# NOS Tide Gauge Network

***Sea Level Analysis***

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## 1. Project Summary

The National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) operates and maintains a network of 210 long-term, continuously operating coastal water level stations on all U.S. coasts and in the Great Lakes. This National Water Level Observation Network (NWLON) also includes stations on Pacific and Caribbean ocean islands, U.S. territories, and possessions. Many of these stations have now been in operation for over 100 years, with a few having been in operation for over 150 years. NOAA, through CO-OPS, has the national legal authority for coastal tides, tidal currents, and water levels, and is the U.S. leader on relative sea level information for all parts of the U.S. The operation of these stations, and their long period of record, is critical to understanding sea level rise and climate variability, both on a global and local scale. Tide gauge records provide relative sea level trends critical for coastal zone management, engineering, and long-term planning and decision-making on a local and national scale. They also provide calibration for satellite altimeters to better understand and measure global sea level changes caused by thermal expansion and changes in freshwater input. While the period of record for satellite altimeters is relatively short, tide gauge records exist for several decades, giving us a better understanding of what changes we have seen, and how that reflects future variability in sea level due to climate change. All NWLON stations are multi-purpose, providing both long-term and real-time water level information to support multiple user communities, including navigation, hazard warning and mitigation, and coastal zone management.

In the climate community alone, immediate users of this data include climate researchers, NOAA and federal partners who use the information to develop climate mitigation strategies for coastal communities or for management decisions, coastal managers responsible for implementing climate change response and mitigation strategies, the general public, climate modelers requiring local information to downscale global models and develop local projections, and many others. All CO-OPS data are available real-time, and products, including long-term trends and monthly and annual means, are available through the CO-OPS *Sea Levels Online* web site, and are

archived at all three Global Sea Level Observing System (GLOSS) archive centers. The data are also available through the Permanent Service for Mean Sea Level. Twenty-five NWLON stations currently comprise the U.S. contribution to the GLOSS Core Network, and 45 are part of the GLOSS-Long Term Trend (LTT) network.

CO-OPS also supports the Global Earth Observation System of Systems (GEOSS) by providing on-line sea level trends and analysis for 240 international stations, including 77 in the GLOSS Core Network and 85 in the GLOSS-LTT network. CO-OPS operates and maintains the GLOSS Altimeter (ALT) tide gauge at the Oil Platform Harvest for satellite altimeter calibration and evaluation, and by maintaining the long-term tide station at Bermuda. These efforts directly support the NOAA Climate Program Office (CPO) deliverable with respect to sea level: to identify changes resulting from trends and variability in climate. Failure to continue operation of CO-OPS' observing systems, update long-term time series, and analyze sea level trends on a national and global scale would cause a large gap in the Global Ocean Observing System for Climate and negatively impact understanding of both local and global sea level changes as an indicator of climate change. Additionally, local sea level trend information is being used more frequently by coastal planners and decision makers as policy is beginning to reflect better climate science. Hindering access to that information through lack of support for *Sea Levels Online* and associated products would force managers to go back to making generalizations, often at the expense and risk of the general public through poor planning.

## 2. Scientific and Observing System Accomplishments

Sea level analysis accomplishments by CO-OPS in the area of climate variability can be divided into four primary tasks, as outlined in the FY13 work plan delivered by CO-OPS to CPO. FY13 work was primarily a continuation of the work begun in previous years, with some added benefit to CPO and the climate community through increased emphasis on global sea level analysis. All four tasks directly support the Climate Program Office's sea level deliverable, to identify changes resulting from trends and variability in climate. These tasks are:

- Update Sea Level Trends Online with yearly trends through 2012
- Complete upgrade CO-OPS water level database to enhance research quality climate database for partners and the public
- Finish automation of the Sea Level Trends product processing and production; continued product development
- Develop East Coast inundation and anomaly climatologies for long term stations continuing product development.

### *2.1 Update Sea Level Trends Online with yearly trends through 2012*

Between January 2003 and September 2008, the Sea Levels Online website displayed sea level trends for CO-OPS stations calculated with data up to the year 1999. Since September 2008,

recalculated trends with data up to the year 2006 have been displayed. CO-OPS has adopted a new policy of recalculating sea level trends every year since 2006 for the stations still in operation and making the updated trends available on Sea Levels Online, in response to the need by our users, such as coastal managers. Since the original trends are based on long data sets (of at least 30 years), the use of a few more years of data only makes the calculated trends slightly more precise. Comparisons of small year-to-year changes in trend should not be taken as evidence of acceleration or deceleration in the rate of sea level change. In FY12, a trend comparison plot, comparing linear mean sea level trends and 95% confidence intervals from 2006-2011 was updated to Sea Levels Online. In FY13, new trends were calculated for all operating long-term CO-OPS stations using all data up to 2012 and added to the website.

