IMPLICATIONS OF CLIMATE CHANGE FOR MODELING COASTAL HAZARDS

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Abstract: If climate changes predicted for the next one hundred years do in fact occur, coastal management plans and physical structures being designed today may face conditions during their design lifetimes that are significantly different from historical climate. This presents a serious challenge to engineers, coastal planners, and emergency managers who have depended on history to be a guide to the future. Climate change may lead directly to changes in the frequency and intensity of storms, or it could lead to environmental changes which would alter the impact of given storm events. Here these problem areas are discussed, along with simulation approaches to assist decision-makers evaluate the potential for altered risk due to climate change. Examples for wind return periods and storm surge modeling are discussed.

INTRODUCTION

Various studies such as those reported by the Intergovernmental Panel on Climate Change (Houghton et al, 1990, 1995) indicate that global weather systems may be changing, in part due to human activities. The rate of change is predicted to be greater than historical rates of change, and this is as much a concern as the change itself. While the subject of global climate change remains contentious, the implications for coastal hazard planning and design are important. Coastal management plans as well as physical structures being designed today may face conditions during their design lifetime that are significantly different from historical climate.

This paper discusses a few of the implications of climate change for the field of numerical modeling of coastal hazards. Some of the challenges presented by climate change are discussed, along with specific instances of how potential changes to the global environment may be factored in to coastal hazard planning. Numerical modeling is an important element in many coastal hazard plans and design standards, especially with respect to extreme events. Modeling is widely used for a variety of coastal engineering

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projects, such as the determination of wind return periods, storm surge modeling, and wave climate as an input to coastal sediment transport models.

FACTORS IN MODELING COASTAL HAZARDS UNDER FUTURE CLIMATE

Climate change influences numerical modeling of specific coastal hazards in a number of ways. Three areas to be considered are:

- Changes to normal weather patterns
- Changes to frequency (intensity) of severe events
- Changes to the impact of both normal weather and extreme events due to environmental alterations

Climate changes can include changes both in timing and in spatial pattern for rainfall, wind, temperature, and other parameters. Of special interest to the coastal hazard planner are potential changes to the frequency and severity of extreme events such as tropical cyclones (hurricanes). In other words, will the frequency of (for example) 90-knot hurricanes be higher in the year 2050 than they are in 2000? The questions do not stop there because departures from historical wind speed and direction can affect long-shore currents and wave climate, causing significant alterations to the rates of sediment transport in the coastal zone. Changes to the environment, such as sea level rise or land cover changes, alter the context in which both normal weather patters and severe events occur. Continuing with the 90-knot hurricane example, the question becomes “will a 90-knot storm in 2050 cause the same amount of flooding that a 90 knot storm did in 1990?”

CHANGES IN INTENSITY AND FREQUENCY

It is difficult at this point to assess any changes to maximum storm intensity or frequency. The current generation of global climate models operates at resolutions measured in hundreds of kilometers. Some regional models such as the Regional Climate Model (RCM) developed by the Hadley Centre use outputs of the global models and generate results for specific areas at resolutions of 20 km. While even these resolutions are far too coarse to resolve most of the features of interest in the coastal zone, they could be used to drive higher resolution models to begin to assess the implications of climate change. But running climate models is an intense computational process requiring CPU-months for a single simulation. Assessing changes in the frequency of extreme events would require simulating hundreds of years of climate with a variety of initial starting conditions, and at sufficient resolution to accurately model individual storms (WASA, 1998). Although multiyear simulations with the goal of assessing impacts to annual weather patterns have been conducted to some extent, to the knowledge of this author, multiple multi-decadal or longer runs with the goal of assessing return periods of extreme events have not been attempted.

An example problem is the intensity of hurricanes. While some models indicate increases in both the frequency and intensity of hurricanes in the Atlantic Basin, others indicate decreases. It was originally speculated (Houghton *et al*., 1990) that hurricane intensities would increase due to higher sea surface temperatures. But more recent research indicates that other factors in hurricane formation and intensification such as increased shear and changes to the lapse rates over the tropics would tend to offset that bias towards stronger storms (Houghton et al, 1995). If warmer climates resemble El-Niño events, as some have speculated, tropical cyclone intensity and frequency in the Atlantic could decrease the risk of storm damage drastically at some sites (Johnson and Watson, 2001).

There is already tremendous variation in the annual activity of hurricanes. Figure 1 shows the hurricane activity in the Atlantic Basin from 1851 to 2000, by summing the energy contained in the wind fields of the hurricanes occurring in each year. As can been readily seen, there is an order of magnitude difference between "active" and "quiet" years. Although there is continuing research, a consensus is emerging that it is unlikely that climate changes theorized to date would exceed the existing natural variability, and that feedback mechanisms should prevent significant increases in maximum intensity, at least for tropical cyclones (Henderson-Sellers, *et al*., 1998).

