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In This Issue:

The Connection Between Sea Level Rise, Climate Change and Ocean Circulation 1

Notes From the Director 3

CCPO Alumni Spotlight: Cristobal Reyes 5

Just the Facts 6

Looking Ahead 8

The Connection Between Local Sea Level Rise, Climate Change and Ocean Circulation

By Tal Ezer and Larry P. Atkinson

In recent years, Norfolk has become a symbol for a city that is already battling the impact of sea level rise (SLR). Street flooding during high tides (Fig. 1, left) is much more common now than in the past, and storm surges (Fig. 1, right) are more severe and last longer. Therefore, as part of Old Dominion University's Climate Change and Sea Level Rise Initiative (CCSLRI), CCPO scientists focus on studies that enhance our understanding of the causes of local SLR and improve our ability to predict future SLR. This information can help policy makers, insurers, city planners and other stakeholders who are addressing the consequences of SLR for an urban area. (Atkinson et al., 2013). (*continued on pg. 2*)

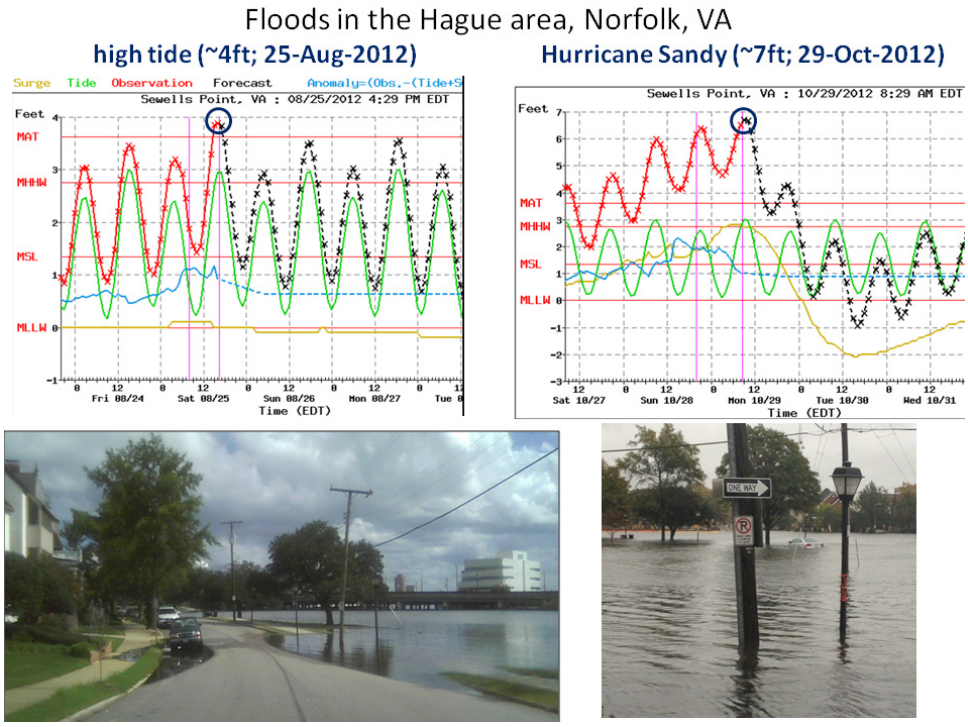


***Fig. 1**. Water level from NOAA prediction (top) and pictures of floods in the Hague area of Norfolk during the same time (bottom). Left panels represent minor flooding during a high tide and right panels are during hurricane Sandy. Green, red, orange and blue lines are the tidal prediction, observations, storm surge and anomaly (forecast error). Note that in both periods, observed water level was about 1 foot above the NOAA storm and tide prediction; this anomaly may have been associated with a change in Atlantic Ocean currents, as suggested by Ezer et al., 2013.*