Additionally, *Sea Levels Online* added a multiyear sea level trends page that exhibits mean trend from year to year (Figure 1). Forty five new trends were calculated for international long-term stations, including 12 additional countries. The global sea level product suite now covers 66 countries worldwide and many critical island stations throughout the Pacific and Atlantic (Figure 2). One hundred and twenty five historical station trends were re-analyzed using all available data (up to 2011). Station metadata records were expanded, with detailed references to earthquakes, land subsidence and anomalous data.

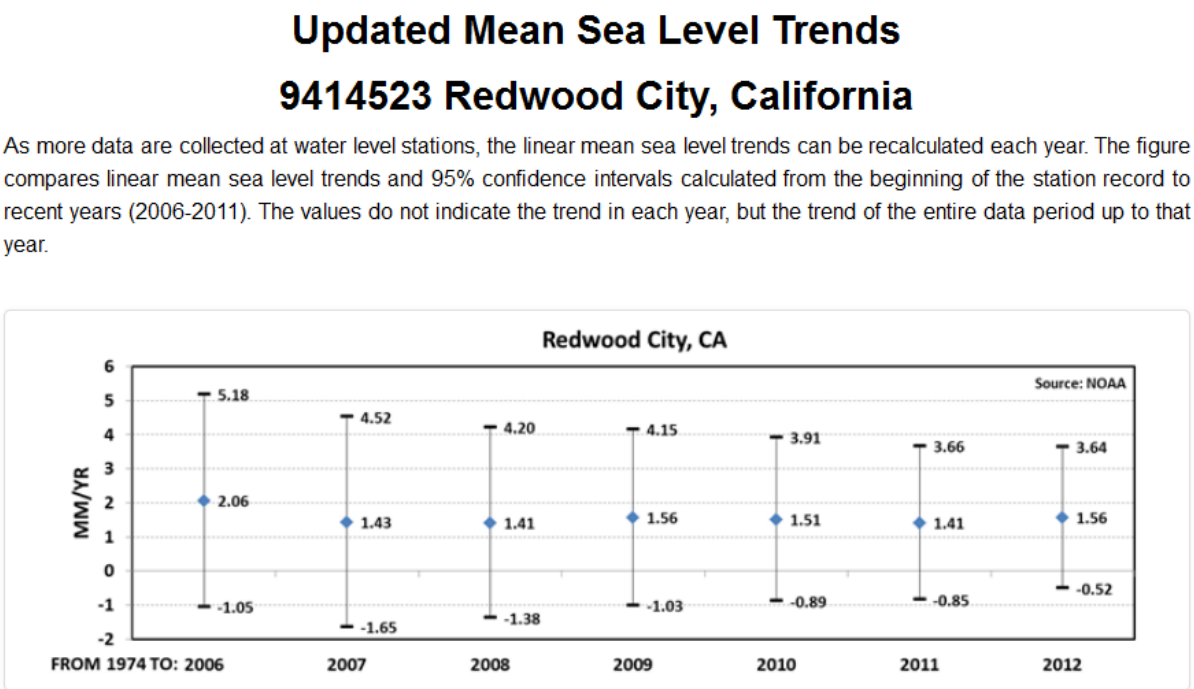


**Figure 1. Depicts yearly trend calculations from 2006-2012.**

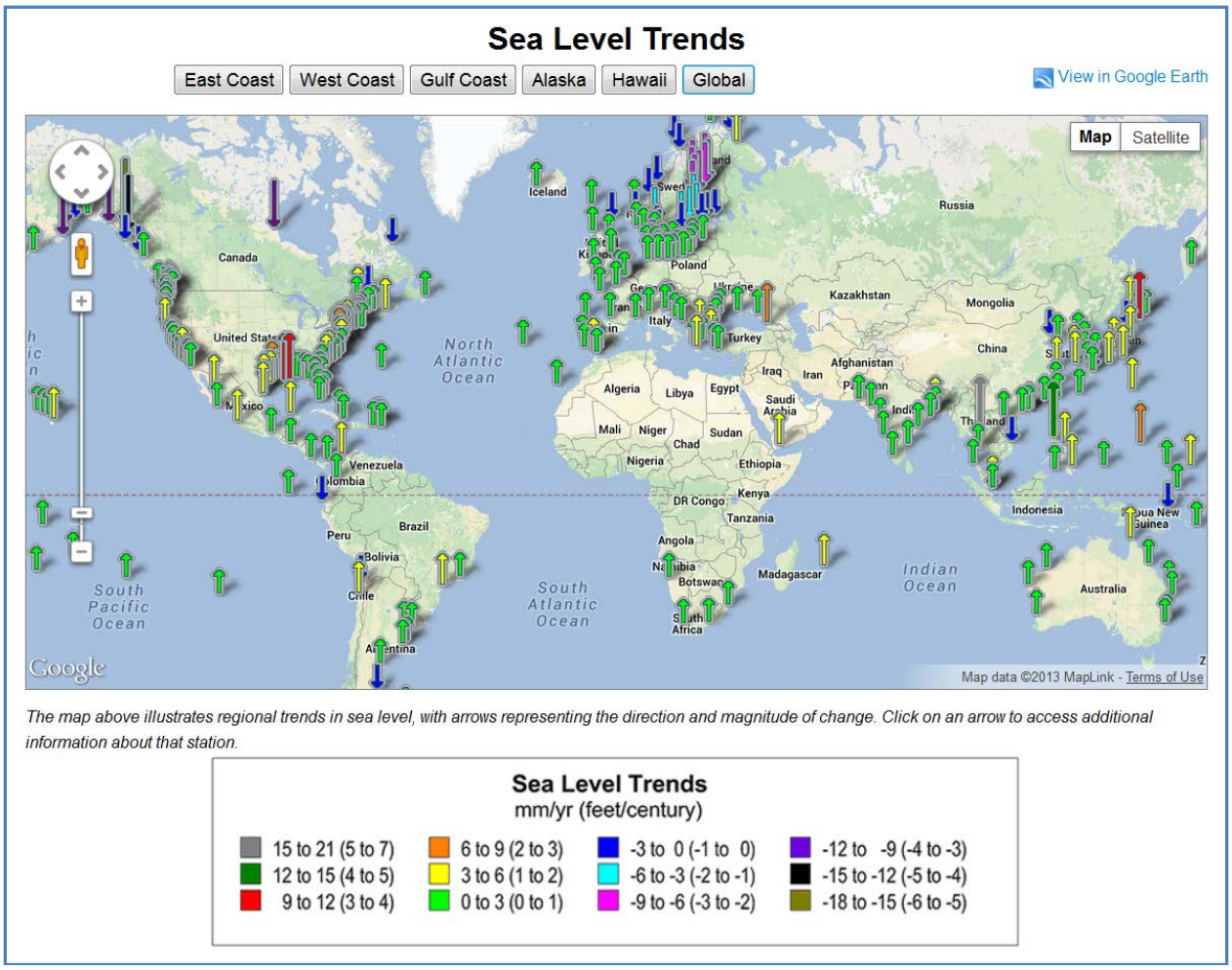


**Figure 2. Online sea level trends and analysis for 240 international stations, using all available data up to 2011.**

In summary of FY13 accomplishments, the identified task was:

- Update Sea Level Trends Online with yearly trends through 2012

The identified deliverables was:

Deliverable a: Update sea level trends through 2012 are posted on *Sea Levels Online*

Deliverable was completed.

## *2.2 Complete upgrade to CO-OPS water level database to enhance research quality climate database for partners and public*

CO-OPS has been compiling and quality controlling the data necessary to produce long term sea level trends. However, there are significant historical data records that are still in non-digital form and/or require additional quality control before public distribution. In addition, some are missing ancillary and metadata information in the existing CO-OPS database structures. By

providing a verified long-term data set and eliminating any discrepancies in historic data, CO-OPS will help eliminate error in the utilization of the data for various climate applications. This will also increase efficiency across the climate community and minimize inaccurate or conflicting information, as currently users of CO-OPS data are often forced to analyze portions of the record themselves if they want a full, verified, sea level record. This effort supports CPO's sea level directive in understanding sea level variability by providing public access to a climate-quality sea level data record for the U.S.

