Disruptive Role of Vertical Land Motion in Future Assessments of Climate Change-Driven Sea Level Rise and Coastal Flooding Hazards in the Chesapeake Bay.

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Abstract

Future projections of sea-level rise used to assess coastal flooding hazards and exposure throughout the 21st century and devise risk mitigation efforts often lack an accurate estimate of coastal Vertical Land Motion (VLM) rate, driven by anthropogenic and non-climate factors in addition to climatic factors. The Chesapeake Bay (CB) region of the United States is experiencing one of the fastest rates of relative sea-level rise on the Atlantic coast of the United States. This study uses a combination of space-borne Interferometric SAR (InSAR), Global Navigation Satellite System (GNSS), Light Detecting and Ranging (LIDAR) datasets, available National Oceanic and Atmospheric Administration (NOAA) long term tide gauge data, and sea-level rise projections from the Intergovernmental Panel on Climate Change (IPCC), AR6 WG1 to quantify the regional rate of RSLR and future flooding hazards for the years 2030, 2050, and 2100. By the year 2100, the total inundated areas from SLR and subsidence are projected to be 454-600 for Shared Socioeconomic Pathways (SSPs) 1-1.9 to 5-8.5 respectively, and 343-627 only from SLR. The effect of storm surges based on Hurricane Isabel can increase the inundated area to 849-1117 km^2 under different VLM and SLR scenarios. We present that accurate estimates of the VLM rate, such as those obtained here, are essential to revise IPCC projections and obtain accurate maps of coastal flooding and inundation hazards. The results provided here inform policymakers when assessing hazards associated with global climate changes and local factors in CB, required for developing risk management and disaster resilience plans.

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The Chesapeake Bay (CB) region of the United States is experiencing one of the fastest rates of relative sea-level rise on the Atlantic coast of the United States. However, future projections of sea-level rise used to assess coastal flooding hazards and exposure throughout the 21st century often lack an accurate estimate of coastal Vertical Land Motion rate. This poses a significant challenge to present and future management efforts and plans as it undermines flooding in coastal communities. In this work we devise a framework to combine space-based techniques and ground measurement to obtain vertical land motion to assess hundred years flooding hazards due to Sea Level Rise, storm surge, and land subsidence in the Chesapeake Bay of the United States. By the year 2100, the total inundated areas from SLR and subsidence are projected to be 454-600 km^2 for very low to very high greenhouse gas scenario 1-1.9 to 5-8.5 respectively and 343-627 km^2 only from SLR. The effect of storm surges based on Hurricane Isabel can increase the inundated area to 849-1117 km^2 under different VLM and SLR scenarios. The results provided here inform policymakers when assessing hazards associated with global climate changes and local factors in CB for disaster resilience.

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Keypoints

- We quantify 21st-century inundation hazards due to sea level rise, storm surge, and land subsidence combining space-based techniques.
- By 2100, inundated areas from sea level rise, and storm surges increases to 849-1117 km^2 for Shared Socioeconomic Pathways 1-1.9 to 5-8.5.
- Islands, wetlands, and National wildlife refuges flooded in even very low and low emissions scenarios such as SSPs 1-1.9-1-2.6.

Abstract

Future projections of sea-level rise used to assess coastal flooding hazards and exposure throughout the 21st century and devise risk mitigation efforts often lack an accurate estimate of coastal Vertical Land Motion (VLM) rate, driven by anthropogenic and non-climate factors in addition to climatic factors. The Chesapeake Bay (CB) region of the United States is experiencing one of the fastest rates of relative sea-level rise on the Atlantic coast of the United

States. This study uses a combination of space-borne Interferometric SAR (InSAR), Global Navigation Satellite System (GNSS), Light Detecting and Ranging (LIDAR) datasets, available National Oceanic and Atmospheric Administration (NOAA) long term tide gauge data, and sea-level rise projections from the Intergovernmental Panel on Climate Change (IPCC), AR6 WG1 to quantify the regional rate of RSLR and future flooding hazards for the years 2030, 2050, and 2100. By the year 2100, the total inundated areas from SLR and subsidence are projected to be 454-600 km^2 for Shared Socioeconomic Pathways (SSPs) 1-1.9 to 5-8.5 respectively and 343-627 km^2 only from SLR. The effect of storm surges based on Hurricane Isabel can increase the inundated area to 849-1117 km^2 under different VLM and SLR scenarios. We present that accurate estimates of VLM rate, such as those obtained here, are essential to revise IPCC projections and obtain accurate maps of coastal flooding and inundation hazards. The results provided here inform policymakers when assessing hazards associated with global climate changes and local factors in CB, required for developing risk management and disaster resilience plans.

Keywords: Sea level rise, Solid Earth Change, Climate Projections, Future Coastal Inundation and hazards, Disaster Resilience, Climate Change

Plain Language Summary

The Chesapeake Bay region of the United States is experiencing one of the fastest rates of relative sea-level rise on the Atlantic coast of the United States. However, future projections of sea-level rise used to assess coastal flooding hazards and exposure throughout the 21st century often lack an accurate estimate of changes in sea level relative to land. This poses a significant challenge to present and future management efforts and plans as it undermines flooding in coastal communities. In this work, we combine satellite techniques and ground measurement to obtain vertical land motion to assess twenty first century flooding hazards due to Sea Level Rise, Hurricane effect, and land movement in the Chesapeake Bay. By the year 2100, the total inundated areas from sea-level rise and subsidence are projected to be 454-600 km^2 for very low to very high greenhouse gas scenarios respectively. The effect of storm surges based on Hurricane Isabel can increase the inundated area to 849-1117 km^2 under different changes in vertical land movement and sea-level rise scenarios. The results provided here inform policymakers when assessing hazards associated with global climate changes and local factors.

1. Introduction

Rising sea levels pose significant challenges to coastal communities and ecosystems (IPCC, 2021). The global sea level rose by 0.20 m between 1901 and 2018, with an average rate of 1.3 mm/year between 1901 and 1971, increasing to 1.9 mm/year between 1971-2006 and further increasing to 3.7 mm/year between 2006 and 2018 with high confidence (IPCC, 2021). This acceleration will likely continue throughout the 21st century (Dangendorf et al., 2019; Frederikse et al., 2020; Nerem et al., 2018). However, on a local scale, the rate of regional sea-level change could be larger than the average global sea-level change due to processes that affect vertical land motions such as groundwater pumping/recharge, sediment compaction, hydrologic loading, long term tectonics, Glacial Isostatic Adjustment (GIA), dynamic topography, and sediment loading (Manoochehr Shirzaei et al., 2021). To quantify the impacts of relative Sea-Level Rise (RSLR) on coastal flooding, socioeconomic exposures, and risks, it is crucial to obtain accurate Vertical Land Motion (VLM) rates at management-relevant resolution (10 s m^2) (Blackwell et al., 2020; Manoochehr Shirzaei et al., 2017). Relative sea-level change refers to sea surface changes over time concerning a local land elevation in response to changing climate and local non-tectonic and anthropogenic processes.

