Fifth International Conference on Construction in the 21st Century (CITC-V)
"Collaboration and Integration in Engineering, Management and Technology"
May 20-22, 2009, Istanbul, Turkey

Vulnerability Assessment of Waterfront Residential Properties to Climate Change

Oz Sahin, Sherif Mohamed
School of Engineering, Griffith University, Gold Coast, Queensland, Australia
o.sahin@griffith.edu.au, s.mohamed@griffith.edu.au

Abstract

This paper is part of an ongoing research project designed to develop a dynamic model for assessing current and future vulnerability of waterfront residential properties to sea-level rise (SLR).

SLR is one of the best recognized effects of projected climate change in recent literature. Increased storm surge height due to SLR can cause significant problems for low-lying coastal areas. Millions of people who live near the sea may be forced to displace due to coastal flooding. As sea level continues to increase due to global warming, decision makers will need to have better tools to understand the extent and timing of coastal hazards.

Considering the complexity and dynamic nature of coastal systems with many feedbacks and dependencies changing over time, the research will focus on modelling temporal and spatial variations of coastal flooding in assessing vulnerability of the systems to SLR and storm surges.

Keywords

Vulnerability assessment, Coastal flooding, Sea level rise, Storm surge, Dynamic modelling

1. Introduction

There is a general consensus among scientists that the climate is significantly and inevitably changing. The Intergovernmental Panel on Climate Change (IPCC) informs that warming of the climate system is now unequivocal, based on observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising sea level (Solomon *et al*., 2007).

SLR is one of the most recognized possible impacts of this anthropogenic global climate change in the literature. It is estimated that the global-mean sea level may rise between 0.18 and 0.59 m by 2100, (Meehl *et al*., 2007). However, if the contribution from the Greenland and Antarctica Ice Sheets is taken into account, the upper ranges of sea level rise for 'Special Report on Emissions Scenarios' (SRES) will increase by 10 to 20 cm. A new empirical analysis published after the conclusion of the IPCC Forth Assessment Report (4AR) suggests a higher range of 0.5 to 1.4 m by 2100 (Rahmstorf, 2007).

SLR, at the estimated rate, will not pose an immediate threat to coastal areas; however a higher sea level will provide a higher base for storm surges to build upon. Thus, storm surges occurring in conditions of higher mean sea levels will enable inundation and damaging waves to penetrate further inland, increasing flooding, erosion and the subsequent impacts on built infrastructure and natural ecosystems (Pearce *et al*., 2007).

SLR is expected to continue for many centuries, even if Greenhouse Gas (GHG) concentrations are stabilised at relatively low levels (Nicholls and Lowe, 2004; Church *et al*., 2001). As a result, SLR will exacerbate the vulnerability of coastal populations and ecosystems via permanent inundation of low-lying regions, inland extension of episodic flooding, increased beach erosion and saline intrusion of aquifers (McLean *et al*., 2001). These physical impacts may result in socioeconomic impacts on the coastal zone such as loss of properties and coastal habitats, and loss of tourism, recreation and transportation functions. Thus, SLR will intensify the stress on coastal zones where adaptive capacities of natural and social systems were weakened.

Considerable human activities and population growth take place in coastal areas. It is well known that SLR will have profound implications for many coastal populations and the systems on which they depend (Brooks *et al*., 2006). The near-coastal population within 100 km of a shoreline and 100 m of sea level is estimated as 1.2 billion people, with average densities nearly 3 times higher than the global average density (Small and Nicholls, 2003). According to Chen and McAneney (2006), about half of Australia's population lives within 7 km of the coast, with as many as 30%, or about six million people, within 2 km of the coast (Chen and McAneney, 2006).

The city of the Gold Coast, like many major cities situated on the coastline of Australia are threatened by natural hazards, mainly storm tides. The Gold Coast is a low-lying coastal city where, as Betts (2002) reported, many of the residential areas are filled to the 1:100 year flood level (Betts, 2002).