In FY13, through no additional CPO funding, work on compiling complete and accurate data sets, with appropriate metadata and ancillary data sets continued, which will be made available to the public. CO-OPS has not yet finished compiling and verifying all data due to CO-OPS being tasked with an unforeseen new reimbursable project (Deepwater Horizon-funded Inundation Analysis of the state of Louisiana water level stations). The data analyst hired for historical data verification was reassigned and ended up spending over 50% of the past year working on the new project which has now been completed. Our data analyst has now returned to this project.

Though no additional funding will be requested, there will be deliverables detailing continued work in the FY14 work plan.

In summary of FY13 accomplishments, the identified task was:

- Complete upgrade CO-OPS water level database to enhance research quality climate database for partners and the public

The identified deliverables were:

Deliverable a: All historic sea level data reviewed and verified
Deliverable b: Research-quality dataset available to the public for 156 NWLON stations
Deliverable c: A complete metadata record for each station, including verified extreme water level information.

Work on deliverable a and b is approximately 60% complete. Progress has also been made on deliverable c and is estimated to be complete in FY14.

### *2.3 Finish Automation of Sea Level Trends product processing and production*

In FY13, substantial progress was made toward automating sea level trends processing and production, despite the impact of personnel changes on the IT division's ability to focus on this project. Major accomplishments include creation and implementation of the new sea level trend database. Previously-calculated US and global sea level trend information have been loaded into the database. Graphics and new webpages have been implemented on our internal development server. The website and data retrieval procedures, however, are not complete yet, as some bugs need to be corrected. A metadata interface allowing for non-IT personnel to make changes to the database has not been designed. This effort is critical for common generation and storage of yearly sea level trends with reduced staff resources allocated to the update.

In summary of FY13 accomplishments, the identified task was:

- Finish upgrade CO-OPS water level database to enhance research quality climate database for partners and the public

The identified deliverables were:

Deliverable 3a: Common storage of yearly sea level trends, timely sea level trend data set availability and reduced staff resources allocated to updating sea level trends
Deliverable 3b: Exceedance probability technical report on CO-OPS website
Deliverable 3c: Updates made to domestic and global sea level trends following common protocols and analysis methods as agreed upon with CPO in previous years

Substantial work has been made regarding Deliverable 3a; the report for Deliverable 3b is finished and awaiting web posting; and Deliverable 3c is complete.

### *2.4 Develop Inundation and Anomaly Climatologies for Long Term Stations Continuing Climate Product Development*

In FY13, CO-OPS continued analysis in partnership with NESDIS/NCDC Pacific Regional Climate Services, and NOAA's Pacific Climate Information System (PaCIS; http://noaaclimatepacis.org/) and product development supporting a locally scaled and multi-component sea level "dashboard" for enhanced situational awareness. This work is also supplying requirements for a similar dashboard for cooperatives of NOAA's Sentinel Site Program (SSP; http://oceanservice.noaa.gov/sentinelsites). This work aims to facilitate smart planning, minimize risks, and maximize benefits over multiple time horizons in an increasingly *nonstationary* environment. It should also compliment a community's living memory of nuisance-to-severe sea level events/impacts needed to motivate societal adaptation as sea levels rise.

In FY13, CO-OPS work consisted of further concept refinement for an East Coast-oriented approach for a select number of NWLOW gauge locations (see Figure 3). Long-term seasonal and interannual frequency of induation and storm surge-related climatologies were derived for East Coast NWLOW stations (panes 2 and 3 in Figure 3). It is anticipated that these data sets will be incorporated into dashboard displays in the near future associated with NOAA SSP mentioned above. Collaborative work with NCDC Pacific Regional Climate Services also is targeting the Seasonal Outlook and Climatology "panes" of the dashboard for several Pacific Islands (most of which are NOAA tide gauge locations).

**Figure 3. Panes of a Sea level dashboard beta for Sewells Point NOAA tide gauge in Norfolk, VA**

In summary of FY13 accomplishments, the identified task was:

- Develop East Coast inundation and anomaly climatologies for long term stations continuing product development

The identified deliverables were:

Deliverable 4a: Complete prototype East Coast Sea Level Alert/ Seasonal Outlook
Deliverable 4b: Develop Standard Operating Procedure for completing inundation and anomaly climatology for long term stations

Deliverable 4c: Begin completing inundation and anomaly climatologies for all CO-OPS' long term stations

Deliverable 4a is complete; Deliverable 4b is complete; Deliverable 4c (for regions other than East Coast) is underway. In addition, partnering with NCDC Pacific RCS and NOAA SSP will facilitate prototype and dissemination for other regions in FY14 and beyond.