Several studies have highlighted sea level rise in coastal Virginia waters and have identified it as a hotspot for rising sea-level due to climate variability and global warming (Davis & Vinogradova, 2017; Ezer & Corlett, 2012; Sallenger et al., 2012). On the land side, recent studies (Bekaert et al., 2017; Buzzanga et al., 2020; Harvey et al., 2021; Karegar et al., 2017) showed that the Hampton Roads area of the Chesapeake Bay region (Fig. 1) is experiencing subsidence and suggested GIA and aquifer compaction as primary drivers (Eggleston & Pope, 2013). The mid-Atlantic region's bedrock is slowly moving downward in response to the melting of the Laurentide ice sheet that covered Canada and the northern United States during the last ice (Sella et al., 2007; J. Boon et al., 2010), generating ~1-2 mm/year of subsidence (Peltier et al., 2018). Further, the region hosts the Coastal Plain Aquifer system comprising unconsolidated sediments overlaying the eastward dipping Precambrian basement (McFarland & Scott, 2006). The Potomac Aquifer, the largest and deepest unit among different layers, is the primary source of freshwater supply in eastern Virginia. As a result, pumping has caused the groundwater level to decline by more than 60 m in some regions, manifesting in localized and rapid land subsidence (Bekaert et al., 2017). Currently, the Sustainable Water Initiative for Tomorrow (SWIFT) project designed by Virginia authorities actively recharge replenishes the Potomac Aquifer with up to one million gallons of drinking water daily to enhance freshwater's long-term sustainability and offset the land subsidence.

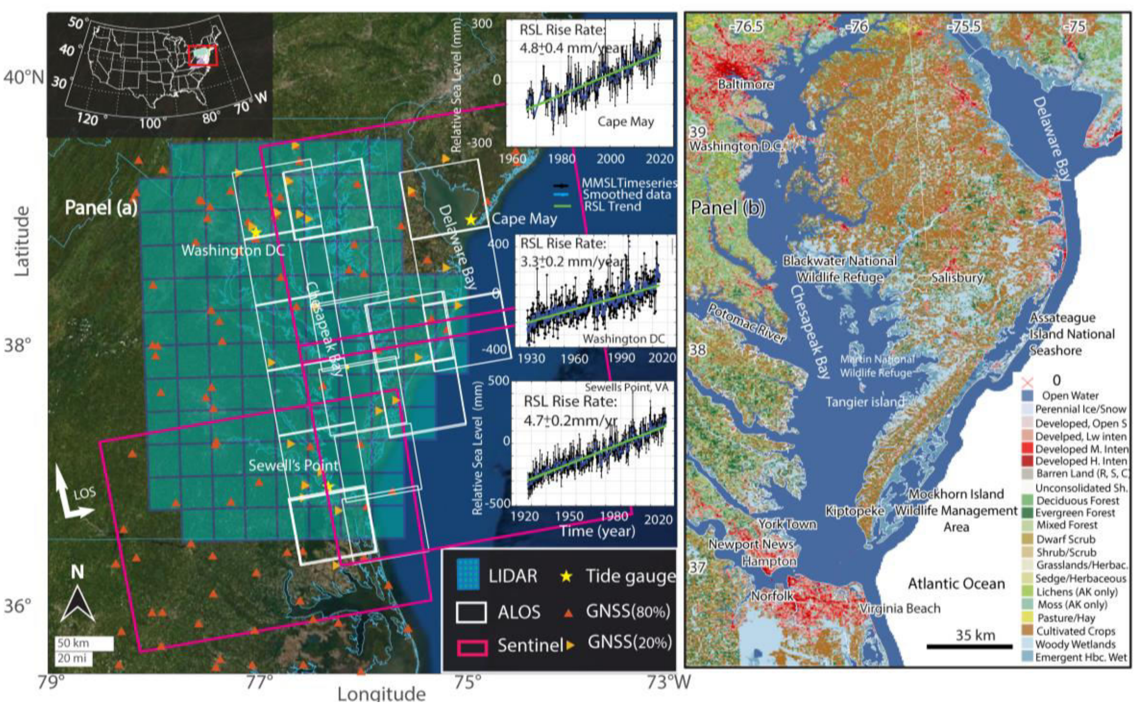

Figure.1. Chesapeake Bay Study Area. **(a)**, shown are the ground footprint of SAR satellites frames, Sentinel-1 A/B, C-band (Magenta) and ALOS PALSAR L-band (white), location of tide gauges (yellow

stars), GNSS stations (80%) used in the analysis (orange triangle) and 20% of GNSS (yellow triangles) used for VLM validation. Further, time-series data of Monthly Mean Sea Level (MMSL) (average of high tides and low tides) from NOAA (National Oceanic and Atmospheric Administration) for three stations, Sewell's Point, VA, Washington DC, and Cape May, are shown. **(b)** shows Landsat-based 30 m resolution land use and landcover area for the study area (Homer et al., 2012).

Chesapeake Bay region is affected by combined flooding from ocean dynamics of the Gulf Stream and Atlantic Meridional Overturning Circulation (Ezer & Corlett, 2012), tidal flooding (Sweet & Park, 2014), and documented increasingly extreme rainfall (Allen & Allen, 2019). On the other hand, increased inundation hazards due to storm surges on the Chesapeake Bay are demonstrated in various studies (Cho et al., 2012; Shen et al., 2006; Sheng et al., 2010). On September 18, 2003, a category 2 Hurricane Isabel made landfall over the mid-Atlantic region generating record conditions for the region's 27 years of monitoring and impact (Smith & Graffeo, 2005), resulting in a historical maximum water level records at eight stations in the Chesapeake Bay (Hovis et al., 2004). On 2012 October 29, Hurricane Sandy (category 1), an Atlantic hurricane on record, made landfall on a long swath of the U.S. Atlantic coastline, including the Chesapeake Bay (Sopkin et al., 2014), with a damaging storm surge imparted to the New Jersey and New York coastlines (Blake et al., 2013). The maximum recorded storm surge from National Oceanic and Atmospheric Administration (NOAA) ranked by amplitude for Hurricane Isabel, September 2003 and Hurricane Sandy, October 2012 is reported in Table 1, which shows that Sewell's Point, Cape May station, and Washington DC experienced a water level of 1.7, 1.0 and 2.4 meters (for Hurricane Isabel) and 1.4, 1.6, and 1.2 meters respectively (for Hurricane Sandy). Further, some areas such as the City of Norfolk already experience "sunny days" or nuisance flooding regularly when there is a high tide or a storm offshore, without a named storm event on land. These increasingly frequent flooding events will require regional and local planning for both evacuations in the face of extreme storm events and longer-term adaptation.

Table 1. Maximum recorded storm surge ranked by amplitude for Hurricane Sandy, recorded in October 2012 (Source: Fanelli et al., 2013, table 3a), and maximum storm surge for Hurricane Isabel (Source: Hovis et al., 2004, table 3-4) recorded on 18-19 September 2003 (meters) at three stations of Chesapeake Bay.

Hurricane	Station Name	Station ID	Date and Time (GMT)	Water level (meters)
Sandy	Sewell's Point, VA	8638610	10/29/2012 07:24	1.394
	Cape May, NJ	8536110	10/29/2012 18:00	1.574
	Washington, DC	8594900	10/30/2012 21:42	1.228
Isabel	Sewell's Point, VA	8638610	09/18/2003 21:00	1.712
	Cape May, NJ	8536110	09/18/2003 23:48	0.951
	Washington, DC	8594900	09/19/2003 09:30	2.470

Space geodetic tools, including Interferometric Synthetic Aperture Radar (InSAR) and Global Navigation System Satellites (GNSS), can measure the movement of the land surface at a millimeter level accuracy (Bürgmann et al., 2000) which is essential in understanding change in relative SLR rate. Such observations improve the understanding of long-term changes in relative sea level. The usefulness of space-based InSAR and GNSS observation are discussed in various studies on earth deformation in the Chesapeake Bay (Bekaert et al., 2017; Buzzanga et al., 2020). However, these studies only focused on short observation periods, spanned by ALOS or a portion of Sentinel-1A/B acquisitions, thus yielding a lower signal-to-noise ratio for the long-term rates. Also, their estimates of the VLM rate are not tied to a reference frame, so they are not suitable for studies of SLR and flooding hazards.