With concern for the consequences of SLR, developing and implementing methodologies to assess the vulnerability of coastal systems to climate change is fundamental in supporting effective policy responses to reduce climate-change-related risks (McFadden *et al*., 2006). There are numerous studies focused on assessing coastal vulnerability on national and global scales. However availability of regional scale comprehensive vulnerability assessments studies, which are required by local stakeholders to design adaptation strategies at local level, are limited (Torresan *et al*., 2008; Cooper *et al*., 2008).

In light of the above observations and studies and in line with the need of regional scale analysis, this research focuses on assessing present and future vulnerability of waterfront residential properties and populations in the Gold Coast area to SLR and storm events. It subsequently examines and evaluates alternative adaptation options for reducing the adverse effects of SLR in the study area.

2. Problem Definition

Designing and applying a robust and flexible method to assess present and future vulnerabilities to SLR, and the need to identify and analyse adaptation options for reducing vulnerabilities, are challenging issues in vulnerability and adaptation research.

Identifying and applying correct adaptation options is a difficult process due to uncertainties in future climate change projections. Therefore, developing an adequately flexible and well structured method is important to provide the vulnerability information for designing more effective adaptation strategies and better management plans for reducing the adverse effects of SLR.

2.1 Study Area

Gold Coast City is located in south-east Queensland (Figure 1), spans across 1402 km^2, featuring more than 270 km of navigable waterways and 70 km of coastline (GCCC, 2008a). The population of the Gold Coast grew from 214,949 in 1986 to 524,667 persons in 2007 and is expected to increase to 886,700 residents in the year 2031 (Queensland Government, 2008; ABS, 2008).

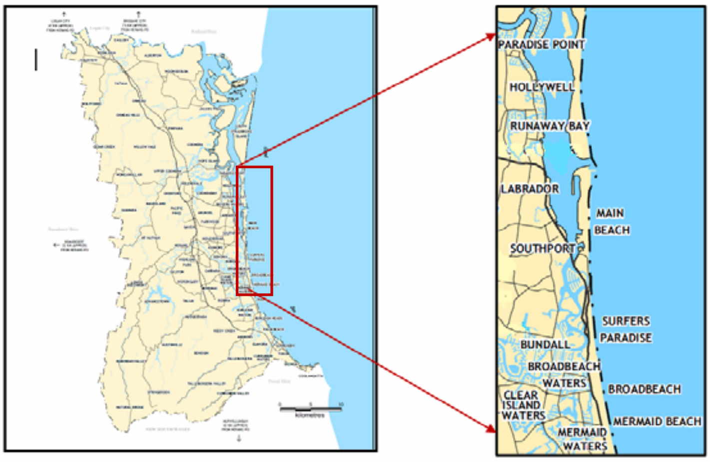

Figure 1: The Gold Coast City Boundaries and Case Study Area

Gross Regional Product increased from $ 9.7 billion in 2001 to $15.6 billion in 2008 and is projected to further increase to $ 17.3 billion in 2011. The area is an extremely popular tourist destination which attracts 82,000 tourists with $12.1 million expenditure daily (GCCC, 2008b).

In this region, the maximum tidal range is 1.8m, and on average, the coast is affected by 1.5 cyclones each year (Boak *et al*., 2001). The area within 3 km of coastal stretch between Paradise Point and Mermaid Waters is selected for case study analyses. The study area encompasses a diverse range of features including sandy beaches, estuaries, coastal lagoons and artificial waterways and is highly vulnerable to sea level rise. Figure 2, which have been generated by using Google-Earth illustrates the implication of SLR (1m - 2m) on a segment of the study area. The first picture shows the current condition, whilst the second and third pictures show the condition under 1-metre and 2-metres SLR.

Figure 2: A Segment of the Study Area (Mermaid Beach to Surfers Paradise)

Overall goals of this research are: (a) to assess present and future vulnerability of Gold Coast waterfront properties and coastal populations to sea-level rise and storm surges based on various climate and socio-economic scenarios and projections and, (b) to identify and evaluate adaptation options for coastal areas in order to cope with altering climatic conditions scenarios.

