulting in a decrease of oxygen near the bottom.

With construction of a large permanent barrier at the mouth, DO condition will be further degraded during the summer (bottom panel (b)) comparing to the current condition (upper panel (a)).

Reference: Shen, J. Hong, B. Kuo, A. 2012. LO, 56(6), 2237-2248.
Residence time is one of the key parameters to quantify overall dynamic condition of an estuary. Nixon et al. (1996) suggest that the retention of and export of nutrients are controlled by the residence time. The retention time is a key parameter that controls nutrient budgets in estuaries. We investigated the influence of a storm surge barrier on change of residence time. We also examined the change of freshwater transport time, which is represented by the water age (Shen and Wang, 2007), due to the use of a temporary and permanent storm surge barrier.

- A short-term closure of the Bay mouth during the storm surge period has a minor impact on residence time.

- A large permanent storm surge barrier will result in a decrease of freshwater transport time. The change of the transport time near the mouth is about 5-10 days. The 200-day contour is moved far outside of the estuary.

We used a conservative tracer to simulate residence time. The tracer was released inside the bay at Day 230, 30 days before hurricane Isabel. Closure of the Bay mouth occurred during Days 260-262.

- The residence time is estimated as the time corresponding to the total mass decrease to the fraction of $e^{-1}$ (e-fold).
- Total mass increased during the storm as outside water began moving into the Bay.
- A short-term closure of the Bay mouth during the storm has minimal impact on residence time.

For a large permanent storm surge barrier with two open deep-water channels, water in the surface layer moves rapidly out of the Bay because of a decrease of tidal mixing. The 180-day contour can reach to the mouth and the 200-day contour is located far outside of the mouth.

In the case of a hypothetical permanent storm surge barrier, the transport time of the freshwater, which is indicative of residence time, will be altered. The magnitude of change depends on the barrier size. With half closure of the Bay mouth, the transport time of the bottom water increases near the mouth. However, the transport time decreases with closure of a large portion of the Bay mouth. The 200-day contour moves further downstream. The different responses of the estuary to the size of the storm surge barrier need more study.

The change in salinity due to the use of different types of temporary storm surge barriers during representative storms was investigated using a numerical model.

- Temporary closure of the Bay mouth during storms will result in a moderate change of salinity.
- Vertical mixing during the storm surge period is dominated by the strength of the local wind forcing; therefore, no significant difference in vertical mixing occurred for different scenarios.
- Noticeable changes in salinity occur near the mouth and middle Bay.

Change in vertical mean salinity in different regions of the Bay during Hurricane Isabel was investigated. Three scenarios, temporary partial-closure of the Bay mouth, temporary near complete closure of the Bay mouth (except for 2 open deep-water channels), and temporary full closure of the Bay mouth for a 2-day period, were examined. The results were compared to current conditions with and without hurricane. The ‘without hurricane’ case was simulated by turning off the wind and replacing open boundary conditions with harmonic forcings. The influence period is about 40 days. A marked difference occurs in the middle Bay region. The salinity difference between the different cases are about 1-2 psu.

Vertical mixing occurred during the hurricane. Local wind is the dominant forcing to cause vertical mixing. A marked change occurs near the mouth among the different scenarios.
Influence of Permanent Storm Surge Barrier on Salinity and Residual Current

The change in salinity due to the placement of a permanent storm surge barrier was investigated using numerical model.

- Permanent partial closure and near complete closure of the Bay mouth exert little change on the mean summer residual current.
- Permanent partial closure and near complete closure of the Bay mouth result in an increase of salinity intrusion.

Change of residual current during summer time was estimated, with respect to a simulated storm surge barrier that either a) permanently closed half of the Bay mouth, or b) almost all of the Bay mouth (with the exception of 2 open deep-water channels). The results were compared to the current conditions for 2003. The change of mean residual current is not very significant. The weak response of mean residual current to different scenarios is not well understood and requires more study.

The summer mean salinity distribution shows that salinity intrusion reaches farther into the Bay for a permanent near complete closure. The increase of salt intrusion is probably due to a decrease of tidal mixing.

Prepared by the Coastal SEES team
The hydrodynamic model generated tidal ranges for current conditions (Figure A) and the closure scenario. The hypothetical storm surge barrier is shown as the black line across the Bay mouth. Currently, the highest tidal ranges occur at the mouth of the Bay and in the upper reaches of the lower Bay tributaries (e.g. James and York Rivers). Lowest ranges occur along the main stem of the Bay.

The current tidal ranges were subtracted from the closure scenario to yield tidal range differences (Figure B). Negative values mean that the closure led to a reduction in the tidal range; positive values mean the closure led to an increase in the tidal range. The hypothetical barrier lessens the tidal range inside the Bay, with a greater effect seen in the lower Bay. Just outside the barrier the tidal range is enhanced.

The change in tidal range has implications for the extent of wetlands and effects of storm surge throughout the Bay.
Marshes in the Chesapeake Bay are currently threatened by slow, continual erosion, periodic storm event erosion, human development and sea level rise.

Sea level rise is a significant pressure, and where human development impacts the shoreline, marshes are being squeezed between shoreline development and rising tides. This is predicted to result in a loss of approximately 40% of marshes by 2100¹.

Given the number of narrow, fringing marshes in the Chesapeake Bay, the loss of even a linear meter of shoreline through erosion or sea level rise can significantly impact total marsh acreage, and the resulting, narrower marshes are less resistant to periodic erosion.