We apply a framework to combine the entire archive of Sentinel-1 and ALOS SAR satellites and GNSS observations to obtain spatially and temporally high-resolution VLM maps and improve their uncertainties. We further evaluate future flooding and inundation hazards extents by combining VLM rates with the LiDAR topographic dataset, SLR projections under different Shared Socioeconomic Pathways (SSPs) scenarios, and storm surge estimates from Hurricane Sandy and Isabel for time period 2030-2100. High-resolution VLM rates with mm-level accuracy, improved forecasts of relative SLR rates, and updated maps of inundation hazards are essential for informing policymakers and authorities and developing flood resiliency plans to compact severe consequences of climate change in the region.

2. Datasets and Methods

2.1. Tide Gauge Data

We used National Oceanic and Atmospheric Administration (NOAA) tide gauges to understand the water level changes in the Chesapeake Bay (Fig. 1). The tide gauge data were obtained from the NOAA website https://tidesandcurrents.noaa.gov/map/index.html. A combined total of 254 years of water level measurements with record lengths varying between 93 years (1927-2020) at the Sewell's Point (8638610), VA, 96 years (1924-2020) at the Washington DC station (8594900), and 55 years (1965-2020) at the Cape May site (8536110) are available. The monthly mean sea level heights recorded at the U.S. tide stations are verified for their accuracy through National Water Level Observation Network (NWLON) quality control procedures. They are referenced to *Mean Sea Level* (MSL), a tidal datum specifically defined in and for the U.S. following Federal law (Gill & Schultz, 2001). Linear trend analysis of the monthly mean sea level (MMSL) data from these three stations adjacent to or within SAR frames showed a relative sea-level of 4.7$\pm$ 0.2 mm/year at Sewell's Point, 3.3$\pm$ 0.2 mm/year, and 4.8 $\pm$ 0.4 mm/year at Washington D.C. and Cape May stations respectively (Fig.1). A study by Boon (2018) has also shown increasing regional sea level using a quadratic model among coastal regions. The MMSL data refers to the water level observed over a calendar month at U.S. tide stations.

2.2. SAR and GNSS Datasets

To obtain a map of high-resolution VLM with respect to a global reference frame and mm-level precision, we applied the framework shown in Fig. 2 to combine all available SAR and GNSS observations. In the following, we detail different components of this framework.

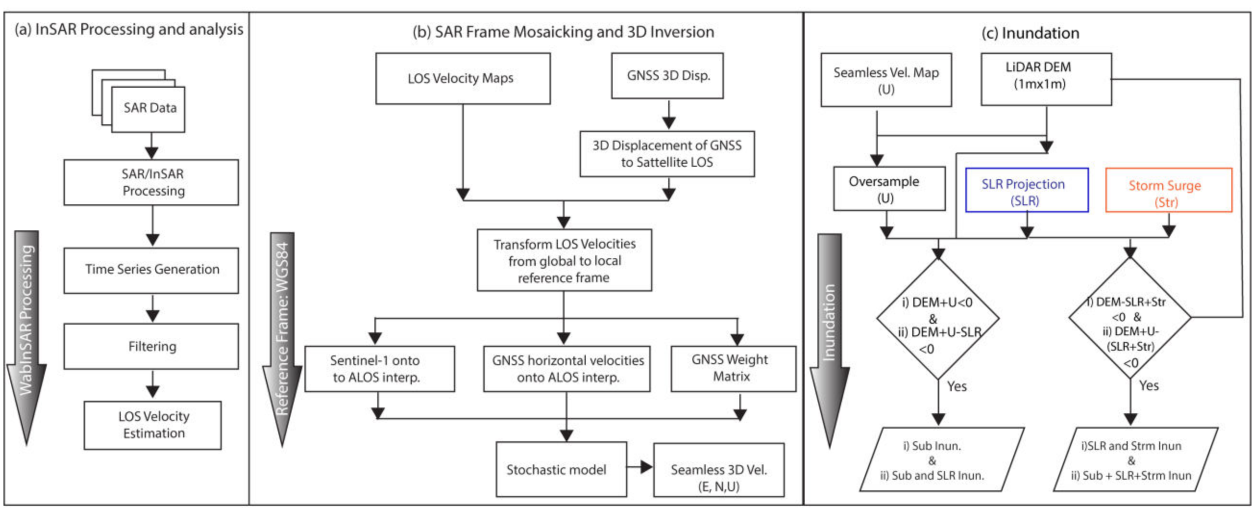

Figure 2. Methodology flowchart. **(a)** The InSAR multitemporal processing and line of sight (LOS) rate estimation, **(b)** Mosaicking and 3D inversion of InSAR and GNSS datasets, **(c)** Flooding and inundation hazard estimation from subsidence, sea-level rise, and storm surge.

2.1.1. Interferogram Generation and Time Series Analysis

To measure vertical land motion in the Chesapeake Bay, a large set of SAR images acquired by C-band Sentinel-1 with Terrain Observation with Progressive Scans acquisition mode (Interferometric Wide Swath -IW mode) with a revisit time of twelve days and the Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) L-band with a revisit time of 46 days in ascending orbit geometry from 2007-2020 were used. We used a multi-looking factor of 32 and 6 in range and azimuth direction and yielded pixel resolution of ~75 m × ~84 m for Sentinel-1 and a muti-looking factor of 4 and 13 in range and azimuth direction, leading to approximately ~50 x ~50 m for ALOS satellite for vertical land motion estimation leading to the ultimate resolution of ~50 x ~50 m. The list of acquisitions is provided in table S1. Here, a level-1 data format was used, including SLC products, orbits, and calibration XML files.

We utilized Gamma processing software (Wegnüller et al., 2016; Werner et al., 2000) for SAR processing and calibration, encompassing preprocessing, range compression, azimuth compression, and multi-look post-processing modules. For multitemporal analysis of the Sentinel-1 TOPS SAR data, we used the wavelet-based InSAR algorithm (Shirzaei, 2013; Shirzaei et al., 2017). All SAR images were co-registered and resampled concerning a common reference image (an image with the shortest temporal and spatial baselines and doppler difference concerning the rest of the datasets) and generated large sets of interferograms. Temporal and perpendicular baselines of 700 days and 500 m were used for the sentinel-1 dataset and 1500 days and 2500 m for ALOS. Here Shuttle Radar Topography Mission (SRTM) version 3-1 arcsec (30 m) DEM and satellite precise ephemeris data were used to calculate and remove the geometrical phase (Franceschetti & Lanari, 1999). Following Shirzaei (2013), less noisy pixels (i.e., elite pixels) were selected through statistical analysis of complex interferometric phase noise time series. To reduce the effects of the residual DEM error, we applied a low pass filter before phase unwrapping. To obtain th absolute phase changes at for each elite pixel, we applied the sparse phase unwrapping algorithm (Costantini & Rosen, 1999) using the minimum cost flow approach (Costantini, 1998). To estimate and remove the effect of a topography correlated component of atmospheric delay, we applied the approach of Shirzaei and Bürgmann (2012). Also, each unwrapped interferogram was corrected for the effect of orbital error following (Manoochehr Shirzaei & Walter, 2011). Next, each elite pixel's time series of phase change/velocities was estimated through an iterative reweighted least squares. In this step, the initial observation weight matrix is estimated based on interferometric coherence. Next, a wavelet-based high-pass filter is applied to reduce the temporal component of the atmospheric delay in the time series. The location of the less noisy pixels was then transformed to a geographic coordinate system (WGS84) from a radar coordinate system. And lastly, linear line-of-sight (LOS) velocity is estimated for each pixel with respect to a reference point.