The research addresses the following questions:

1. What is the present vulnerability in the study area in terms of number of residential properties and population within the 1/100 year flood level?
2. How vulnerable is the study area to future SLR and associated storm surges (number of residential properties, their value and people at risk)?
3. What are the potential physical (Inundation, flood and storm surge damage) and socio-economic (people at risk and properties, loss of properties) impacts of SLR and storm surges on the study area?

3. Approach

The ultimate goal of vulnerability assessment is to produce recommendations on actions to reduce vulnerability. It includes both the present and future vulnerability assessments and available adaptation options. There are two general types of assessment approaches described in the literature; impact led and vulnerability led approaches (Adger *et al*., 2004; Dessai and Hulme, 2004; Carter *et al*., 2007; Richards and Nicholls, 2005). The impact approaches begin with the climate system scenarios and move through biophysical impacts towards socio-economic assessment and mainly focus on potential long-term impacts of climate change (Dessai and Hulme, 2004), whereas the vulnerability led approaches commence with local scale by addressing socio-economic responses to climate and focus on adaptation with stakeholders' involvement (Carter *et al*., 2007).

What is desirable, however, is if these approaches were to be merged in a manner that can begin with present vulnerabilities but can integrate long-term risks posed by climate change. Mindful of this, the conceptual framework proposed for this research is mainly based on UNDP Adaptation Policy Frameworks for Climate Change (Lim *et al*., 2004) and UNEP'S Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies (Feenstra *et al*., 1998). This is an attempt to merge both approaches in order to provide a flexible model addressing both short and long term vulnerability assessments issues (Figure 3).

Vulnerability in this study is considered as people-at-risk and loss of residential property due to exposure to SLR and related storm surge. Therefore, the research focuses on natural and socio-economic systems that are already vulnerable to climate variability by analysing their current conditions, then analyse the systems under various scenarios to identify how climate variability will affect the already troubled systems over time.

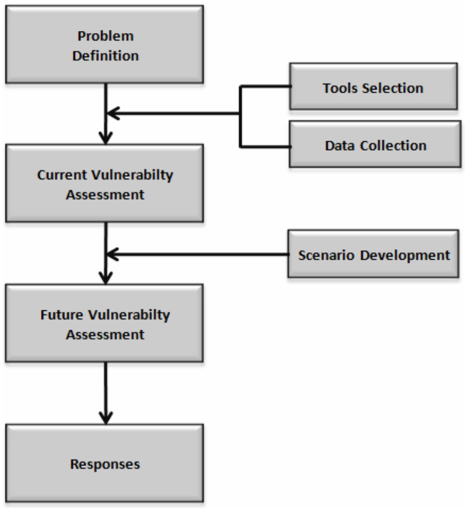

Figure 3: Conceptual Model for Vulnerability Assessment

3.1 Assessment Tools

Traditional modelling approaches focus on either temporal or spatial variation, but not both. There is important feedback between time and space, and they have to be examined together (Ahmad and Simonovic, 2004). Considering the complexity and dynamic nature of coastal systems with many feedbacks and dependencies changing over time, this research focuses on modelling temporal and spatial variations of coastal processes in assessing vulnerability of the systems to SLR and storm surges. In order to achieve this, the following two methods are combined:

- ✓ System Dynamics (SD) modelling, and
- ✓ Geographical Information Systems (GIS) modelling

By combining SD and GIS approaches and linking them through a dynamic data exchange between SD and GIS, the proposed model will provide feedback in time and space. While GIS provides spatial information to the SD, the SD model will capture changes in spatial features over time and feed them back to GIS. As a result, the dynamic nature of coastal processes and their interactions can be captured in time and space.

3.1.1 System dynamics approach

System Dynamics (SD), created by Professor Jay W. Forrester, is a powerful methodology and computer simulation modelling technique for understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system (Figure 4).