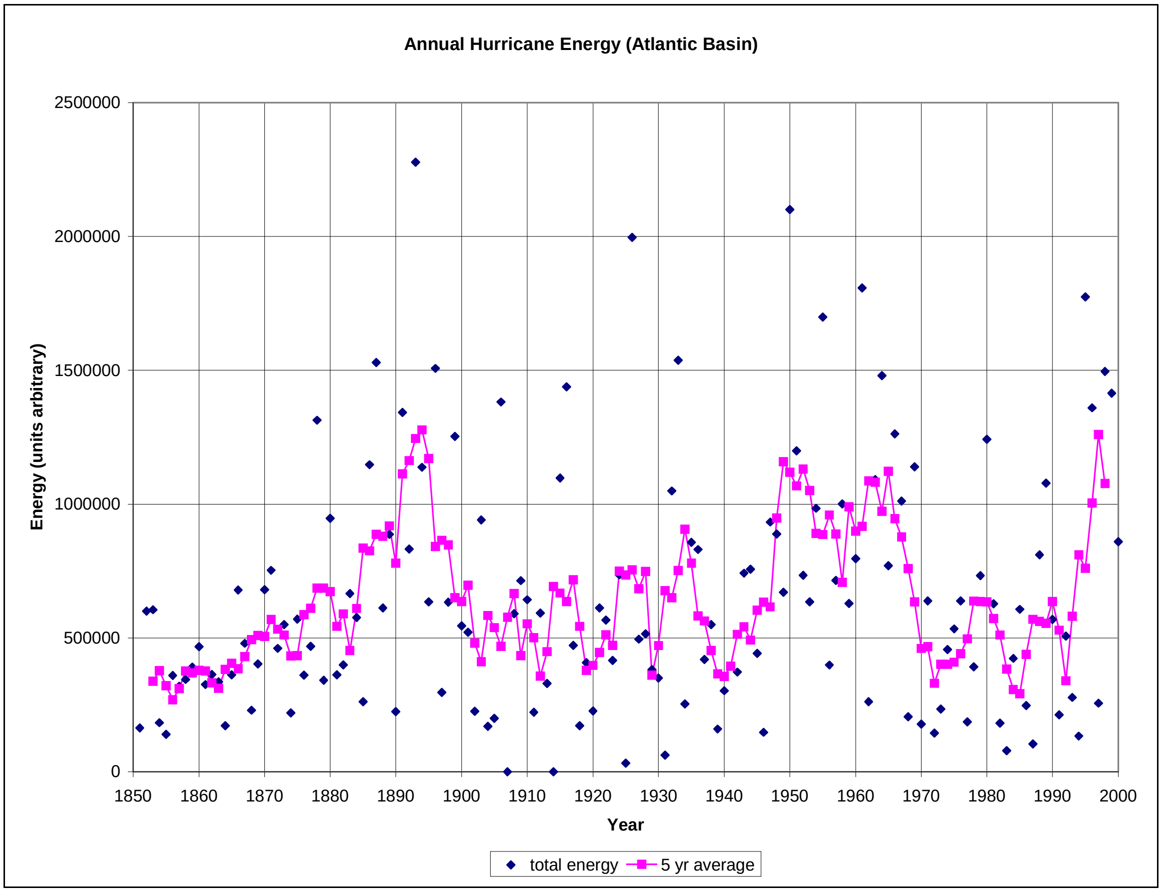

Figure 1: Annual Hurricane Energy in the Atlantic Basin based on cumulative energy contained in the wind fields of storm occurring in that year.

How can existing variability be used as a hedge against climate change? Figure 2 shows an excerpt from a TAOS Statistical Analysis Package (Watson and Johnson, 1999) wind analysis done for the Four Seasons Resort on the island of Nevis, in the northern Leeward Islands of the Caribbean. Of special interest is the analysis of the return times for hurricane force winds during the three phases of the El-Niño/Southern Oscillation, which is based on average May East Pacific Sea Surface Temperatures (SST). "COLD" SST (aka La Niña) conditions are deemed to exist when May SSTs are 2.5 degrees C below the long-term average (NORMAL). Likewise, "WARM" SSTs are when May temperatures are 2.5 degrees C above the long-term average, the condition corresponding to El Niño. Using this classification scheme, approximately 25% of years are "Warm", 25% "Cold", and 50% "Normal". Note that when May SSTs are warm there is less than half the chance of the site experiencing hurricane force winds or higher than when SSTs are cold (7.16% vs. 16.09%).