2.1.2. SAR frame mosaicking

To obtain two seamless LOS velocity maps for Sentinel-1 and ALOS frames, SAR frames are mosaiced following Ojha et al. (2018). To this end, we used pixels within overlapped areas of adjacent frames as tie points. We implemented an affine transformation (including translation and two rotations) to align datasets and ultimately obtain seamless LOS velocity maps for all tracks covering the Chesapeake Bay.

Next, we obtain GNSS observations from the study area, provided by Nevada Geodetic Laboratory with respect to IGS14 reference frame (Blewitt et al., 2018). Data from 99 stations, whose observations date to 2007 with minimum lengths greater than three years, were obtained. After applying relevant corrections (such as step correction), we estimate trends using a robust regression and refine the vertical velocity field using a median filter, following (Hammond et al., 2016). We randomly split the dataset into sets of 80% (tie) and 20% (check) stations. The check stations were not used in the analysis and only kept for validating results. The tie datasets used to constrain parameters of an affine transformation to convert LOS velocities from local to the global reference frame. To this end, we projected 3D displacement velocities from GNSS onto satellite LOS direction using local incidence and heading angle of the satellite and then applied an affine transformation. Figures 3 A and B show the seamless maps of LOS rate for ALOS and Sentinel-1, respectively.

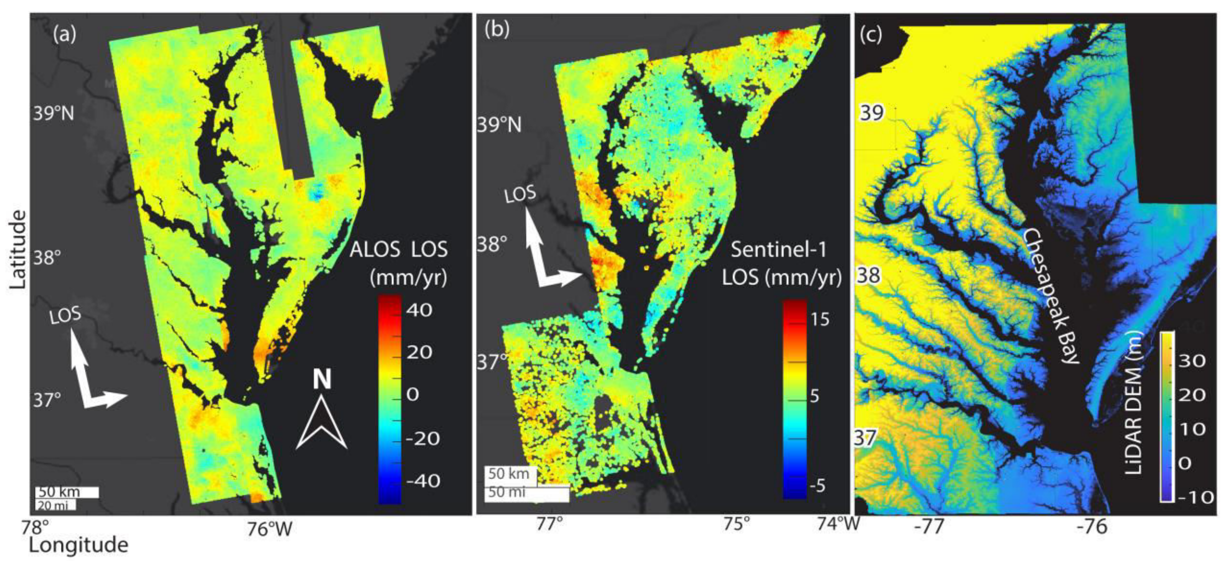

Figure 3. Mosaiced ALOS LOS rate **(a),** Mosaiced Sentinel-1 LOS rate **(b)** Lidar DEM **(c)**.

2.1.3. 3D displacement rate inversion

Next, we interpolated the LOS velocities and standard deviations of Sentinel-1 track and GNSS horizontal velocities on the location of ALOS pixels, using a Kriging interpolation approach with inverse distance weighting (Trochu, 1993), resulting in four observations per pixel, including two LOS velocities and two GNSS velocities (E-W and N-S components) with three unknowns, including velocities in the east (E), north (N) and up (U).

The interpolated GNSS east and north standard deviations, σ^e and σ^n for interpolated values is modeled based on their distance (D) to the nearest GNSS station as follows;

$$\sigma^e = s_e * \left(1 + \frac{D}{10}\right)$$
$$\sigma^n = s_n * \left(1 + \frac{D}{10}\right) \qquad (1)$$

where, s_e and s_n are the standard deviation of GNSS station located at a distance of $D\ km$ to a given pixel.

Provided interpolated LOS velocities and variances for a given pixel namely $\{y_{sa}, y_{aa}\}, and\ \{\sigma_{sa}^2, \sigma_{aa}^2\}$ respectively, with a subscript indicating Sentinel-1 ascending (sa) and ALOS ascending (aa), we implement the following stochastic model to generate a seamless, high spatial resolution map of the east (*E*), north (*N*), and vertical (*U*):

$$y_{sa} = C_e^{sa} E + C_n^{sa} N + C_u^{sa} U + \varepsilon^{sa}$$
$$y_{aa} = C_e^{aa} E + C_n^{aa} N + C_u^{aa} U + \varepsilon^{aa}$$
$$E_G = E + \varepsilon^e$$
$$N_G = N + \varepsilon^n \qquad (2)$$

Here, C represents the unit vectors projecting the 3D displacements onto the LOS (Hanssen, 2001). The interpolated GNSS velocities in the E-W and N-S directions are E_G, and N_G. ε is the observations error with N (0, σ) probability distribution (σ is the SD). Note that in equation 2, E and N are unknown while E_G, and N_G are observed.

Solution to equation 1 is obtained as below:

$$X = (A^T PA)^{-1} A^T \mathrm{PL} \quad (3)$$

where,

$$X = (E\ N\ U)^T, \quad (4)$$

$$\mathrm{A}=\begin{pmatrix} C_e^{sa} & C_n^{sa} & C_u^{sa} \\ C_e^{aa} & C_n^{aa} & C_u^{aa} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \quad (5)$$

$$P=\begin{pmatrix} \frac{1}{(\sigma^{sa})^2} & 0 & 0 & 0 \\ 0 & \frac{1}{(\sigma^{aa})^2} & 0 & 0 \\ 0 & 0 & \frac{1}{(\sigma^{e})^2} & 0 \\ 0 & 0 & 0 & \frac{1}{(\sigma^{n})^2} \end{pmatrix} \quad (6)$$

The parameter variance-covariance matrix is $Q_{xx} = \sigma_u^2\ (A^T PA)^{-1}$, where $\sigma_u^2 = \frac{r^T Pr}{n-u}$, $r = L - Ax, n$ is the number of equations and u is the number of unknowns. Combining of ALOS and Sentinel-1 datasets, allowed us to increase our redundancy, thus refining errors.