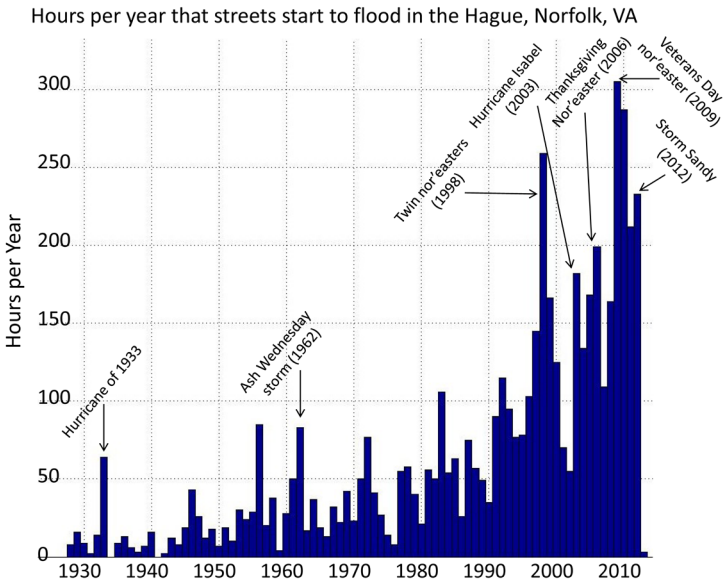


Fig. 2. *The number of hours per year that streets in the Hague area start to flood (~4ft or 1.2m above MLLW). Some of the major storms that passed through the region are indicated.*

Statistics of the frequency of flooding (Fig. 2) show that before the 1980s, streets in the Hague area of Norfolk flooded on average only ~20 hours/year, and severe floods occurred mostly during major storms or hurricanes. However, over the past decade or so, flooding increased dramatically to ~150-300 hours/year, and storm surges that occurred in the past every 30 years, now occur every five years.

So why has the risk of floods in the Hampton Roads area increased so dramatically? The reason is that local sea level is rising in this region much faster (~4-6 mm/year) than global SLR (~1.5 mm/year) from global tide gauges since the early 1900s and ~3.2 mm/year from altimeter data since 1993. Moreover, recent studies show that SLR in this region is accelerating (Sallenger et al., 2012; Boon, 2012; Ezer and Corlett, 2012a), so the region between Cape Hatteras and Cape Cod is now called an "accelerated SLR hotspot."

To understand the causes of relative coastal SLR (observed local SLR relative to land), one must consider three main components: 1) global SLR due to melting ice sheets and thermal expansion of sea water, 2) land movement (e.g., land in the Chesapeake Bay area is sinking due to post-glacial rebound) and 3) changes in ocean dynamics. The last component includes climatic changes in ocean circulation that are not yet well understood.

Climate models predict that in the future, a warmer climate will slow the Atlantic Meridional Overturning Circulation (AMOC) and the Gulf Stream (GS). As a result of the GS, the sea level along the mid-Atlantic coast on the onshore side of the GS is maintained at ~1m lower than the sea level in the offshore side of the GS (Fig. 3). Since the GS surface current is proportional to the sea level gradient across the stream, changes in the GS could potentially affect the coastal sea level along the U.S. East coast (Fig. 3). This theoretical framework is based on physical oceanographic principles and climate model predictions. However, the main question is whether or not observations can confirm this theory, and that is the purpose of the recent study by Ezer et al., (2013). (*continued on pg. 4*)

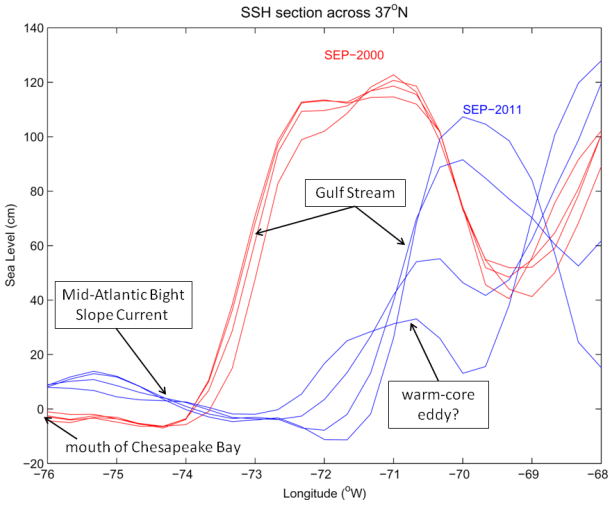


Fig. 3. *Examples of sea surface heights from satellite altimeter data at weekly intervals from September 2000 (red) and September 2011 (blue). The cross section is along 37°N, from the mouth of the Chesapeake Bay in the west to the GS in the east. Note that when the GS moved offshore and was less robust in 2011, sea level in the Chesapeake Bay rose by ~12cm relative to 2000.*

Notes from the Director

John Klinck,
Professor
and Director,
CCPO

The Earth's climate is changing-it always is. Human society is trying to understand how these variations affect processes around the globe. We want to know how changes affect human choices and how we can reverse these changes or mitigate the effects that we cannot change.

