VERTICAL LAND MOTION in the CHESAPEAKE BAY

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FEBRUARY 28, 2020

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AGENDA

8:00 a.m. – 8:30 a.m.	*Registration Opens*
8:30 a.m. – 8:45 a.m.	**Welcome** Fredrika Moser, *Maryland Sea Grant*
8:45 a.m. – 11:00 a.m.	**PART I: STATE of the SCIENCE**
8:45 a.m.	KEYNOTE PRESENTATION **The first few meters: How compaction of uppermost Holocene sections can lead to elevated rates of land loss in certain deltaic regions** Timothy Dixon, *University of South Florida*
9:20 a.m.	**Relative sea level rise at Galveston Pier 21, Texas, USA: Contributions from land subsidence** Yi Liu, *Morgan State University*
9:40 a.m.	**Co-evolution of wetland landscapes, flooding and human settlement in the Mississippi River Deltaic Plain: An update** Robert Twilley, *Louisiana Sea Grant College Program and University of Louisiana*
9:55 a.m.	**What geologic processes could influence vertical land motions** D. Sarah Stamps, *Virginia Tech*
10:10 a.m.	**A review of vertical land motion caused by fluid withdrawals in the eastern US and beyond** Kurt McCoy, *Virginia-West Virginia U.S. Geological Survey Water Science Center* Andrew Staley, *Maryland Geological Survey*
10:30 a.m.	**Vertical land motion considerations in environmental monitoring** Linda Blum, *University of Virginia*
10:45 a.m.	*Break*
11:00 a.m.	**Get it out there—how to communicate your work through traditional methods and digital platforms** Lisa Tossey, *Maryland Sea Grant*
11:15 a.m.	**Discussion session I**

11:45 a.m. – 12:30 p.m.	**PART II: MEASUREMENT TECHNIQUES**
11:45 a.m.	**Vertical land motion monitoring methods and October 2019 Chesapeake Bay subsidence surveys** Russ Lotspeich, *Virginia-West Virginia USGS Water Science*
12:15 p.m.	**NISAR and applications of SAR interferometry** Batuhan Osmanoglu, *NASA Goddard Space Flight Center*
12:30 p.m. – 1:15 p.m.	*Networking lunch*
1:15 p.m. – 2:40 p.m.	**PART III: MANAGEMENT IMPLICATIONS for COASTAL ECOSYSTEMS**
1:15 p.m.	**Vertical land movement estimated in the Harris-Galveston, Texas, region: A case study of using GNSS-derived ellipsoid heights to measure crustal movement** David B. Zilkoski, *Geospatial Solutions by DBZ*
1:35 p.m.	**Groundwater management and regulation in coastal Virginia** Scott Kudlas, *Office of Water Supply, Virginia Department of Environmental Quality*
1:50 p.m.	**Salt marsh restoration for coastal resilience in an era of accelerated SLR** Carolyn Currin, *NOAA NOS National Centers for Coastal Ocean Science*
2:05 p.m.	**Discussion session II**
2:40 p.m. – 3:30 p.m.	**PART IV: SUSTAINING WHILE SUBSIDING: A PANEL on FUTURE INVESTMENTS**
	Timothy Dixon, *University of South Florida* Debbie Herr Cornwell, *Maryland Department of Planning* Whitney Katchmark, *Hampton Roads Planning District Commission* Robert Twilley, *Louisiana Sea Grant College Program and University of Louisiana*
3:30 p.m.	**Closing Remarks**

WORKSHOP BRIEF

Vertical land motion (VLM) can be a major contributor to relative sea level rise (RSLR) in the Mid-Atlantic region, and differences in VLM are a primary driver of local variation in RSLR. In the Chesapeake Bay (CB), rates of VLM occur at the millimeter-per-year scale, ranging from -4.00 mm/yr in the southern CB to -1.11 mm/yr in Washington, DC **(1)**. High-resolution, accurate measurements of VLM across the CB are critical to improving predictions of RSLR and thus help planners better manage resources sensitive to RSLR. In this workshop, we will explore processes that contribute to VLM in the CB, current measurement techniques to estimate VLM rates, and how those estimates may affect predictions of RSLR around the CB. We will use a **co-production approach**, in which all workshop participants have an equal voice to collectively define problems and solutions about how to translate the latest science into useable knowledge for the management community. This is the first of two workshops made possible through the National Science Foundation's Coastlines and People grant #ICER–1940218.

WORKSHOP TENANTS

- Treat all participants with respect, dignity, and consideration, in the spirit of valuing a diversity of views and opinions;
- Be considerate, respectful, and collaborative in your communication and actions;
- Discuss differences and constructive criticism in a non-confrontational manner with due regard for the viewpoints of others;
- Demeaning, discriminatory, or harassing behavior and speech will not be tolerated.

WORKSHOP GOALS

- **Goal 1:** Improve understanding of mechanisms causing land subsidence in the CB. Determine data gaps and research needs to improve VLM rate estimates and where these rates may be most critical for land use planning.
- **Goal 2:** Create a communication strategy on how variability in local VLM rates could affect planning for RSLR. Discuss communities' information needs and planning response to areas most vulnerable to local variations in VLM.
- **Goal 3:** Strengthen collaborations across VLM experts and stakeholders.