2.2. LiDAR Dataset

Next, we obtained a Light Detection and Ranging (LiDAR) elevation model a $1\text{m} \times 1\text{m}$ resolution for Chesapeake Bay from the United States Geological Society (OCM Partners, 2021) (Fig.3 C). The 2016 USGS CoNED (Coastal National Elevation Database) Topo bathymetric Model (1859-2015): Chesapeake Bay dataset were obtained as a raster digital elevation model with vertical accuracy of 30 cm and horizontal accuracy of 100 cm with vertical Datum NAVD88 (North American Vertical Datum of 1988). This data has a temporal range of the input topography of 1859 to 2015.

The vertical land motion rates obtained in section 2.2.3 are resampled on this LiDAR DEM that is referred to the geographic coordinate system. We then adjust the DEM to incorporate subsidence projection following the assumption of a linear rate for the VLM during 21st century (Manoochehr Shirzaei et al., 2021). We subject the adjusted elevation model for VLM projections to multiple SLR and storm surge scenarios by subtracting the height of the transformed DEM from the SLR projection height (Figure 3C). A similar approach is used in Miller and Shirzaei (2021).

2.3. IPCC SLR Scenarios from AR6

We use future SLR scenarios from the latest Sixth Assessment Report (AR6) (Fox-Kemper et al., 2021; Garner et al., 2021, Garner et al., In prep) following SSPs (O'Neill et al., 2014; Riahi et al., 2017) adopted by the IPCC for projection periods of 2030, 2050 till 2100, relative to a baseline of 1995-2014 with medium confidence. In AR6 scenarios, a broader range of emissions futures is covered than considered in fifth assessment report, AR5, including high CO_2 emissions scenarios without climate change mitigation as well as a low CO_2 emissions scenario reaching net zero CO_2 emissions around mid-century (IPCC, 2021). SSPs scenarios offer a more comprehensive assessment of climate drivers and responses and offer unprecedented detail of input data for Earth System Model (ESM) simulations than in the Representative Concentration Pathways (RCPs) used in the AR5 (IPCC, 2021).

SLR projections account for contributions from global processes such as melting of the Greenland Ice Sheet (GIS), Antarctic Ice sheet (AIS), land water storage changes, and Sterodynamic processes, as well as long-wavelength vertical land motion signals due to Glacial Isostatic Adjustment (GIA). A detailed description of the process is found in IPCC AR6 report Box 9.1 (Fox-Kemper et al., 2021). We use the 50th percentiles (i.e., median) projections for different SLR scenarios of SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 at the location of three tide gauge stations within the Chesapeake Bay area, including Sewell's Point, Cape May, and Washington DC (Table 2) to investigate inundation hazards. Here, SSP3-7.0 and SSP5-8.5 indicate high and very high greenhouse gas (GHG) emissions and CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively, SSP2-4.5 is scenarios with intermediate GHG emissions and CO_2 emissions remaining around current levels until the middle of the century, and SSP1-1.9 and SSP1-2.6 represent scenarios with very low and low GHG emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions (IPCC, 2021, Summary for Policy Maker, Box SPM 1). The details of each SSPs are provided at the header of table 2.

For our analysis, we obtained the SLR projections without the effect of VLM as well as SLR due only to the effect of VLM. The former is used in combination with our measured VLM rates to investigate inundation hazards in the region, while the latter is used to assess the accuracy of VLM rates used in the IPCC projections compared to our observed VLM.

Table 2. Projected SLR without the contribution of vertical land motion in meters at three stations of Chesapeake Bay area including Sewell's point, Cape May, and Washington DC. Sea level projections considering projections with *medium confidence* are provided, relative to the period 1995–2014, for five Shared Socioeconomic Pathway (SSP) scenarios. The details of the scenarios can be found in the Working Group 1 contribution sections TS1.3 and 1.6 and Cross-Chapter Box 1.4 and are described as below. **SSP1-1.9** indicates net zero CO_2 emissions around the middle of the century and corresponds to warming to approximately 1.5°C above 1850-1900 in 2100 after slight overshoot (median). **SSP1-2.6** stays below 2.0°C warming relative to 1850-1900 (median) with implied net zero emissions in the second half of the century. **SSP2-4.5** is approximately in line with the upper end of aggregate Nationally Determined Contribution (NDC) emission levels by 2030. **SSP3-7.0** indicates a medium to high reference scenario resulting from no additional climate policy under the SSP3 socioeconomic development narrative. SSP3-7.0 has particularly high non-CO_2 emissions, including high aerosols emissions. **SSP5-8.5** is a high reference scenario with no additional climate policy (Source: IPCC AR6).

Tide gauge Station		***Median (50th Percentile) (m)***		
	Relative to 1995-2014	***2030***	***2050***	***2100***
Sewell's Point	SSP 1-1.9	0.138	0.260	0.458
	SSP 1-2.6	0.146	0.270	0.520
	SSP 2-4.5	0.142	0.282	0.651
	SSP 3-7.0	0.139	0.286	0.770
	SSP 5-8.5	0.148	0.312	0.862
Cape May	SSP 1-1.9	0.142	0.260	0.458

	SSP 1-2.6	0.146	0.278	0.522
	SSP 2-4.5	0.144	0.286	0.664
	SSP 3-7.0	0.141	0.286	0.784
	SSP 5-8.5	0.151	0.318	0.884
Washington D.C.	SSP 1-1.9	0.14	0.260	0.454
	SSP 1-2.6	0.145	0.275	0.520
	SSP 2-4.5	0.142	0.286	0.660
	SSP 3-7.0	0.140	0.287	0.778
	SSP 5-8.5	0.150	0.316	0.875

2.4. Strom surge estimates

We obtained recorded storm surge levels for Hurricane Isabel (Hovis et al., 2004) and Hurricane Sandy (Fanelli et al., 2013), in September 2003 and October 2012, respectively, to create indignation scenarios due to sea-level rise and storm surges, assuming that Sandy-like surges are likely to occur in the future (Lin et al., 2012). Here storm surge is defined as the local change in the elevation of the ocean along a shore due to a storm and represents the observed water level/storm tide-minus predicted astronomical tide levels, e.g., water motion which would result from Earth’s rotation and gravitation effects following NOAA report (Fanelli et al., 2013; Hovis et al., 2004). Recorded details on storm surge levels, dates and time from Hurricane Sandy and Isabel used for our analysis for flood inundation can be found in Table 1. We only evaluate the effect of storm surge on inundation hazards for the high reference scenario with no additional climate policy namely SSP 5-8.5 for SLR.

3. Results

3.1. VLM rate and Validation

We obtained vertical land motion for 2007-2020 after processing an extensive set of Sentinel-1 and ALOS SAR acquisitions and further estimated uncertainty in the rate (Fig. 4). Over the Chesapeake Bay, a spatially variable subsidence rate up to -5.5 mm/year and a standard deviation of maximum 1.6 mm/year is observed. A few subsidence hotspots are highlighted in Figure. 4. Panels I, II, III show Southern Chesapeake Bay, Cape May, and Washington DC areas where tide gauge stations are located. The southern Chesapeake Bay area, mainly the Hampton region and Newport News, is undergoing subsidence with -3± 0.4 to -4± 0.4 mm/year (highlighted by zoomed in panel I). To validate the InSAR-based estimate of VLM, we use a subset of selected GNSS stations, comprising 20% of available stations, which were chosen randomly and were not used in our analysis. We found a good agreement between the dataset, with a standard deviation of 0.34 mm/yr for the difference between InSAR-based VLM and GNSS vertical rate (Fig.4 panel III). Small uplift signals are observed near Calvert County, Maryland, likely due to aquifer recharge, observed in the groundwater level measurement at sites Prince Frederick, MD (Fig. 5A) and Cover Point, MD (Fig. 5B) from 2017 to 2021.