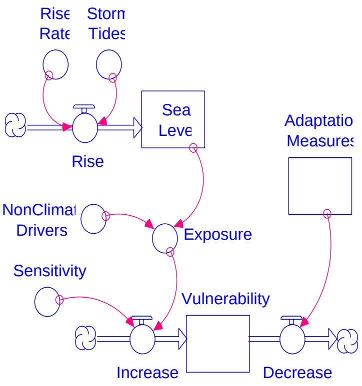

Figure 4: A Simple Stock and Flow Diagram – Modelling Vulnerability

SD modelling is becoming increasingly popular in addressing complex natural processes. SD is used for; modelling sea-level rise in a coastal area (Ruth and Pieper, 1994); modelling environmental issues (Ford, 1999); simulating flooding in the Red River basin Canada (Ahmad and Simonovic, 2004); US flood policy analyses (Deegan, 2006) and evaluating adaptation options for responding to coastal flooding in Metro Boston USA (Kirshen *et al*., 2008). Temporal process is adequately represented in SD models; however, spatial dimensions are not explicitly dealt with.

3.1.2 Geographical information systems - GIS

Geographic Information System (GIS) is used for geospatial data management and analysis, image processing, graphics/maps production, spatial modelling, and visualization. Owing to its capability of analysing spatial data, the GIS approach has been widely used in vulnerability and impact analyses. Many researchers used GIS in coastal vulnerability assessments (Al-Jeneid *et al*., 2008; Gravelle and Mimura, 2008; Lathrop and Love, 2007; Szlafsztein and Sterr, 2007; Hennecke and Cowell, 2000; Poulter and Halpin, 2008).

However, GIS, like System Dynamics, has its own strengths and weakness. While having strong capabilities of modelling the spatial dimensions of the real world, GIS has difficulties in handling temporal dimensions.

3.1.3 Combining system dynamics (SD) and geographical information systems (GIS)

By considering weaknesses and strengths of both, SD and GIS, a combination of these two approaches would provide the potential to simultaneously address temporal and spatial problems. Some researchers have combined SD and GIS to enhance the temporal and spatial aspects of these two approaches. For example; a model was developed for a coastal process (Ruth and Pieper, 1994), SD and GIS were combined to capture space-time interaction in overland flood modelling (Ahmad and Simonovic, 2004) and a model in which nitrogen flows are simulated for 16 cells within a catchment (Ford, 1999).

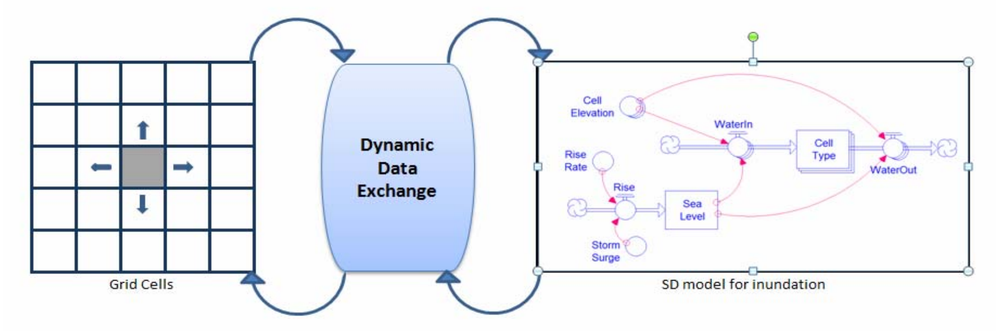

Figure 5: Conceptual Framework of SD-GIS Coupling

Advantages of both approaches will be combined in the dynamic model while eliminating their shortcomings (Figure 5). As a result, the model dynamically captures the changes in time and space by obtaining and processing temporal data from SD and spatial data from GIS through dynamic data exchange. Microsoft Excel will be employed for exchanging data between the two models due to ease of use. Data can be automatically transferred between an Excel spreadsheet and models by creating import/export links.

3.2 Vulnerability Assessment (VA)

The VA will start by analysing current conditions in the study area in order to provide a reference map to compare future conditions, and then continues with assessing how future SLR may apply additional stress to these already troubled systems.

Increased flood risk associated with storm surges is one of the primary impacts of SLR on low-lying coastal areas. These areas, depending on the rate of sea level rise which will provide an elevated base for a storm surge, most likely will face increased flooding before being permanently inundated due to increased flood levels. Therefore, for the future VA, the research will consider only coastal flooding resulting from sea level rise and storm surge. The extent and timing of coastal flooding and its impacts under various scenarios will be assessed in terms of two indicators: (1) Population within the 1/100 year flood level and, (2) Number of residential properties within the 1/100 year flood level.