PART I: STATE of the SCIENCE

The first section of the workshop provides an overview of the current state of VLM science, how VLM factors into sea level rise calculations, and its potential impacts on coastal processes (Goal 1). Presentations are followed by a discussion session.

DISCUSSION SESSION I

This first discussion session addresses Goal 2. It will begin with an overview of effective communication strategies. We will then discuss as a group the questions below and then each group will work through a possible outreach product. Each table will have a facilitator (as noted by a blue sticker) and a notetaker (yellow sticker) to help with the discussion and exercise.

Questions

- *What* do you think is most important for your stakeholders to know about VLM based on what you have heard so far?
- *Who* are your stakeholders?
- *How* can this information, given limited resources, be effectively communicated to your stakeholders? What information delivery method is most appropriate?

PART II: MEASUREMENT TECHNIQUES

The second section of the workshop focuses on measurement techniques to quantify VLM in the CB region, including a description of a recent Bay-wide Global Positioning System (GPS) a measuring campaign. Rates of VLM change occur at the millimeter-per-year scale, so high-precision measurements are needed to evaluate the VLM contribution to local RSLR. Several different instruments are used to collect data in CB, including GPS, Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR), extensometers, and tide gauges (Goal 1).

PART III: MANAGEMENT IMPLICATIONS for COASTAL ECOSYSTEMS

The third section of the workshop focuses on the implications of VLM on coastal communities, coastal ecosystems, and coastal restoration management. Presentations will focus on strategies for mitigating VLM contributors (i.e. groundwater withdrawal) and incorporating VLM information into planning decisions (i.e. marsh restoration).

DISCUSSION SESSION II

This discussion session addresses Goal 1 and 3 by identifying data gaps, research needs, and potential collaborations or projects that would improve VLM rate estimates and/or improve management response to RSLR. Each table will have a facilitator (as noted by a blue sticker) and a notetaker (yellow sticker) to help the group identify one to three research needs or ideas. In the post-workshop survey, participants will have the opportunity select any needs or ideas they would like to be further involved with.

Questions

- Where do you see current data gaps or areas that require further research in VLM measurement relative to coastal management efforts?
- What research and/or resources could improve management decisions or actions?
- What types of collaboration and/or projects can meet current research, management, or communication needs?

PART IV: SUSTAINING WHILE SUBSIDING: A PANEL on FUTURE INVESTMENTS

Using the information from the day's presentations and discussions, we conclude this workshop with a variety of perspectives on what we can ultimately do to improve our resilience to RSLR given current VLM uncertainties, possible mitigation strategies, and coastal management implications. The panel will share their thoughts on which geographic areas deserve future VLM measurements, top priorities for new research, and smart considerations for long-term land-use planning. This will be an opportunity for workshop attendees to ask outstanding questions from the workshop as a whole.

FUTURE WORKSHOP: EVALUATING LAND USE TRADEOFFS in the CHESAPEAKE BAY

As coastal communities experience the effects of accelerated RSLR, there is increasing need to understand the extent of these risks on land-management options and to assess the adaptive capacity of each. Later this year, we will host a second workshop which will bring together scientists and stakeholders (i.e. land conservation groups, agriculturalists/agriculture specialists, local governments, and community leaders) to discuss RSLR risks, mitigation options, and economic trade-offs. How these stakeholders make decisions can provide some indication of what the future of the CB landscape will look like, what research is necessary to better inform the effects these changing landscape have on land use, and what social science can tell us about collaboration between these stakeholders and the lands they own or manage. More information will be posted online in the coming months—visit: ChesapeakeBaySSC.org

SPEAKER BIOGRAPHIES

LINDA K. BLUM
University of Virginia

Dr. Linda K. Blum is a research associate professor of environmental sciences at the University of Virginia. Her current work focuses how soil forming processes are linked with geomorphic changes in salt marshes. Her research includes a long-term interest in the linkage between plant-soil-microbe interactions. She has chaired the National Research Council Panel to Review the Department of the Interior's Critical Ecosystem Studies Initiative, was a member of the Committee on Restoration of the Greater Everglades Ecosystem, the Committee on Independent Review of Everglades Restoration Progress, and the Committee on Challenges and Opportunities in Earth Surface Processes. She earned a B.S. and an M.S. in forest science from Michigan Technological University and a Ph.D. in soil science from Cornell University.

CAROLYN CURRIN
NOAA NOS National Centers for Coastal Ocean Science

Dr. Carolyn Currin is a research scientist working for the NOAA NOS National Centers for Coastal Ocean Science (NCCOS) in Beaufort, NC. Her recent work has investigated the response of salt marshes to sea level rise, carbon accumulation in salt marsh habitats, and marsh response to fertilization. Research results are utilized to provide guidance for coastal resilience efforts, including living shorelines and beneficial use of dredged sediments. She is adjunct faculty at the University of North Carolina at Chapel Hill, and her education includes a B.S. in zoology from North Carolina State University and Ph.D. in marine sciences from University of North Carolina at Chapel Hill.