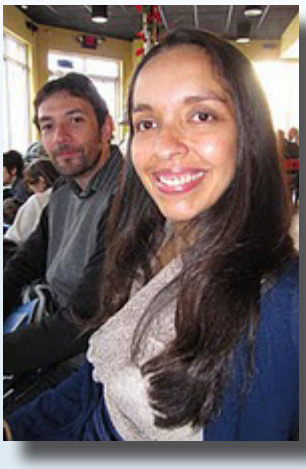
Some changes are literally in our face, as we find in our area where rising sea level and storms cause localized flooding. Larry and Tal are looking at the local and regional processes that influence local water level. Mike, Pierre and others are looking at more remote effects on Antarctic Ice Sheets, whose melting leads to higher global sea level. Eileen is participating in and managing international programs that look at changes in biological and chemical processes that affect ecosystems, and the responses and consequences for society.

It is an exciting time to be involved in ocean science research. CCPO is proud to be part of this global effort to understand our planet.

CCPO Graduate and Postdoctoral Researcher Accepts Position at Yale

CCPO would like to wish the best of luck to Andrea Piñones, who was a Ph.D. student and postdoctoral researcher. In December 2012, Andrea took a postdoctoral position at Yale University as part of the Yale Climate and Energy Institute-YCEI (http://climate.yale.edu). Her supervisor, Alexey Fedorov, leads the Ocean and Climate Dynamics Group at the Department of Geology and Geophysics and is part of the YCEI. Andrea's research focus will be on understanding the response of the Antarctic ecosystem to future projected changes in the environmental conditions of the Southern Ocean.

During her time at CCPO, Andrea worked with Eileen Hofmann, John Klinck and Mike Dinniman on developing models to investigate the transport of Antarctic krill larvae along the western Antarctic Peninsula, connectivity of Antarctic krill populations and the effects of potential climate change on the early life stages of Antarctic krill. These studies have now been published or are in press. As part of her postdoctoral work, Andrea moved to the Ross Sea where she focused on using hydrographic data obtained from tags deployed on seals to characterize seasonal and annual variability of the upper water column. She also continued her focus on transport pathways, but with a focus on crystal krill larvae as well as Antarctic krill larvae. Andrea continues to collaborate with CCPO scientists and has several manuscripts in preparation, as well as starting new research projects with new colleagues at Yale.



Andrea Piñones with
Diego Narváez, CCPO
postdoctoral researcher

Ezer et al., (2010) analyzed the GS elevation gradient obtained from satellite altimeter data, the Florida Current transport obtained from cable measurements across the Florida Straits, and coastal sea level obtained from 10 tide gauge stations in the Chesapeake Bay and the mid-Atlantic coast. They used an Empirical Mode Decomposition (EMD) method to separate oscillating modes from decadal and long-term trends (Fig. 4); the method was introduced for the first time for studies of SLR trends by Ezer and Corlett (2012a,b).