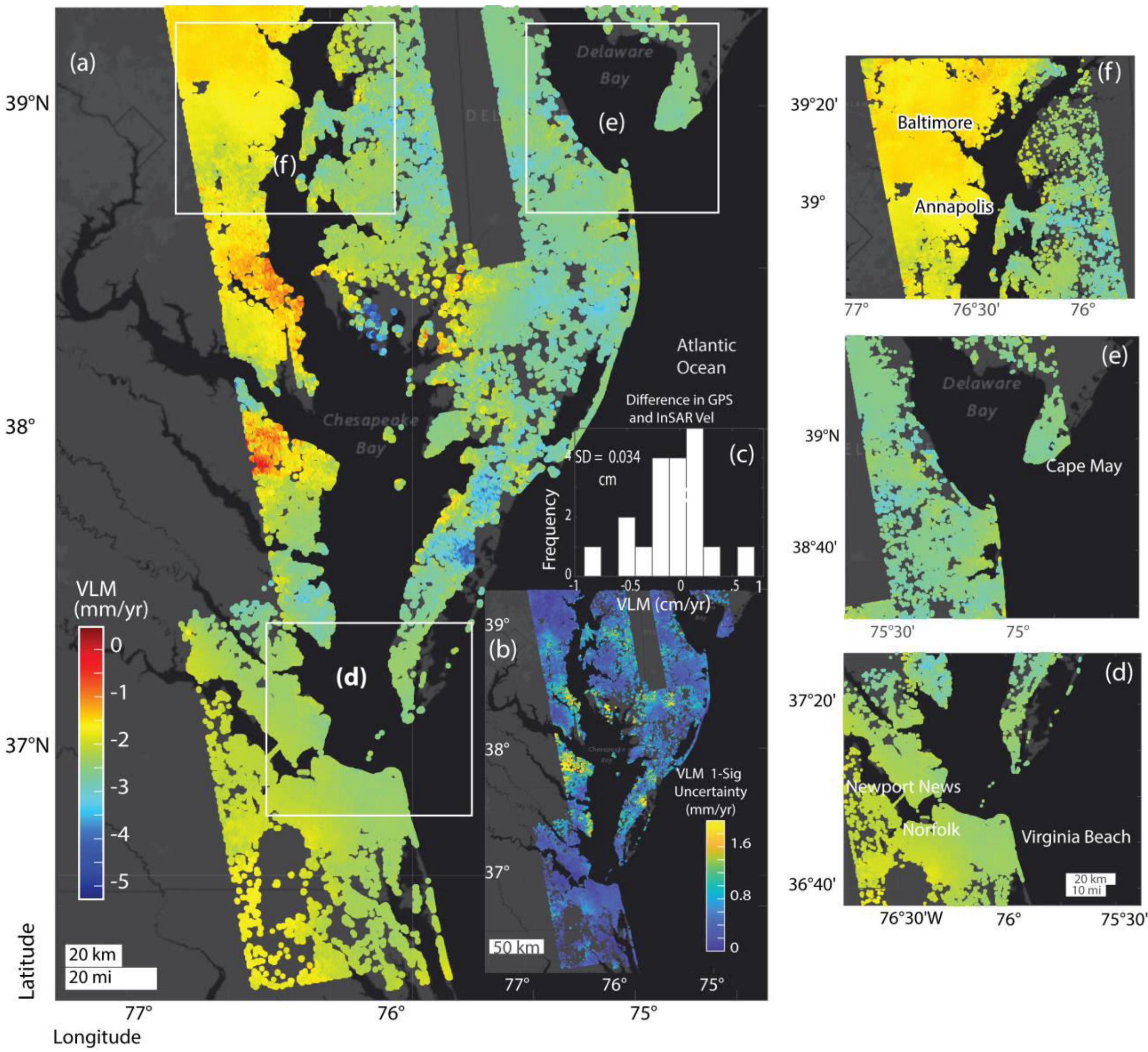

Figure.4. (a) VLM rate (mm/yr) over the Chesapeake Bay from 2007-2020 as a combination of ALOS PALSAR, Sentinel-1A and GNSS datasets. **(b)** VLM 1σ standard deviation. The validation results between the 20% GNSS station data and the estimated VLM is conducted in panel **(c)** (cm/yr). Further, boxes (d), (e), (f) show three zoomed-in locations of Chesapeake Bay, highlighted in panel (a).