TIMOTHY DIXON
KEYNOTE SPEAKER
University of South Florida

Dr. Timothy Dixon is a professor of geology and geophysics at the University of South Florida in Tampa. His current research includes the use of high precision GPS to study coastal subsidence and flood hazards. He is a fellow of the American Geophysical Union (AGU), the American Association for the Advancement of Science (AAAS), and the Geological Society of America (GSA). In 2010, he was awarded GSA's Woollard Medal for excellence in geophysical research. He is the author of *Curbing Catastrophe: Natural Hazards and Risk Reduction on the Modern World*, published in 2017 by Cambridge University Press. He earned his B.S. in geology from University of Western Ontario and his Ph.D. in geology and geophysics from University of California.

DEBBIE HERR CORNWELL
Maryland Department of Planning

Ms. Deborah Herr Cornwell has worked as a licensed landscape architect in the private, non-profit and government sectors over the past 30 years. Drawing on her experiences working in a multi-disciplinary design firm and as a sole practitioner, she has designed and constructed environmentally sensitive projects for private and government clients. Prior to coming to the Maryland Department of Planning in 2017, she worked for nine years at the county government level assisting citizens in navigating the development review and approval process, preserving agricultural lands and developing local policies. Ms. Cornwell received her B.S. in environmental planning and landscape architecture from Rutgers University.

WHITNEY KATCHMARK

Hampton Roads Planning District Commission

Ms. Whitney Katchmark joined the Hampton Roads Planning District Commission (HRPDC) in 2006. She leads the Water Resources Department which coordinates multi-jurisdictional efforts in the areas of drinking water, wastewater, stormwater, sea level rise, coastal zone management, and water quality. Prior to joining HRPDC, she worked for the Naval Facilities Engineering Command for eight years. She received her B.S. in environmental engineering from the University of Notre Dame and a M.S. in civil engineering from the University of Virginia.

SCOTT KUDLAS

Office of Water Supply, Virginia Department of Environmental Quality

Mr. Scott Kudlas manages the Office of Water Supply at the Virginia Department of Environmental Quality (DEQ), where he oversees a diverse staff of technical professionals in the management of Virginia's water resources. He led Virginia's effort to reduce coastal aquifer groundwater withdrawals by 52% and the creation of the Local and Regional Water Supply Planning Program. He has 34 years of experience as an environmental professional focusing on variety of land-use, water quantity, and water quality issues. He has spent the last 27 years in Virginia state government in various management and policy positions at DEQ, the Virginia Economic Development Partnership, and the Chesapeake Bay Local Assistance Department. Prior to his state service, he worked for several local governments in multiple states and for a private sector land planning firm. He is the longest serving member of the Interstate Commission on the Potomac River Basin, and an active member of the American Water Resources Association, for which he serves as president-elect and lead faculty for their National Leadership Institute for State Officials. He is also a graduate of the Virginia Natural Resources Leadership Institute. He holds a B.A. in Political Science from the College of St. Thomas in Minnesota and completed his Master's work in Landscape Architecture at Virginia Tech.

YI LIU

Morgan State University

Dr. Yi Liu is an assistant professor in the Department of Civil Engineering at Morgan State University, and a professional geoscientist registered in Texas. He teaches geotechnical engineering and groundwater hydrology for undergraduates and graduate students. His research interests are land subsidence and sea level rise. His current NSF project is "Identification of urban flood impacts caused by land subsidence and sea level rise in the Houston-Galveston region." He received his B.E. and M.E. in hydrogeology from China University of Geosciences. His D.Eng. is in civil engineering from Morgan State University.

RUSS LOTSPEICH

Virginia–West Virginia U.S. Geological Survey Water Science Center

Mr. Russ Lotspeich is a hydrologist and the surface water specialist for the Virginia–West Virginia USGS Water Science Center (WSC). He has worked for the USGS since 2000 as a hydrologic technician, responsible for his own network of streamgages and water quality monitoring sites, as a field office chief, overseeing the daily activities of the Richmond, Virginia, field office, and now as the surface water quality assurance expert for the VA–WV Water Science Center. In addition to researching innovations in surface water monitoring methods, he is actively involved in the Chesapeake Bay subsidence monitoring efforts; assisting with the operation of three borehole extensometers in Virginia, and coordinating benchmark surveys for the Hampton Roads Benchmark Monitoring and the Chesapeake Bay Regional Subsidence Monitoring networks. He received his B.S. in geological and earth sciences from the College of William and Mary.

KURT McCOY

Virginia-West Virginia U.S. Geological Survey Water Science Center

Mr. Kurt McCoy is a supervisory hydrologist in the Virginia-West Virginia USGS Water Science Center and current acting Chief of the USGS Water Mission Area, Observing Systems Division, Hydrologic Networks Branch. His background is in hydrogeology and he has authored or coauthored over 30 publications and presented this work at many national and regional conferences. Since 2016, he has served as secretary of the International Standards Organization Subcommittee on groundwater monitoring. His team focuses on facilitating and communicating science to inform coastal communities facing flooding risks from sea level rise and assisting rural communities with water resource availability needs. He received his M.S. in hydrology and water resources science from West Virginia University.