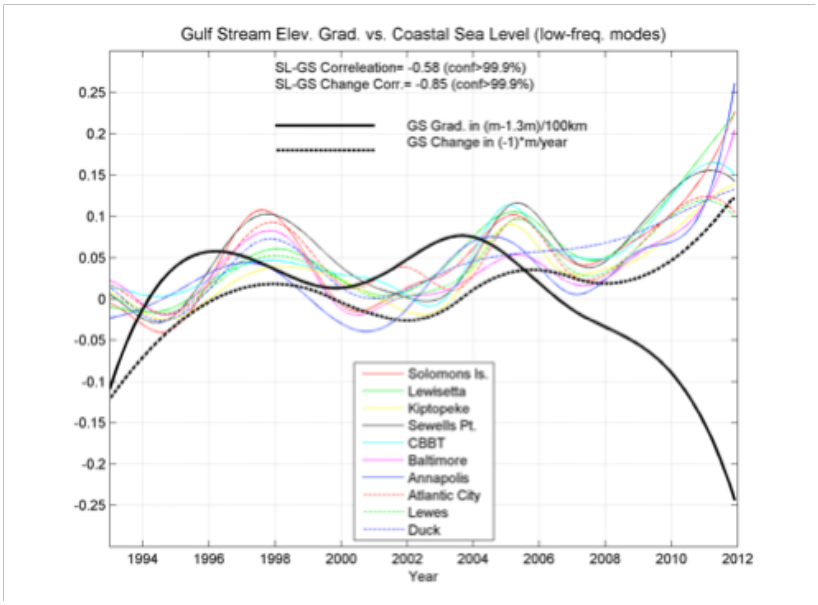


Fig. 4. *Observed sea level variations obtained for the low-frequency modes of the EMD analysis of tide gauge stations (colored lines). The black solid line is the elevation gradient across the Gulf Stream (in m relative to 1.3m over 100km) and black dash line is the reverse change of the gradient with time (e.g., the GS gradient increased by ~0.12 m/y in 1993 but decreased by ~0.12 m/y in 2012; this is equivalent to ~10% change in GS strength per year).*

Somewhat surprising was the high coherency found between sea level records located hundreds of kilometers apart in different coastal environments (colored lines in Fig. 4). Why, for example, would sea level in Atlantic City, NJ, have the same oscillations as those well inside the Chesapeake Bay at Baltimore, M.D., or along the Outer Banks coast at Duck, N.C., if not for a common forcing from the GS?. In fact, changes in the GS strength were found to be highly correlated with variations in SL on time scales ranging from months to decades and longer. It also appears that the GS started weakening around 2004, which was followed by an increase in coastal sea level at all the stations after 2007. While climate-related weakening of the AMOC and the GS has been predicted by climate models, the new findings show that this critical aspect of climate change may have started already, and probably explain the "accelerated SLR hotspot" phenomenon (land subsidence is a slow process that cannot contribute to fast changes in SLR).

More studies are needed to better understand the impact of climate-related changes in ocean dynamics on SLR and use of this information to improve regional projections of SLR. The study may also open the door for improved short-term flood risk predictions by monitoring real-time variations in the GS.

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CCPO Alumni Spotlight on Cristobal Reyes

Cristobal Reyes graduated in 2001. His dissertation title was "Tidal and Subtidal Lateral Structures of Density and Velocity in the Chesapeake Bay Entrance."

I came to CCPO and ODU as a Ph.D. student in 1995, two years after finishing my Master of Science at CICESE in Ensenada Baja California, Mexico. Being used to the arid landscape in Baja California, the contrasting view of Norfolk's Botanical Garden and all the water avenues visible from the plane made a strong and lasting impression as we arrived in the city. Dolores, my wife, and I still recall the warm welcome from Dr. Arnoldo Valle-Levinson and his wife, Anne, who kindly and generously helped us get settled in the area. (Dr. Valle-Levinson was an associate professor at ODU from 1993-2005, and is now a professor at the University of Florida.) Once at CCPO, I quickly got a sense of estuaries, when by about the third day after my arrival, I was participating in the Chesapeake Bay Mouth (CBM) monthly cruises on board the *R/V Holton*. Unfortunately, the short-term sea level variations across the CBM worked as effectively as those in the Gulf of California in making me seasick.

Although estuaries were not initially a strong focus of my research, working with Dr. John Klinck and Dr. Valle-Levinson modeling the seasonal stratification in the Chesapeake Bay led to my work with Arnoldo studying the fortnightly variability of the flow and density across the Chesapeake Bay entrance. I received my Ph.D. in August 2001; my dissertation title was "Tidal and Subtidal Lateral Structures of Density and Velocity in the Chesapeake Bay Entrance." One lasting impression or riddle for me was that depth differences between the Chesapeake Channel and the North Channel seemed to produce contrasting fortnightly mixing responses and therefore transverse velocity variations. Even today, when I review my notes and data about the Chesapeake Bay, I feel compelled to finish things that somehow were left out of my dissertation and perhaps not entirely understood.