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MLE BASED WIND RETURN TIMES
WIND SPD       PROB     RETURN PD
  50KTS        0.2014      5.0 YRS
  64KTS        0.1078      9.3 YRS
 100KTS        0.0176     56.7 YRS

 RETURN TIME OF 64KT WINDS BASED ON MAY PACIFIC SST
   SST      FRAC HIT   RTN PD     STAT DATA
   COLD      0.1609      6.2 YRS   (CHI^2   14.1)   0.2308 ACTUAL P
   NOMINAL   0.1036      9.6 YRS   (CHI^2    9.2)   0.0806 ACTUAL P
   WARM      0.0716     14.0 YRS   (CHI^2    4.5)   0.0870 ACTUAL P

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 PREDICTION LIMITS

 YEAR       MLE     75%      90%     95%     99%
 10YR:     66.4    69.0    71.4    73.2    76.8
 25YR:     85.3    89.3    93.5    96.9   108.8
 50YR:     98.5   104.1   110.8   116.7   132.7
100YR:    110.7   118.9   128.7   136.8   157.3
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Figure 2: Excerpt of TSAP return-period analysis for the Four Seasons Resort, Nevis

Given historical uncertainty, the users of hazard data can analyze historical variability to produce estimates of the range of natural variability through the use of prediction limits (Watson, this volume, Johnson and Watson, 1999). Also indicated in Figure 2 are the prediction limits based on the analysis of the site. The prediction limit calculations include the natural variability caused by events such as the ENSO cycles. Prediction limits allow the user to adjust risk levels during design, according to how vital the project is. This can shield the user from the variability anticipated from climate change. Naturally, there is a tradeoff in project costs or difficulty, but in the case of the 50 year winds the difference between the MLE, or best estimate wind speed, and the 75% prediction limit is only 6 knots.

Even if the frequency and intensity of storms remains within historical variability, secondary environmental changes due to climate change can significantly increase or decrease the severity of a given event. Fortunately, this is somewhat easier to predict and analyze. As one example, in the Caribbean, coral reefs are an important part of the near-shore environment. Secondary environmental change such as stress from increased ocean temperatures may cause protective barrier reefs to die off, become more vulnerable to storm damage, or be unable to grow upward in response to sea level change. As these reefs are destroyed, increased coastal erosion and direct wave damage may result in areas formerly protected by the reef. Sea level changes may occur faster than the rate of growth of a reef, thus allowing more wave energy to enter lagoons, changing the dynamics of these systems through increased wave damage, or increased currents and erosion. As another example, the barrier islands of southeastern North America are in quasi-equilibrium. Sand eroded at high tide is replenished by onshore winds blowing over sand exposed at low tide. A sea level change of only a few centimeters would increase the erosion while leaving the sand flooded more of the time. These impacts are all within the simulation capabilities of existing coastal circulation and wave models. How sea level change could impact storm surge and extreme event damage is discussed in the following section.

SIMULATION OF THE IMPACT OF SEA LEVEL RISE ON STORM SURGE

A rise in sea level is a significant component of most scenarios of climate change. The source of this change is from a variety of sources including the increase in volume of water due to increased temperature, melting of polar and high mountain ice caps, and changes to the hydrological cycle. Current estimates for sea level rise range from 1cm to in excess of 2 meters by 2100, with most estimates clustering in the 50cm to 1 meter range (Titus and Narayanan 1995). When normal geologic rates of change are included (such as the return of the continents to hydrostatic equilibrium after the last ice age), one meter over the next 100 years seems a reasonable target value (IPCC, 1991). How a one meter sea level increase would impact the storm surge from a given storm is not straightforward. Recent studies (Watson and Johnson, 2001) indicate that due to the nonlinear interaction between water depth, bottom friction, and wave action, simply adding sea level rise to observed historical storm surges is unlikely to produce useful results. Adding one meter to sea level generated surges anywhere from .6 meters to nearly 2 meters above surges computed in 100 knot storms at locations such as Kingston, Jamaica, Miami Florida, and Savannah, Georgia.

The actual increase in surge was spatially diverse and depended greatly on both on and offshore topography, land cover, and bottom type. The influence of astronomical tides is also a factor. With increased sea levels, normal tides are altered, and the interactions of tide heights and currents with the incoming long period surge wave was highly non-linear. Thus, simply adding one meter to storm surges computed using existing water levels either underestimated (by as much as one meter) or overestimated (in some cases by 0.5 meters) the ultimate water levels. When wave action is included, significantly higher structure damage resulted in many areas due to the loss of protective reefs. To adequately model wave phenomena such as refraction, diffraction, and breaking waves, grid resolutions approaching the wavelength of the incoming waves are required. Therefore, was is concluded that relatively high resolution (grid cells of 6 arc second – 182 meters - or less) were required to fully assess the impact of sea level rise on storm surge impacts. Few storm surge models are designed to accommodate either the high spatial resolution or the immense data required for this type of modeling (Boyd, 2000).

CONCLUSIONS

Scenarios of potential climate change present challenges to planners and engineers who must think in terms of project life cycles ranging to 50 or 100 years. However, the risk can be assessed and appropriate countermeasures taken by using existing methodologies, including numerical modeling. In numerical modeling, the non-linear interactions of various coastal processes must be assessed carefully. Climate change would bring shifts in the probabilities of storm events, and prediction limits help the user to take them into account. Finally, the linkages and interactions between various scales of models, from low resolution global models to high resolution coastal simulations must well understood and the appropriate data sets developed and simulated.

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Key Words: Climate Change, Storm Surge, Wave Climate, Sea Level Rise,
Numerical Models