BATUHAN OSMANOGLU

NASA Goddard Space Flight Center

Dr. Batuhan Osmanoglu is a research physical scientist who holds a B.S. in telecommunications engineering from Istanbul Technical University and a Ph.D. in synthetic aperture radar (SAR) interferometry from University of Miami. He has been a part of Istanbul Technical University, University of Miami, and University of Alaska Fairbanks developing his primary area of expertise in radar remote sensing, and he has worked on applications for observing surface deformation, measuring target velocities, and radar design. Since 2013 he has been working at the NASA Goddard Space Flight Center. He is working on instrument and algorithm development of P- , L-, X-, and Ku-band SAR systems. He also serves as one of the NISAR Deputy Application Leads NASA, and one of the Disasters Program coordinators at Goddard. He is a member of the IEEE and American Geophysical Union. He also chairs the Microwave Remote Sensing workgroup under International Society for Photogrammetry and Remote-Sensing. He takes part in several remote sensing projects, for which he uses various radar imagery collected using domestic and international sensors.

ANDREW STALEY

Maryland Geological Survey

Mr. Andrew Staley is a hydrogeologist with the Maryland Geological Survey, where his work has focused primarily on aquifer property and framework characterization, water-supply issues, and groundwater-level mapping. He received his B.A. in geology and environmental studies from Macalester College, and his M.S. in geology from the University of Wisconsin-Madison.

D. SARAH STAMPS
Virginia Tech

D. Sarah Stamps is an Assistant Professor of Geophysics and National Geographic Explorer in the Virginia Tech Department of Geosciences. Her group, the Geodesy and Tectonophysics Laboratory, uses GNSS/GPS geodesy and numerical modeling to quantify surface motions and elucidate the physical processes driving those surface motions. She is working with the United States Geological Survey (USGS), National Geodetic Survey, and Hampton University to quantify millimeter precision vertical land motions (VLM) across the Chesapeake Bay region with GPS geodesy, as well as investigate the geologic processes driving the VLM using numerical modeling. She received her B.S. in earth sciences from the University of Memphis and her Ph.D. in geophysics/geodesy from Purdue University.

ROBERT TWILLEY
Louisiana Sea Grant College Program and Louisiana State University

Dr. Robert Twilley is executive director of the Louisiana Sea Grant College Program and professor in the Department of Oceanography and Coastal Science at Louisiana State University. His research has focused on coastal systems ecology and ecosystems, and more recently has been involved in developing ecosystem models coupled with engineering and landscape designs to formulate adaptation strategies for coastal communities. He received his B.S. and M.S. from East Carolina University, Ph.D. from University of Florida, and completed his post-doctoral studies were at University of Maryland Center for Environmental Studies.

LISA TOSSEY
Maryland Sea Grant

Ms. Lisa Tossey is assistant director for communications and outreach at Maryland Sea Grant. She has diverse experience in science communication as an outreach specialist, social media manager, writer, photographer, multimedia producer, and web editor in higher education, state agencies, and non-profit organizations. She has a M.A. in multiplatform journalism from University of Maryland, a B.S. in biology from Salisbury University, and is currently completing an Ed.D. at University of Delaware, with a focus on using emerging technologies for science outreach and storytelling.

DAVE ZILKOSKI
Geospatial Solutions by DBZ

Mr. David B. Zilkoski received a B.S. in forest engineering from the College of Environmental Science and Forestry at Syracuse University in 1974 and a M.S. in geodetic science from The Ohio State University in 1979. He was employed by National Geodetic Survey (NGS) for 35 years and served as director from October 2005 to January 2009. During his career with NGS, he established partnerships with state and local governments and private industry to develop advanced surveying and mapping techniques. Since retiring from government service, he provides technical guidance on issues related to NGS modernization of the National Spatial Reference System, reviews the results of GNSS survey projects, and performs training sessions on guidelines for estimating GNSS-derived coordinates, procedures for performing leveling network adjustments, the use of ArcGIS for analyses of adjustment data/results, and the proper procedures to follow when estimating crustal movement rates using GNSS and geodetic leveling data.

GLOSSARY

This glossary provides some of the terms commonly used when discussing vertical land motion. Here, we include some terms used in describing land elevation as well as measurement techniques and geophysical processes acting on land elevation changes. These are not meant to be all encompassing definitions, but rather a quick reference.

CONTINUOUSLY OPERATING REFERENCE STATION (CORS) NETWORK
Long-term GPS stations that continuously record three-dimensional position data. CORS are stationary **(2)**.

EXTENSOMETER
An extensometer is used to measure compaction or expansion of an aquifer system, usually by measuring changes in the distance between two points in a well. When combined with surface monitoring techniques, extensometers can be used to determine the portion of total land subsidence attributable to aquifer-system compaction. Extensometers have sub-millimeter precision, low spatial coverage, and high temporal detail (long, continuous record). There are three extensometers (Franklin, VA; Suffolk, VA; Chesapeake, VA) in the Chesapeake Bay **(2)**.

GLACIAL ISOSTATIC ADJUSTMENT
The rise or fall of bedrock as a result of glaciers pushing on the Earth's crust. Eighteen thousand years ago the Larentide ice sheet pushed down on Canada and the northern United States, which in turn caused the Chesapeake Bay region's bedrock to rise (glacial forebulge, think see-saw). As the ice melted and its weight was removed in areas north of the Chesapeake Bay, glacial forebulge areas, including the Chesapeake Bay, began sinking and are still sinking at an estimated 1 mm/yr today **(2)**.

GLOBAL POSITION SYSTEM (GPS)/ GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) RECEIVERS
These are portable instruments that collect satellite data used to determine land elevations and horizontal coordinate locations. As these receivers are portable, they may be moved around to multiple locations to collect data. However, these receivers are not typically set up to collect measurements continuously for long periods of time. The longer the receivers can occupy a location and collect data, the uncertainty of the vertical measurements decrease **(2)**.