Three SLR scenarios are considered in this research: the IPCC lower and upper range projections (including 10-20 cm icesheet contribution) and Rahmstorf’s (2007) estimation together with additional local adjustment. Thus, while the lower (0.5 m) and mid range (1.0 m) scenarios match approximately to relative SLR projections (the IPCC projection for global SLR plus CSIRO projection for local subsidence), the higher range (1.5 m) scenario combines the local subsidence with the global SLR projection proposed by Rahmsorf (2007).

4. Characteristics of the Proposed Model

- ✓ It is flexible and modular therefore other elements affecting costal systems can be integrated as needed.
- ✓ It is dynamic in terms of capturing feedbacks and dependencies changing over time.
- ✓ It takes into account spatial characteristics of the study area.
- ✓ It involves multiple stakeholders in designing and assessing adaptation measures.

5. Expected Outcomes

The complexity that arises from climate, coastal systems and their interactions in space and time can easily overwhelm the ability of decision makers to thoroughly investigate the outcomes of alternative actions. This research intends to provide a dynamic model for a comprehensive current and future vulnerability assessment of Gold Coast waterfront properties focusing on changes in sea level, therefore assisting decision makers in identifying and evaluating alternative adaptation policies for reducing climate change impacts.

6. References

ABS. (2008). Regional Population Growth, Australia, 2006-07. Australian Bureau of Statistics.

Adger, W. N., Brooks, N., Bentham, G., Agnew, M., and Eriksen, S. (2004). New indicators of vulnerability and adaptive capacity. Norwich, UK, Tyndall Centre for Climate Change Research.

Ahmad, S. and Simonovic, S. P. (2004). Spatial System Dynamics: New Approach for Simulation of Water Resources Systems. *Journal of Computing in Civil Engineering, ASCE*, 18**,** 331-340.

Al-Jeneid, S., Bahnassy, M. and Raey, S. N. M. E. (2008). Vulnerability assessment and adaptation to the impacts of sea level rise on the Kingdom of Bahrain. *Mitigation and Adaptation Strategies for Global Change,* 13**,** 87-104.

Betts, H. (2002). "Flood damage analysis using GIS at Gold Coast Council". *Australian Journal of Emergency Management*, 17**,** 33-37.

Boak, L., McGrath, J., and Jackson, L. A. (2001). "A case study: The Northern Gold Coast Beach protection strategy". IN EDGE, B. L. (Ed.) *27th International Conference on Coastal Engineering.* Sydney, Australia, American Society of Civil Engineers.

Brooks, N., Hall, J. and Nicholls, R. (2006). Sea-Level Rise: Coastal Impacts and Responses. Berlin, The German Advisory Council on Global Change (WBGU).

Carter, T. R., Jones, R. N., Lu, X., Bhadwal, S., Conde, C., Mearns, L. O., O'Neill, B. C., Rounsevell, M. D. A. and M.B. Zurek (2007). "New assessment methods and the characterisation of future conditions", *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK.

Chen, K., and McAneney, J. (2006). "High-resolution estimates of Australia's coastal population". *Geophysical Research Letters*, 33.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D. and Woodworth, P. L. (2001). "Changes in sea level". *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, U.K. and New York, NY, USA, The IPCC.

Cooper, M. J. P., Beevers, M. D., and Oppenheimer, M. (2008). "The potential impacts of sea level rise on the coastal region of New Jersey, USA". *Climatic Change,* 90**,** 475-492.

Deegan, M. A. (2006). "Defining the policy space for disaster management: A system dynamics approach to U.S. flood policy analysis". *The 24th International Conference of the System Dynamics Society*, The Netherlands.

Dessai, S., and Hulme, M. (2004). "Does climate adaptation policy need probabilities?". *Climate Policy,* 4**,** 107-128.

Feenstra, J. F., Burton, I., Smith, J. B., and Tol, R. S. J. (1998). *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, UNEP - United Nations Environment Programme.