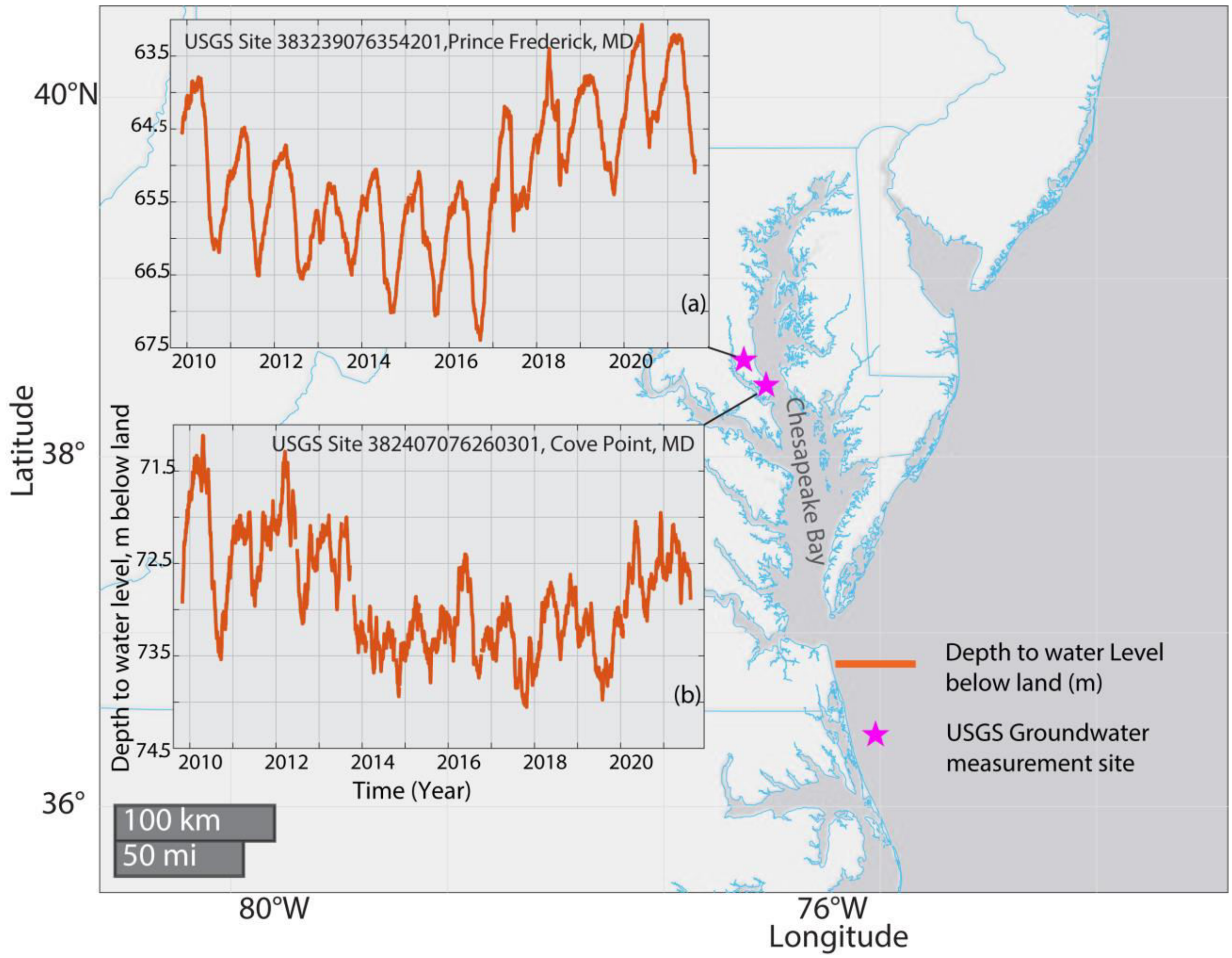

Figure 5. Timeseries of groundwater level, measured as depth to water below land at two USGS sites **(a)** Prince Frederick, MD, **(b)** Cove Point, MD.

3.2. Non-GIA Contributions

To examine the non-GIA contributions in the estimated VLM, we used the GIA ICE-6G-D model (Peltier et al., 2018) and removed its effect from the observed VLM. VLM from the GIA model projected on InSAR pixels (Fig.6A) shows a persistent collapsing forebulge of the Laurentide Ice Sheet in the study area with a median rate of -1.88 mm/yr (and range of -2.14 - -1.36 mm/yr). The InSAR-based VLM map exhibit a similar pattern but at a higher subsidence rate up to -5 mm/year, as shown in Fig. 6B (and 6A). After removing the effect of GIA (Fig. 6C and D), the VLM rate map mainly comprises the influence of non-GIA contributions, including groundwater extraction and sediment compaction. We observe non-GIA subsidence rates as high as -4 mm/yr in some areas, 2-3 times faster than long-term geologic rates, consistent with that reported in earlier studies (e.g., Karegar et al. (2016)). After removing the GIA effect, a broader region, mainly along the coastline, shows a slow uplift rate of up to 1 mm/yr, corresponding with rebounding aquifers and possibly aggrading wetlands (Holmquist et al., 2021).

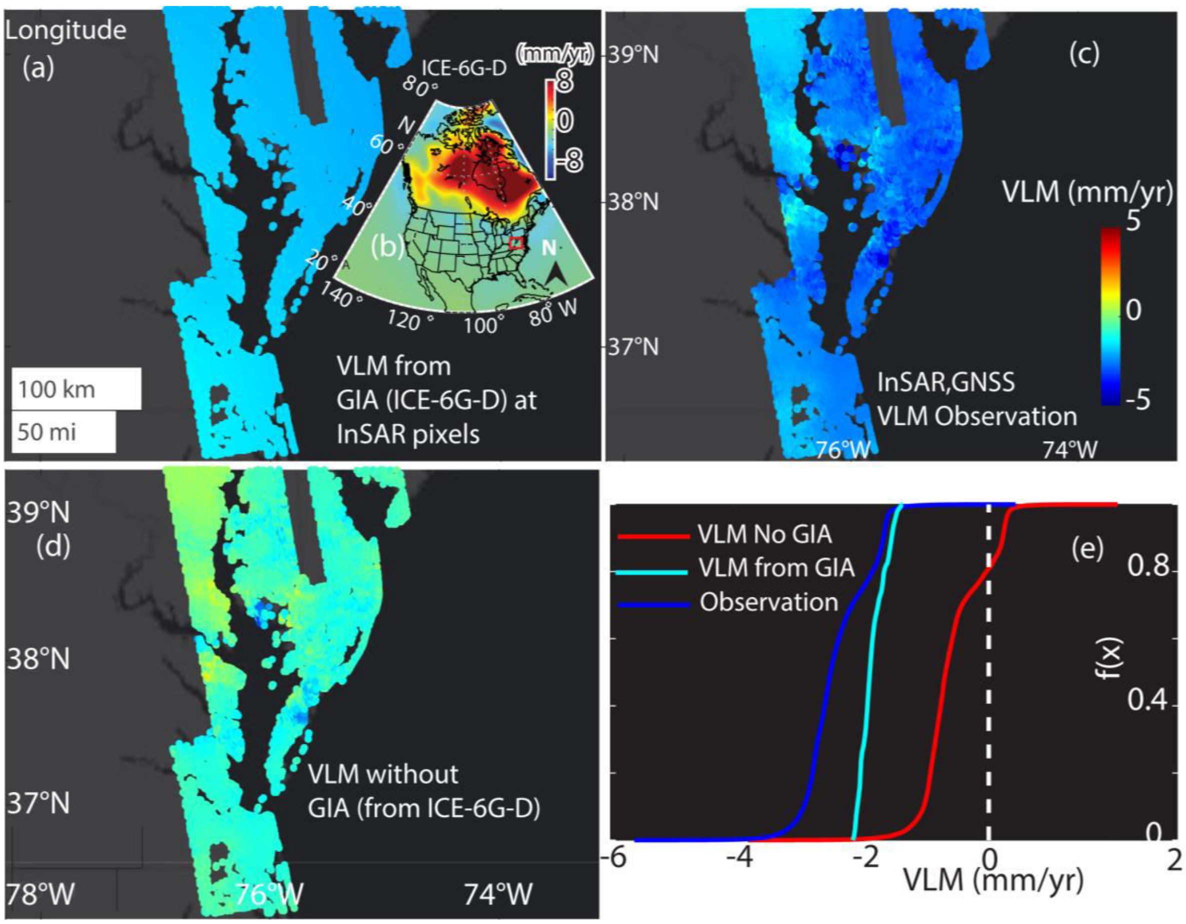

Figure 6. VLM rate with and without the influence of glacial isostatic adjustment (GIA). **(a)** VLM from GIA oversampled on InSAR pixels, data from using ICE-6G-D model (Peltier et al., 2018). **(b)** estimated VLM in this study InSAR and GNSS, and VLM. **(c)** VLM rate after removing the effect of GIA. **(d)** Empirical cumulative distribution function for datasets shown in Panels **(a), (b), (c).** Note that panels **(a), (b), (c)** have same color bar.

3.3. Comparison with IPCC VLM projections

We compared projected vertical land motion information used in IPCC Sixth Assessment Report AR6, considering its median estimates (50 percentile) with a linear projection of our VLM rates at two tide gauge stations (Fig. 7) till the 2150 time period from 2020. For vertical land motion at the tide gauge location, we selected pixels within a radius of 200 m and obtained the average rate. We found IPCC sea-level change from VLM projection was overestimated in Sewell's Point with a value of 2.85 mm/year compared to our estimate of 2.36 mm/year and underestimated in Cape May with values 2.25 mm/year versus 2.91 mm/year estimated here. This comparison highlights the need for incorporating high-resolution observation of VLM in future projections of SLR to obtain accurate estimates of future flooding and inundation hazards.