INTERFEROMETRIC SYNTHETIC APERATURE RADAR (InSAR)
Satellites make multiple passes over the same area at different times to create synthetic aperature radar (SAR) images, which can show land-surface elevation changes. InSAR provides broad spatial coverage (250 x 250 km). These images are frequently used to identify hot spots and unexpected areas of subsidence **(2)**. However, there is concern about range of error, especially in dense vegetation and dynamic surface conditions (e.g. tidal areas, snow covered areas, etc). Interferometric displacement measurements require the same target to be observed at different times and changing vegetation or surface cover can impact the similarity of observations. Ground-truth elevation data are needed to calibrate and evaluate InSAR results. InSAR technology was first showcased using satellite imagery before and after the 1992 Landers Earthquake demonstrating the power of SAR imagery for measuring earth movements. European Space Agencies' Sentinel-1A and 1B satellites provide SAR data free-of-charge since 2014 and 2016 respectively. This openly available

interferometric data set resulted in wider use of InSAR for deformation studies (B. Osmanoglu, personal communication, Feb 17, 2020).

LAND SUBSIDENCE
Land subsidence is a gradual settling or sudden sinking of the Earth's surface due to removal or displacement of subsurface earth materials. The principal causes include aquifer-system compaction associated with groundwater withdrawals, drainage of organic soils, underground mining, and natural compaction or collapse, such as with sinkholes or thawing permafrost. Subsidence is a global problem, and in the United States more than 17,000 square miles in 45 States have been directly affected by subsidence **(3)**.

LIGHT DETECTION and RANGING (LiDAR)
A remote sensing method that measures Earth's topography using a mounted on airborne system (e.g fixed wing aircraft or drone). LiDAR data are used to create digital elevation models for specific areas of interest (landscape level). There is also concern about the range of error. Ground-truth elevation data are needed to calibrate and evaluate LiDAR results **(4,5)**.

NASA-ISRO SYNTHETIC APERTURE RADAR (NISAR)
An active InSAR mission between NASA and the Indian Space Research Organization **(6)**.

RELATIVE SEA LEVEL RISE (RSLR)
The change in the height of sea water level with respect to a particular land location **(7)**.

SHORELINE RETREAT
The shoreline moves landward due to numerous possible processes (e.g. sea level rise, subsidence, and erosion) **(8)**.

SURFACE ELEVATION TABLE (SET)
A portable mechanical leveling device for measuring the relative elevation change of wetland sediments with millimeter precision **(9)**.

TIDE (WATER LEVEL) GAUGE
An instrument for measuring the rise and fall of the tide (water level) **(10)**.

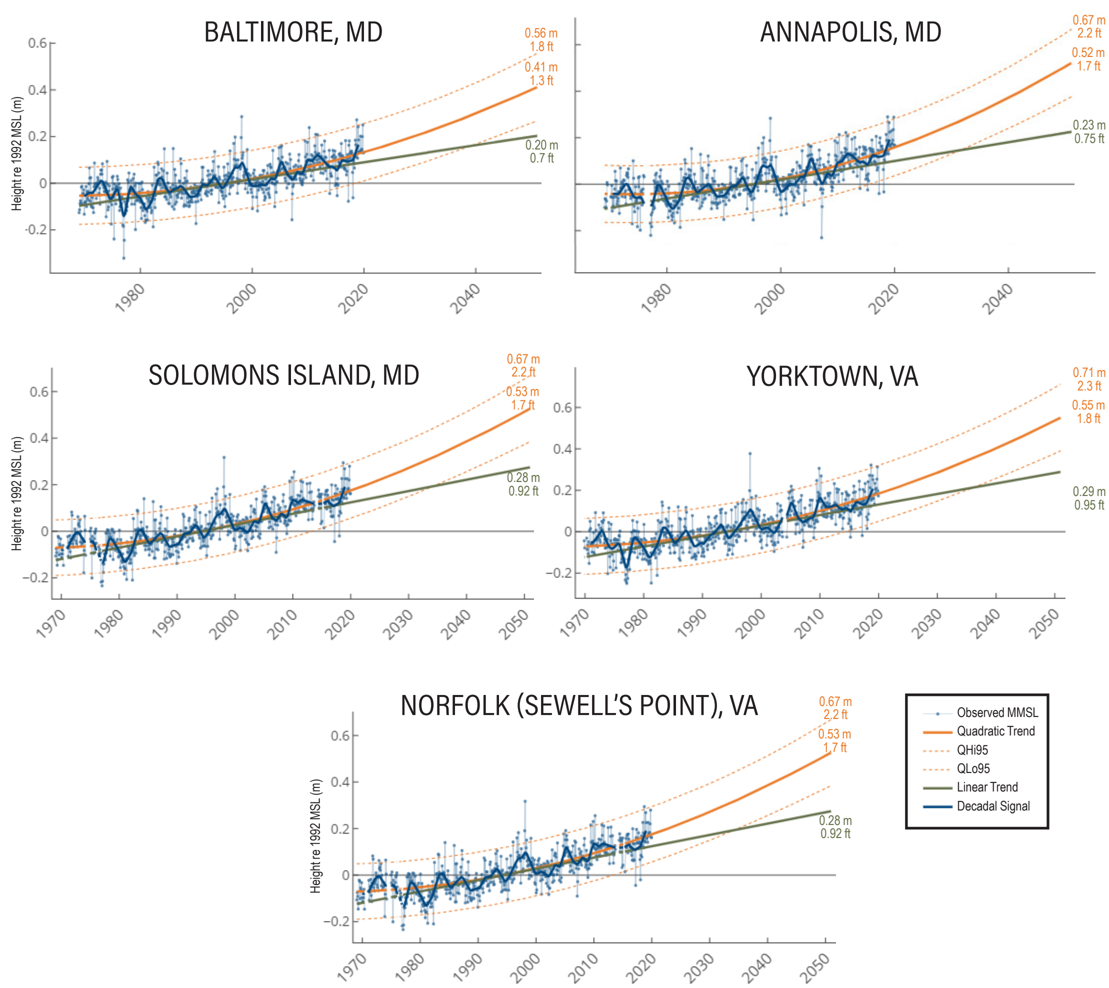
VERTICAL LAND MOTION (VLM)
The average long-term rate of change in the elevation, over multiple years or decades or millennium (e.g. glacial scales), of the land surface as measured relative to the Earth's center of mass **(11)**.