The Chesapeake Bay and its tributaries (MD and VA) have approximately:
- 27,438 ha of Salt Marsh
- 123,651 ha of Brackish Marsh
- 26,345 ha of Tidal Freshwater Marsh

Marsh communities are controlled by both inundation and salinity level. Marshes typically grow between mid-tide and spring tide elevations, with an expanse of mudflat occupying the low to mid-tide elevations. Extensive marshes are found throughout the Bay; however, marshes have been lost over the past century to shoreline erosion and shoreline protection efforts.

Closing the mouth of the bay affects tide range, which then shifts the appropriate habitat to new areas. The model shows a loss of approximately 10% of total marsh area.

Marsh locations are shown before and after changes in water level due to closure of the mouth of the Bay at a site in Virginia (left) and Maryland (right).

Prepared by SEES Research team

There are many species of SAV in the Bay; however, there are only two species capable of living in the higher salinity zones: eelgrass and wigeongrass.

Eelgrass (*Zostera marina*) distribution has declined over time in the Bay; beginning with a wasting disease in the 1930’s and then followed by impacts from large storm events and increased turbidity and pollution in the middle of the 20th century. Despite restoration efforts, the eelgrass population has never recovered in many areas of the Bay and its tributaries.

Eelgrass is particularly sensitive to low light and high nutrient conditions. In turbid waters, eelgrass cannot photosynthesize sufficiently to thrive. In areas with high nutrients, excess epiphytic algal growth coats the eelgrass, also reducing photosynthesis. Where the two conditions occur in concert, the impacts to eelgrass are multiplied.

Eelgrass can help stabilize sediments, reduce turbidity, and serves as a nursery habitat to many prey and fishery species (including blue crabs). Loss of eelgrass beds are expected to resonate up the food chain.

Stresses related to climate change that affect eelgrass survival include:

- Increased frequency and duration of high summer water temps, > 30°C (86°F)
- Increased rainfall = Increased runoff of sediments and nutrients = Decreased light availability
- Light requirements of eelgrass increase with increasing temps
- Increased storm intensity and frequency
- Increased water level or shoreline hardening = declines in habitat area

*A massive bay-wide decline in SAV populations was observed during 2005 due to high summer temperatures (>30°C)*
The Chesapeake Atlantis Model

Currently, there are multiple, ongoing and large-scale system changes taking place in the Chesapeake Bay system. Some of these changes are a consequence of climate change, while others are mandated by current regulations to improve Bay water quality. One consequence of climate change is more frequent, large storm events like type A and B hurricanes (Pore 1965) which will have specific effects on the Chesapeake system. One short term effect (with long term, and far-reaching consequences) is the projected loss of current, preferred marsh habitat in the system. Simulations suggest such marsh loss may produce a synergistic loss of submerged aquatic vegetation (SAV). Simultaneously, there have been ongoing, efforts coordinated by EPA to decrease both nitrogen and sediment loads to the system. Once likely physical changes to the system have been simulated by hydrodynamicists, the effect of these changes has to be understood in terms of the biological and ecological changes that are likely to result in the system. For this study, this is accomplished with an ecosystem modeling approach called "Atlantis."

The code for the model was developed by scientists at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia (Fulton, 2004 #1864; Fulton, 2004 #1866). Atlantis integrates physical, chemical, ecological, and fisheries dynamics in a spatially-explicit, three dimensional model structure. The approach has been identified as the best ecosystem model in use by the U.N. Food and Agriculture Organization {Plagányi, 2007 #1828}, and has been used to advise decision-making for nearly a decade in Australia and it has been applied in multiple applications in the US as well (reviewed by Fulton et al, 2011).

In this comparison of three different scenarios of habitat change, the productivity effects that result from the system changes are compared to a status quo scenario based on conditions of the current Chesapeake system (dashed line). Plotted lines are median values for 20-30 years of predicted ecosystem dynamics, where: (1) 50 percent of marsh (biomass and area covered) is lost (blue), (2) 50 percent of submerged aquatic vegetation is lost (green), and (3) suspended solids are decreased (pink).

When marsh is lost, most fish groups decrease substantially, but forage fish decrease only slightly from status quo; however, submerged aquatic vegetation (SAV) production also decreases by 30 percent, while phytoplankton and birds both increase. In contrast, when the system suffers a loss of SAV, relatively little difference is seen in fish groups, while all other plants increase and birds increase by more than 40%. When suspended sediment loads are decreased, bird production again increases strongly, but under these conditions, all fish also become much more productive, resulting in a net loss of both SAV and marsh when compared to status quo conditions. (continued)
One of the greatest strengths of the Atlantis modeling approach is that it provides resource managers with information of the trade-offs predicted to result from different system changes (or management actions). In the plot above, all biological groups are modeled simultaneously, in nitrogen units, consequently, all axes are relative to one another, and trade-offs can easily be compared between different scenarios.

The Chesapeake Atlantis Model (CAM) is structured by salinity, depth, and bottom type. The 97 spatial polygons of the model are also divided into four depth layers and an additional sediment layer, in which both anaerobic and aerobic bacteria live and cycle nutrients, and which allows both flora and fauna to live in and on (flora also contribute to nutrient cycling), and where bioturbators burrow and vertebrates forage. There are 56 active biological groups that grow, reproduce, and interact in CAM.

Though starting conditions of all scenarios are identical (except for the specified change from status quo), the biogeophysical Atlantis model predicts the differences between these potential system changes are substantial, and each realization will have unique societal impacts as well. This approach provides the needed connectivity between models that predict the physical effects of climate change to, in turn, inform socioeconomic models, providing resource managers with a full suite of societal trade-offs to consider in their decision-making.

Selected References