Ford, A. (1999). *Modelling the Environment: An Introduction to System Dynamics Modelling of Environment Systems,* Washington DC, USA, Island Press.

GCCC. (2008a). Facts and figures. Gold Coast, Australia, Gold Coast City Council.

GCCC. (2008b). Gold Coast City Economic Profile. Gold Coast, Gold Coast City Council.

Gravelle, G., and Mimura, N. (2008). "Vulnerability assessment of sea-level rise in Viti Levu, Fiji Islands". *Sustainability Science,* 3**,** 171-180.

Hennecke, W. G., and Cowell, P. J. (2000). "GIS modeling of impacts of an accelerated rate of sea-level rise on coastal inlets and deeply embayed shorelines". *Environmental Geosciences,* 7**,** 137-148.

Kirshen, P., Knee, K., and Ruth, M. (2008). "Climate change and coastal flooding in Metro Boston: Impacts and adaptation strategies". *Climatic Change,* 90**,** 453-473.

Lathrop, R. G., and Love, A. (2007). Vulnerability of New Jersey's Coastal Habitats to Sea Level Rise and American Littoral Society. New Brunswick, NJ, USA, Grant F. Walton Center for Remote Sensing & Spatial Analysis, Rutgers University

Lim, B., Spanger-Siegfried, E., Burton, I., Malone, E., and Huq, S. (2004). *Adaptation Policy Frameworks for Climate Change,* Cambridge, Cambridge University Press.

McFadden, L., Nicholls, R., and Penning-Rowsell, E. (2006). *Managing Coastal Vulnerability,* Burlington, Elsevier.

McLean, R. F., Tsyban, A., Burkett, V., Codignotto, J. O., Forbes, D. L., Mimura, N., Beamish, R. J., and Ittekkot, V. (2001). "Coastal zones and marine ecosystems". *Climate Change 2001: Impacts, Adaptation, and Vulnerability* Cambridge, UK and NY, USA.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., and Zhao, Z. C. (2007). "Global climate projections". *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA, The IPCC.

Nicholls, R. J., and Lowe, J. A. (2004). "Benefits of mitigation of climate change for coastal areas". *Global Environmental Change,* 14**,** 229-244.

Pearce, K., Holper, P., Hopkins, M., Bouma, W., Whetton, P., Hennessy, K., and Power, S. (2007). "Climate change in Australia", Technical Report 2007.

Poulter, B., and Halpin, P. N. (2008). "Raster modelling of coastal flooding from sea-level rise". *International Journal of Geographical Information Science,* 22**,** 167 - 182.

Queensland Government. (2008). Queensland Government population projections to 2056: Queensland and statistical divisions, 2008 edition. Brisbane, Australia, Queensland Government.

Rahmstorf, S. (2007). "A semi-empirical approach to projecting future sea-level rise". *Science,* 315**,** 368-370.

Richards, J., and Nicholls, R. (2005). Handbook on Vulnerability and Adaptation Assessment. *Vulnerability and Adaptation Assessments Hands-on Training Workshop of the Consultative Group of Experts (CGE) on National Communications from Parties not included in Annex I to the Convention for the Africa Region.* UNFCC.

Ruth, M., and Pieper, F. (1994). "Modeling spatial dynamics of sea-level rise in a coastal area". *System Dynamics Review,* 10**,** 375-389.

Small, C., and Nicholls, R. J. (2003). "A global analysis of human settlement in coastal zones". *Journal of Coastal Research,* 19**,** 584-599.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., M.Tignor and Miller, H. L. (2007). *Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*

Szlafsztein, C. F., and Sterr, H. (2007). "Climate change, sea-level rise and coastal natural hazards: A GIS-based vulnerability assessment, State of Pará, Brazil". *Journal of Coastal Conservation,* 11, 53-66.

Torresan, S., Critto, A., Valle, M. D., Harvey, N., and Marcomini, A. (2008). "Assessing coastal vulnerability to climate change: Comparing segmentation at global and regional scales". *Sustainability Science,* 3**,** 45-65.