RELATIVE SEA LEVEL RISE RATES in the CHESAPEAKE BAY

MONTHLY MEAN SEA LEVEL (1970–2019) and PROJECTED TRENDS

The graphs shown below are from Virginia Institute of Marine Science's 2019 Sea Level Report Card which reports trends and projected sea level heights. The data are calculated from NOAA's tide gauge data collection network in the Chesapeake Bay (1970–2019). The first set of graphs below shows time-series data for observed monthly mean sea level (MMSL) heights, as well as projected linear and quadratic trends through 2050.

The MMSL shows the height of the water at each tide gauge location averaged over a calendar month of measurements corrected by removing predictable tidal variations (i.e. the sharp ups and downs reflect almost entirely non-tidal changes in water level due to storms or shifts in ocean circulation). The straight line through the MMSL plots shows the linear rate that is fitted to the time-series of MMSL heights. However, Virginia Institute of Marine Science (VIMS) chooses to base its sea level rise projections on the curved, quadratic line so as to incorporate acceleration rates into thier sea level rise estimates **(12)**.



The 2019 Sea Level Report Card table below shows the annual rise rate for the time-series analysis beginning in 1969 (1969–2019, 51 years). The five stations show linear increases in sea level rise rate (3.66–5.33 mm/yr), all of which exceed the current global average sea level rise rate of 1.9 mm/yr. It also shows the acceleration rate with positive acceleration (0.131–0.190 mm/yr^2) defined as the non-linear rate of sea-level change at each station with the time-series analysis beginning in 1969.

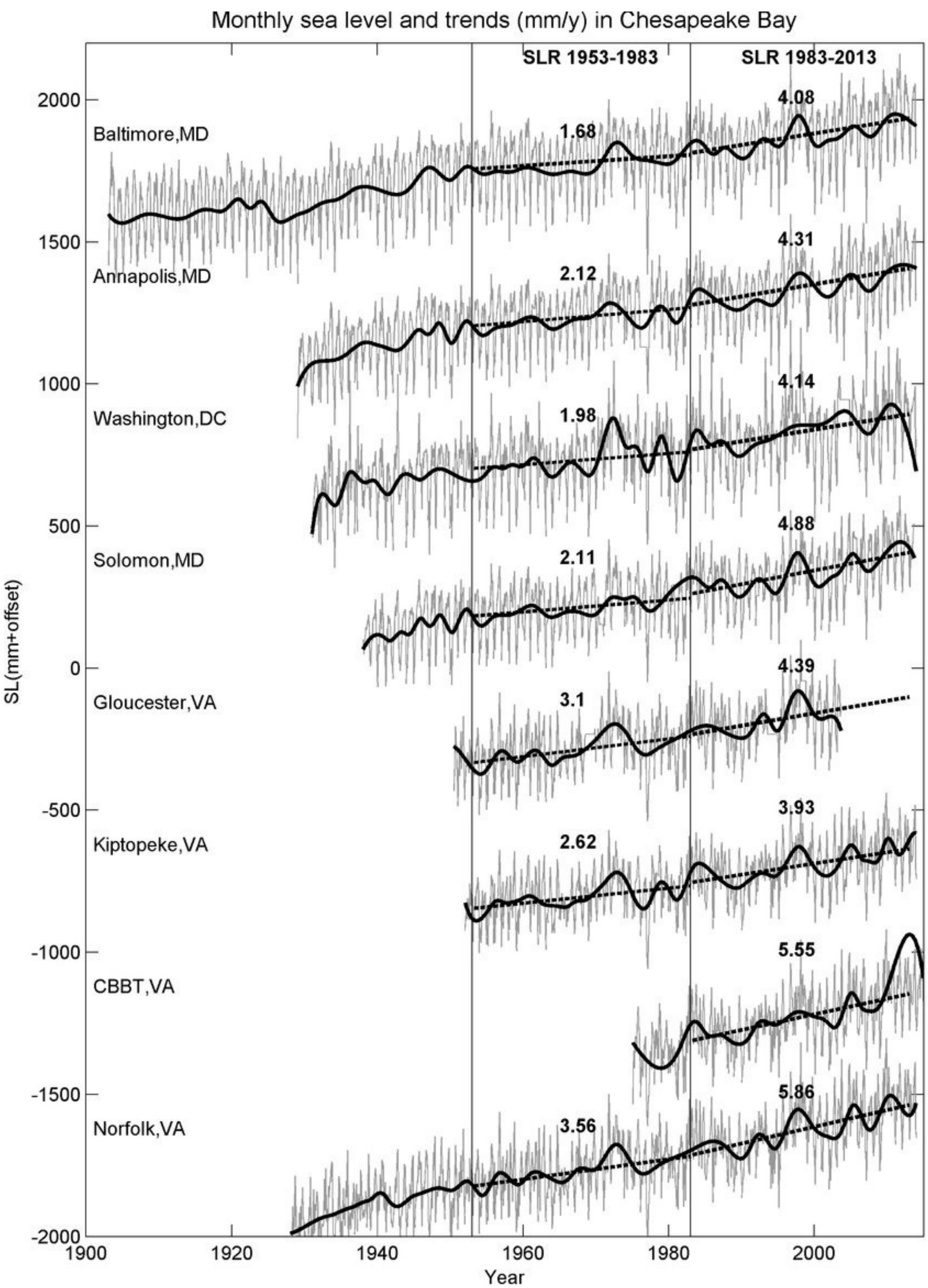
The last two columns are the projected change in sea level height in the year 2050 based on the linear rate (no acceleration) and quadratic rate (acceleration). Note the difference in sea level height (m) when acceleration is incorporated (e.g. for Annapolis with acceleration the sea level is projected to be 18 cm higher than without acceleration). Importantly, vertical land motion process contributes to these differences in estimated rates of sea level rise, but exact rates of vertical land motion throughout the Chesapeake Bay are not well known **(12)**.