After returning to Mexico in February 2002, I began teaching and researching for the Universidad del Mar (UMAR) at the campus in Puerto Angel. The UMAR campus in Puerto Angel is small, with about 400 students, offering majors in Marine Biology, Environmental Engineering and Oceanography, as well as a Master of Science in Marine Ecology. Puerto Angel is in southern Mexico on the western tip of the Gulf of Tehuantepec (GT). It is famous for its rough seas during the boreal winter, when continental cold air masses from North America end at the Gulf of Mexico, and cross the Tehuantepec Isthmus through a gap in the Sierra Madre Sur as really vigorous winds. Since my arrival, I've had the chance to collaborate with people from other institutions in Mexico, dedicated to studying the Gulf of Tehuantepec. The location of UMAR is ideal for that purpose.

No less interesting, though less studied, are the seasonal dynamics of the GT and also the seasonal dynamics of the coastal lagoons in Oaxaca. As with most of Mexico, the coast of Oaxaca experiences a dry and a rainy season, each about six months in length. We have had the chance to verify that some bays show density dependence in some seasons, and therefore its dynamics can change from oceanic to estuarine. Coastal lagoons are abundant in Oaxaca and also have a strong dependence on the two seasons. Many of them have open communication with the sea only during the rainy season; therefore, substantial seasonal variability in their dynamics is also present. These are my main subjects of interest today.

Committees

Eileen Hofmann, Member, External Review Committee, Department of Earth Sciences, Millersville University, September 2012.

Publications

Ashford, J. R., **M. S. Dinniman,** C. Brooks, A. H. Andrews, **E. E. Hofmann,** G. Cailliet, C. Jones & N. Ramanna, (2012). Does large-scale circulation structure life history connectivity in Antarctic toothfish (*Dissostichus mawsoni*)? *Canadian Journal of Fisheries and Aquatic Sciences, 69*(12), 1903-1919, doi:10.1139/f2012-111.

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Knutson, T. R., R. J. Sirutis, G. A. Vecchi, S. Garner, M. Zhao, H. S. Kim, M. Bender, **R. E. Tuleya**, I. M. Held & G. Villarini, (2012). Dynamical downscaling projections of 21st century Atlantic hurricane activity: CMIP3 and CMIP5 Model-based scenario, *Journal of Climate, 26*.

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Presentations

Atkinson, L. & **T. Ezer,** Sea level rise: Science and preparedness, Symposium on History, Property and Climate in the Former Colonies. Washington and Lee University, Lexington, VA, October 12, 2012.

Atkinson, L., T. Ezer, R. DeYoung, M. McShane & B. McFarlane: Accelerating sea level rise and stakeholder response. 2012 GSA, Geological Society of America Annual Meeting, Charlotte, NC, November 4-7, 2012.

Atkinson, L. IOOS Summit, Herndon, VA, November 13-15, 2012.

Atkinson, L., Presentation, Norfolk Rotary, Norfolk, VA, November 20, 2012.

Atkinson, L., T. Ezer, R. De Young, M. K. McShane & B. McFarlane: Increased flooding risk – accelerating threat and stakeholder response, AGU Fall Meeting, San Francisco, CA, December 3-7, 2012.

Dinniman, M. S., Circumpolar Deep Water Intrusions onto Antarctic continental shelves: Why we care and how might it change, invited seminar, Virginia Institute of Marine Science Biological Sciences Noon Seminar Series, Gloucester, VA, October 8, 2012.

Dinniman, M. S., Sensitivity of Intrusions of Circumpolar Deep Water onto Antarctic continental shelves to changes in the atmosphere, invited seminar, Lamont-Doherty Earth Observatory Division of Ocean and Climate Physics Seminar Series, Palisades, NY, November 9, 2012.

Ezer, T. & W. B. Corlett: Analysis of relative sea level variations and trends in the Chesapeake Bay: Is there evidence for acceleration in sea level rise?, OCEANS'12 MTS/IEEE Meeting, Virginia Beach, VA, October 14-19, 2012.

Ezer, T., Analysis of sea level rise and variability: On the connections between observed sea level and climatic changes in ocean circulation. AGU Fall Meeting, San Francisco, CA, December 3-7, 2012.

Martinat, G, C. E. Grosch & A. E. Tejada-Martinez, POD analysis of Langmuir circulation interacting with a crossed pressure gradient driven flow, American Physical Society DFD meeting, San Diego, CA, November 18-20, 2012.

Sinha, N., A. E. Tejada-Martinez, **C. E. Grosch** & **G. Martinat,** Evaluation of turbulence models in RANSS of wind-driven flow with full-depth Langmuir circulation, American Physical Society DFD meeting, San Diego, CA, November 18-20, 2012.