### *2.5 National Water Level Observation Network Data Availability*

All CO-OPS real-time and long-term water level data and sea level trends are available through several channels. Real-time water level data are available for all CO-OPS tide gauges via the internet, web services, and the Global Telecommunications System. All raw and verified data and products, standards and procedures, and data analysis reports can be accessed through http://tidesandcurrents.noaa.gov. Data can also be accessed through the IOOS web portal at http://opendap.co-ops.nos.noaa.gov/content/. Sea level products are also available online, through the CO-OPS *Sea Levels Online* web site for U.S. (http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml) and global (http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml) stations, as well as through the NOAA National Oceanic Data Center and others, which provide links to the CO-OPS website. Real time data are also available through the IOC Sea Level Station Monitoring Facility (http://www.ioc-sealevelmonitoring.org/) and CO-OPS works routinely with Vlaams Instituut voor de Zee to ensure data continuity and availability. Data are archived regularly in-house, and sea level data sets are provided to all GLOSS archive centers for U.S. GLOSS stations. One-minute water level data are archived weekly at the NOAA National Geophysical Data Center in Boulder, CO. CO-OPS personnel routinely verify access to the data through these channels to ensure availability. In 2013, data availability from the National Water Level Observation Network was over 96%.

### *2.6 Summary of Accomplishments*

In FY13, Sea Level Trends were recalculated with data collected from NWLON tide gauges through 2012. Significant progress was made toward enhancing CO-OPS water level database with review and verification of thousands of data records. Further progress was made towards automating the resource intense process of updating Sea Level Trends, which when complete, will allow freed resources to work on further product development. The Exceedance products were completed and progress was made toward completing a Sea Level Advisory/Sea Level Outlook product while working closely with a number of stakeholders. We were fortunate to receive near-level funding in FY13. If that funding support is decreased in the future, all of the work above will be at risk. Without the information and tools that CO-OPS provides, climate researchers would not have the raw data they need to understand changes in sea level, and coastal decision makers would not have that translated information available for management decisions that protect life and property.

## 3. Outreach and Education

NOS/CO-OPS routinely engages in education and outreach to multiple stakeholders. In particular, there is a growing need to translate technical climate data and products (especially sea level trends) into understandable and actionable information. CO-OPS personnel works closely with coastal managers, through training and one-on-one technical guidance, to explain and provide recommendations on incorporating sea level information into policy and planning.

Additionally, CO-OPS is very involved in activities through NOAA's Coastal Resilience Objective, as defined in the Next Generation Strategic Plan. Through this objective, CO-OPS has been working with other NOS offices to document protocols necessary for establishing NOAA Trust Resources as "sentinel sites for climate change impacts," one component of NOAA's emerging Sentinel Sites Program. This includes determining which areas require additional sea level monitoring, and how to tie sea level stations to geodetic infrastructure, to establish a complete picture of local land/sea interactions and local coastal processes in the face of climate change. Through this cross-NOAA effort, we have also been working with the National Estuarine Research Reserve's Coastal Training Program and NOAA's Coastal Services Center (CSC) to inform sea level training and education activities. We worked with CSC and partner agencies on a new sea level rise visualization tool for the Gulf Coast, and are working with CSC and the National Weather Service to improve protocols for coastal flood warnings by integrating CO-OPS' statistical inundation analysis with CO-OPS sea level trends. We have also worked with a number of internal and external partners to provide guidance on utilization of CO-OPS sea level trends in conjunction with sea level projections for various coastal applications, including habitat restoration, coastal engineering, and land acquisition and planning. We have specifically been supporting the U.S. Army Corps of Engineers with their development of formal engineering guidance for including sea level change in project planning and design.

## 4. Publications and Reports

### *4.1. Publications by Principal Investigators*

The following publications were completed in the last Fiscal Year, and include one or more of the project PIs.