2019 SEA LEVEL REPORT CARD for FIVE LOCALITIES in the CHESAPEAKE BAY

Location	**Rise rate (mm/yr)**	**Acceleration (mm/yr^2)**	**Linear 2050 (m)**	**Quadratic 2050 (m)**
Baltimore, MD	3.66	0.131	0.20	0.38
Annapolis, MD	4.04	0.190	0.21	0.48
Solomons Island, MD	4.87	0.160	0.27	0.51
Yorktown, VA	5.08	0.167	0.29	0.55
Norfolk, VA	5.33	0.132	0.30	0.49

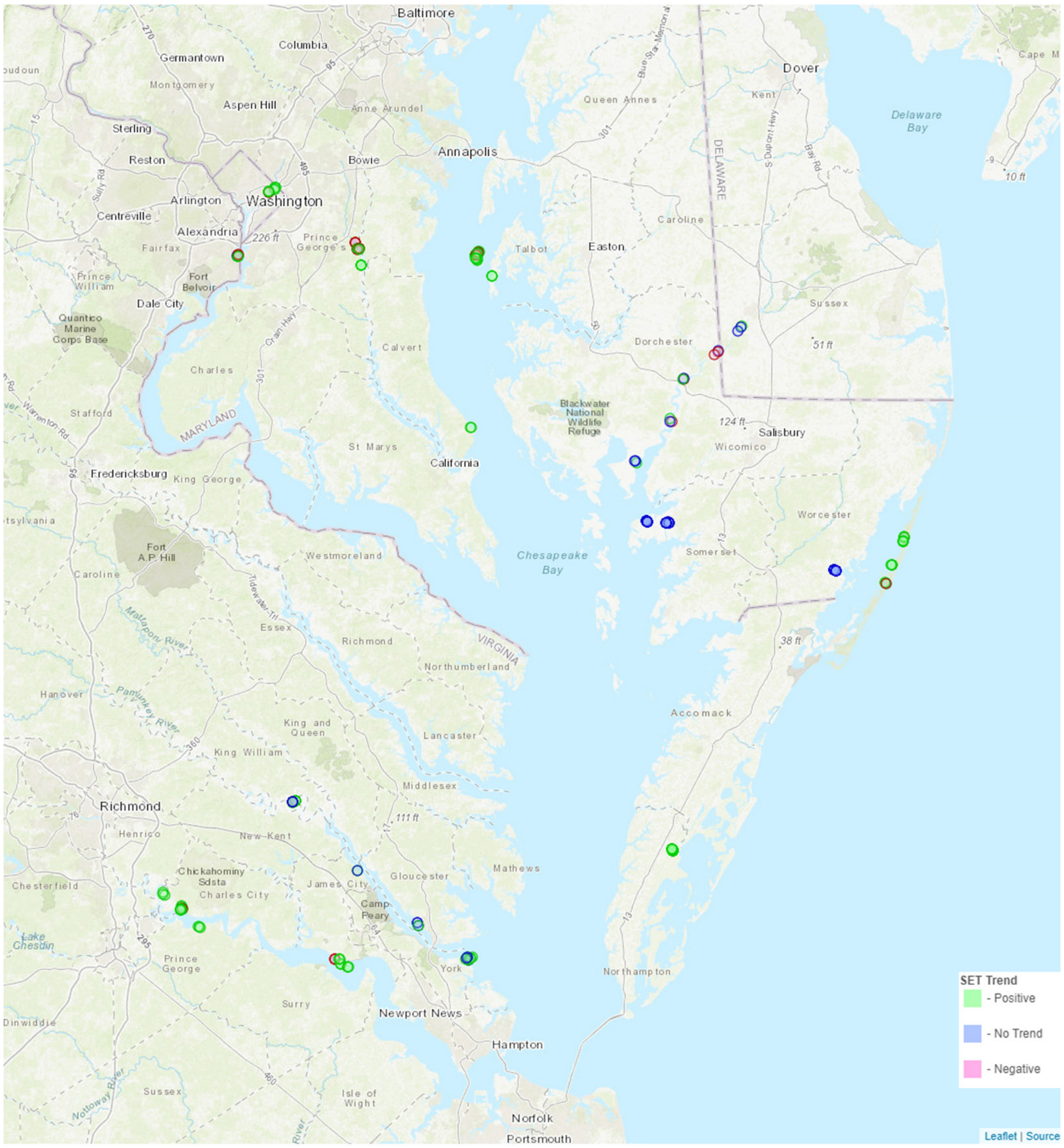
HISTORICAL MONTHLY MEAN SEA LEVEL

In another approach to study sea level rise rates across eight Chesapeake Bay stations over time. The graph below shows monthly averaged sea level heights from NOAA tide gauges as well as inter-annual variations (the heavy black line) and linear trends (the dash lines) at eight tide stations in the Chesapeake Bay through 2013. The graph divides the sea level rise rates into two 30-year periods, showing how the linear rate has increased (due to acceleration in sea level rise rates) across all stations, with an average rate of 2.45 mm/yr for 1953–1983 and an average of 4.73 mm/yr for 1983–2013. Change in acceleration of sea level rise rates are due to multiple processes, including vertical land motion **(13)**.



SURFACE ELEVATION TABLE (SET) RATES in the CHESAPEAKE BAY

Each dot represents a SET in the Chesapeake Bay from contributing sentinel sites and associated research sites in the Chesapeake Bay Sentinel Site Cooperative. A marsh has the ability to adjust to sea level rise if it gains elevation at a rate equal to or greater than relative sea level rise. Green dots show a gain in elevation, red shows a loss in elevation, and blue shows no trend. This map does not show the rate of elevation gain or loss as compared to the rate of sea level rise **(14)**.



REFERENCES

(1) Boon, J. D., Brubaker, J. M., & Forrest, D. R. (2010). Chesapeake Bay land subsidence and sea level change: An evaluation of past and present trends and future outlook. https://scholarworks.wm.edu/reports/706/

(2) Eggleston, Jack, and Pope, Jason, 2013, Land subsidence and relative sea level rise in the southern Chesapeake Bay region: U.S. Geological Survey Circular 1392, 30 p., https://dx.doi.org/10.3133/cir1392