St-Laurent, P., J. M. Klinck & **M. S. Dinniman,** Influence of ocean circulation patterns on ocean heat transport to ice shelves, West Antarctic Ice Sheet (WAIS) workshop, Eatonville, WA, September 19-22, 2012.

Tejada-Martinez, A. E., C. Akan, **C. E. Grosch** & **G. Martinat,** Scalar transport in large-eddy simulation of Langmuir turbulence in shallow water, American Physical Society DFD meeting, San Diego, CA, November 18-20, 2012.

Thais, L., **T. B. Gatski** & G. Mompean, Analysis of polymer drag reduction mechanics from energy budgets, 7th International Symposium on Turbulence, Heat and Mass Transfer, Palermo, Italy, September 24-27, 2012.

Tuleya, R. E., Sea Level Rise and Inundation Workshop: What? So What? NowWhat? Tropical cyclones and climate change, OCEANS'12 MTS/IEEE Meeting, Virginia Beach, VA, October 15, 2012.

Updyke, T. G. & **L. P. Atkinson,** A study of surface currents in the coastal ocean outside Chesapeake Bay using HF radar, OCEANS'12 MTS/IEEE Meeting, Virginia Beach, VA, October 14-19, 2012.

Walker, R., A. E. Tejada-Martinez, **G. Martinat** & **C. E. Grosch,** Large-eddy simulation of open channel flow with surface cooling, American Physical Society DFD meeting, San Diego, CA, November 18-20, 2012.

Meetings

The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, one of the international global environmental change programs, holds an IMBIZO every two years. In January 2013, Eileen Hofmann attended the IMBIZO III, which was held at the National Institute of Oceanography in Goa, India. IMBIZO, a Zulu word meaning a gathering, brings together scientists for three concurrent but interacting workshops designed to synthesize information on topical research areas in marine science. IMBIZO III focused on multidimensional approaches to challenges of global change in continental margins, open ocean systems, and dependent human societies. The workshops, one devoted to each topic, provided a forum for stimulating discussion among interdisciplinary experts, and encouraged the linkage between biogeochemistry, ecosystem and social science research. The focus on research at the interface of natural and human was an important theme for each workshop because the issues and problems now facing society require the two communities to come together. The results of the workshops are being prepared for publication in special issues of journals and in synthesis papers. Presentations made at IMBIZO III and more information are available at: http://www.imber.info/index.php/Meetings/IMBIZO/IMBIZO-III.

IMBIZO III provided the start of preparations for IMBER's transition to transdisciplinary research under the International Council for Science's *Future Earth* framework. *Future Earth* is intended to build on the success of the existing global change programs to provide science in support of global sustainability. The next step in developing the transition plan for IMBER will be an Open Science Conference, scheduled for June 2014 in Bergen, Norway. The theme for this conference is "Future Oceans Research for marine sustainability: multiple stressor, drivers, challenges and solutions." More information on *Future Oceans* is available at www.imber.info.

Looking Ahead: Upcoming Events

July 10, 2013

The Hampton Roads Adaptation Forum will host a meeting from 9:00 a.m. to 4:00 p.m. at the Virginia Beach Higher Education Center that will address concerns, best practices and plans for adaptation and response to climate change and sea level rise in Hampton Roads. The forum will be composed of academic institutions and local, regional, state and federal agency officials with authority and responsibility for critical infrastructure and facilities in Hampton Roads (engineers, planners, facility managers, administrators, etc.).

For more information, visit the CCSLRI website at http://www.odu.edu/research/initiatives/ccslri/2013 or contact Liz Smith at exsmith@odu.edu.

October 30-31, 2013

Access EU-A Hampton Roads Initiative will host a European-American Conference with the topic "Rising Sea Levels – Atlantic Solutions: Moving Beyond the Threat." The project will be the signature conference bringing European and American experts together to discuss the technical, economic, social, and political issues connected to adaptation to rising sea levels.

For more information please visit the website http://al.odu.edu/accesseu/content/activities.shtml or contact:
Regina Karp, ODU, Conference Chair – 757-683-5700; rkarp@odu.edu
Larry Atkinson, ODU, Conference Co-Chair–757-683-4926; latkinso@odu.edu

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