**Proceedings from Conferences:**

Lindley, C. and **C. Zervas.** 2012. Exceedance probability statistics: The likelihood that coastal water levels will reach extreme elevations. Oceans, 2012. IEEE, 2012. https://docs.google.com/a/noaa.gov/viewer?a=v&pid=sites&srcid=bm9hYS5nb3Z8bm9zLWNvLW9wcy1hYXR8Z3g6NmRhNDlkOTkwM2Q0MDUyMg - This is a NOAA internal address

**Published:**

Marra, J. J., Merrifield, M. A., **Sweet, W. V**. 2012. Sea Level and Coastal Inundation on Pacific Islands. In V. W. Keener, J. J. Marra, M. L. Finucane, D. Spooner, & M. H. Smith (Eds.), Climate Change and Pacific Islands: Indicators and Impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.

http://www.cakex.org/sites/default/files/documents/NCA-PIRCA-FINAL-int-print-1.13-web.form_.pdf

Merrifield, M., P. Thompson, R. Nerem, D. Chambers, G. Mitchum, M. Menéndez, E. Leuliette, J. Marra, **W. Sweet**, S. Holgate (2013). Sea level variability and change [in "State of the Climate in 2012"]. Bull. Amer. Meteor. Soc. http://journals.ametsoc.org/doi/suppl/10.1175/2013BAMSStateoftheClimate.1/suppl_file/2013bamsstateoftheclimate.2.pdf

**Sweet, W.V., C. Zervas, S. Gill**, J. Park. 2013.. Hurricane Sandy Inundation Probabilities Today and Tomorrow [In "Explaining Extreme Events of 2012 from a Climatic Perspective"], Bull Amer. Meteor. Soc., 94 (9), S17-20. http://www1.ncdc.noaa.gov/pub/data/cmb/bams-sotc/extreme-events/2012/BAMS-Extremes-of-2012-Section-06.pdf

**In press:**
Park, J., **W. Sweet**, and R. Heitsenrether (Submitted): The National Water Level Observation Network: A potential coastal wave observation network. *J. of Atm. and Ocean. Tech.*

**Technical Report:**
**Zervas, C., S. Gill, W. Sweet.** 2013. Estimating vertical land motion from long-term tide gauge records. NOAA Technical Report, NOS CO-OPS 65, Silver Spring, Maryland. http://tidesandcurrents.noaa.gov/publications/Technical_Report_NOS_CO-OPS_065.pdf

### *4.2. Other Relevant Publications*

**Significant Publications:**

Ezer, T., L. P. Atkinson, W. B. Corlett and J. L. Blanco. 2013. Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. J. Geophys. Res. Oceans, 118, 685–697, doi:10.1002/jgrc.20091.

Merrifield, M. A., A. S. Genz, C. P. Kontoes, and J. J. Marra (2013), Annual maximum water levels from tide gauges: Contributing factors and geographic patterns, J. Geophys. Res. Oceans, 118, 2535–2546, doi:10.1002/jgrc.20173.

Thompson, Philip R., Gary T. Mitchum, Cedric Vonesch, Jianke Li, 2013: Variability of Winter Storminess in the Eastern United States during the Twentieth Century from Tide Gauges. *J. Climate*, **26**, 9713–9726. doi: 10.1175/JCLI-D-12-00561.1

**Other Publications:**

Becker, Austin H. A. OCT 2013. Note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. CLIMATIC CHANGE.

Burkett, Virginia. 2013. Coastal Impacts, Adaptation, and Vulnerabilities: A Technical Input to the 2013 National Climate Assessment. Island Press.

Gonneea, Meagan Eagle. JUN 16 2013. Climate-driven sea level anomalies modulate coastal groundwater dynamics and discharge. GEOPHYSICAL RESEARCH LETTERS. 40, 2701–2706, doi:10.1002/grl.50192.

Gonneea, Meagan Eagle, Ann E. Mulligan, and Matthew A. Charette. 2013. Seasonal cycles in radium and barium within a subterranean estuary: Implications for groundwater derived chemical fluxes to surface waters. Geochimica et Cosmochimica Acta.

Haines, Bruce J. APR 15 2013. GPS monitoring of vertical seafloor motion at Platform Harvest. ADVANCES IN SPACE RESEARCH.

Lee, Han Soo. SEP 2013. Estimation of extreme sea levels along the Bangladesh coast due to storm surge and sea level rise using EEMD and EVA. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS.

Lupia, Arthur. AUG 20 2013. Communicating science in politicized environments. PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA.

Merrifield, Mark A. MAY 2013. Annual maximum water levels from tide gauges: Contributing factors and geographic patterns. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS.

Moskalski, Susanne M., and Christopher K. Sommerfield. 2013. Effects of Northeaster Storms on Water Level and Turbidity in a Delaware Bay Subestuary. Journal of Coastal Research.

Park, J, Dusek, G. ENSO components of the Atlantic multidecadal oscillation and their relation to North Atlantic interannual coastal sea level. OCEAN SCIENCE. 9:3. 535-543.