(3) Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (2000, December). Groundwater resources for the future: Land subsidence in the United States. U.S. Geological Survey publication. Retrieved February 24, 2020, from https://water.usgs.gov/ogw/pubs/fs00165/SubsidenceFS.v7.pdf

(4) NOAA. (2020, January 7). What is LIDAR. Retrieved February 24, 2020, from https://oceanservice.noaa.gov/facts/lidar.html

(5) Katchmark, W. (2016, March 2). Land Subsidence in Hampton Roads. Retrieved February 24, 2020, from https://www.hrpdcva.gov/uploads/docs/Attachment_01C_Land Subsidence_03-02-16.pdf

(6) NASA-ISRO SAR Mission (NISAR). (n.d.). Retrieved from https://nisar.jpl.nasa.gov/

(7) U.S. Environmental Protection Agency. (n.d.). Sea Level. Report on the Environment. Retrieved February 24, 2020 from https://cfpub.epa.gov/roe/indicator_pdf.cfm?i=87

(8) University of Houston. (n.d.). The Nature of Shoreline Change. Retrieved February 24, 2020, from https://uh.edu/~jbutler/physical/coastal/shorelinechange.html

(9) Lynch, J. C., Hensel, P., & Cahoon, D. R. (2015). *The surface elevation table and marker horizon technique: A protocol for monitoring wetland elevation dynamics* (No. NPS/NCBN/NRR—2015/1078). National Park Service.

(10) Tides and Currents Glossary. (n.d.). Retrieved February 24, 2020, from https://tidesandcurrents.noaa.gov/glossary.html

(11) Miller, I. M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., & Grossman, E. (n.d.). Appendix C: Vertical Land Motion Background and Analysis. In *Projected seal level rise for Washington State—A 2018 assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey.* Prepared for the Washington Coastal Resilience Project.

(12) Virginia Institute of Marine Science. (n.d.). Sea-Level Report Cards: Chesapeake Bay. Retrieved February 25, 2020, from https://www.vims.edu/bayinfo/bay_slrc/index.

(13) Ezer, T. and L. Atkinson (2015), Sea level rise in Virginia—causes, effects and response. Virginia Journal of Science, 66(3), 355-359, Publication of the Virginia Academy of Science.

(14) Howard, J. NOAA NGS. (n.d.). Chesapeake Bay Sentinel Site Cooperative SET Inventory. Retrieved February 24, 2020, from http://chesapeakebayssc.org/maps/