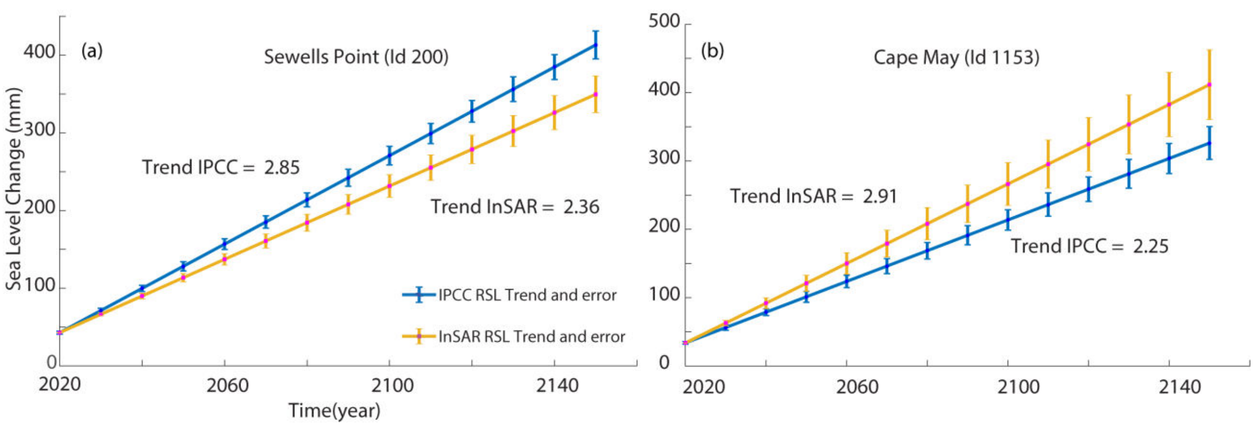

Fig. 7. Comparison of sea-level change due to vertical land motion from IPCC Sixth Assessment Report AR6, using median datasets (50 percentile) and comparison of sea-level change from our VLM estimate, at three selected tide gauge stations **(a)** Sewell's Point and **(b)** Cape May. 1-sigma error is also shown for each station. The PSMSL (Permanent Service for Mean Sea Level) ID numbers are shown based on IPCC datasets (Garner et al., 2021).

3.4. Projected Inundation Hazards

The projections of current VLM rates combined with LiDAR topographic data, SLR projection scenarios, and storm surge heights allow evaluation of future inundation hazards. These projections are required to improve preparedness and have important implications for flood mitigation and resiliency. The projected inundation areas due to only VLM in three-time snapshots, 2030, 2040, and 2100 are shown in Fig. 8, indicating increasing inundation near the wildlife reserve and coastal plains area. Inundation projections from SLR and VLM at five different climate scenarios, SSPs, from SSP 1-1.6-5-8.5 at three-time scales (2030-2050-2100) are shown in Fig. 9-13, sea-level rise inundation for 2100 time-period for all SSPs in Fig. 14 and inundated area (km^2) in Fig. 15. We observed increased inundation areas in all five SSPs 1-1.9-5-8.5 for SLR, ranging from 343, 410, 522, 587, and 627 $km^{2,}$ respectively in 2100 timeframe and 454, 483, 533, 571, and 600 from both SLR and VLM with 2100 time-period (Fig. 15, Table 3). CB's spatial inundation maps highlight areas such as Tangier island, Smith island, Mockhorn island, wetlands and National wildlife refuges such as Blackwater national wildlife refuge and Plumtree national wildlife refuge that are flooded in even very low and low GHG emissions scenarios such as SSPs 1-1.9-1-2.6 (Fig. 9 and Fig. 10). The flooded area starts extending toward mostly river channels as the climate scenarios and projection time-period increase. Further, the flooded area grows toward mostly river channels as the climate scenarios and projection time-period increase.

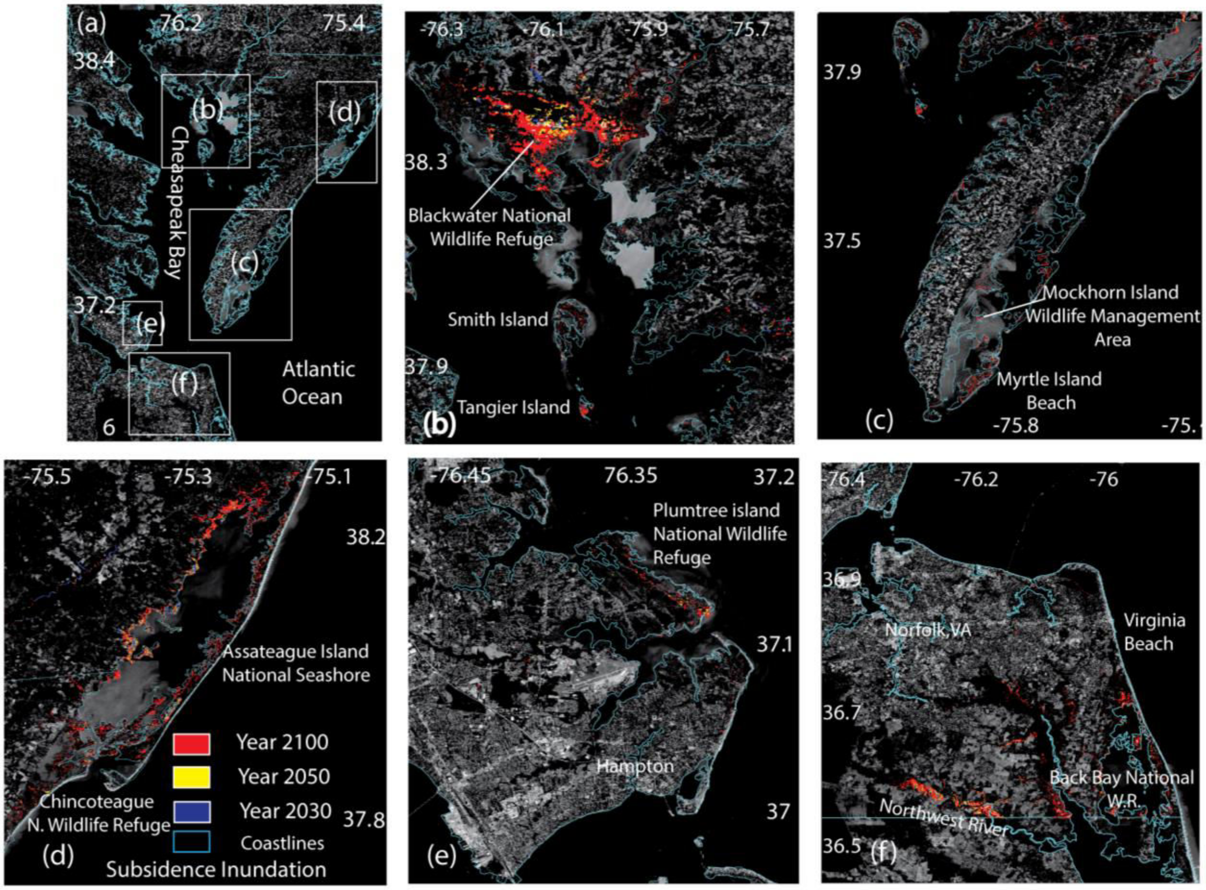

Figure 8. Projected inundation area from subsidence at year 2030, 2050, and 2100 using our VLM measurement. Panel **(a)** shows the overview and panels **(b), (c), (d), (e), (f)** highlights the zoomed-in subsidence inundation for three timescales.

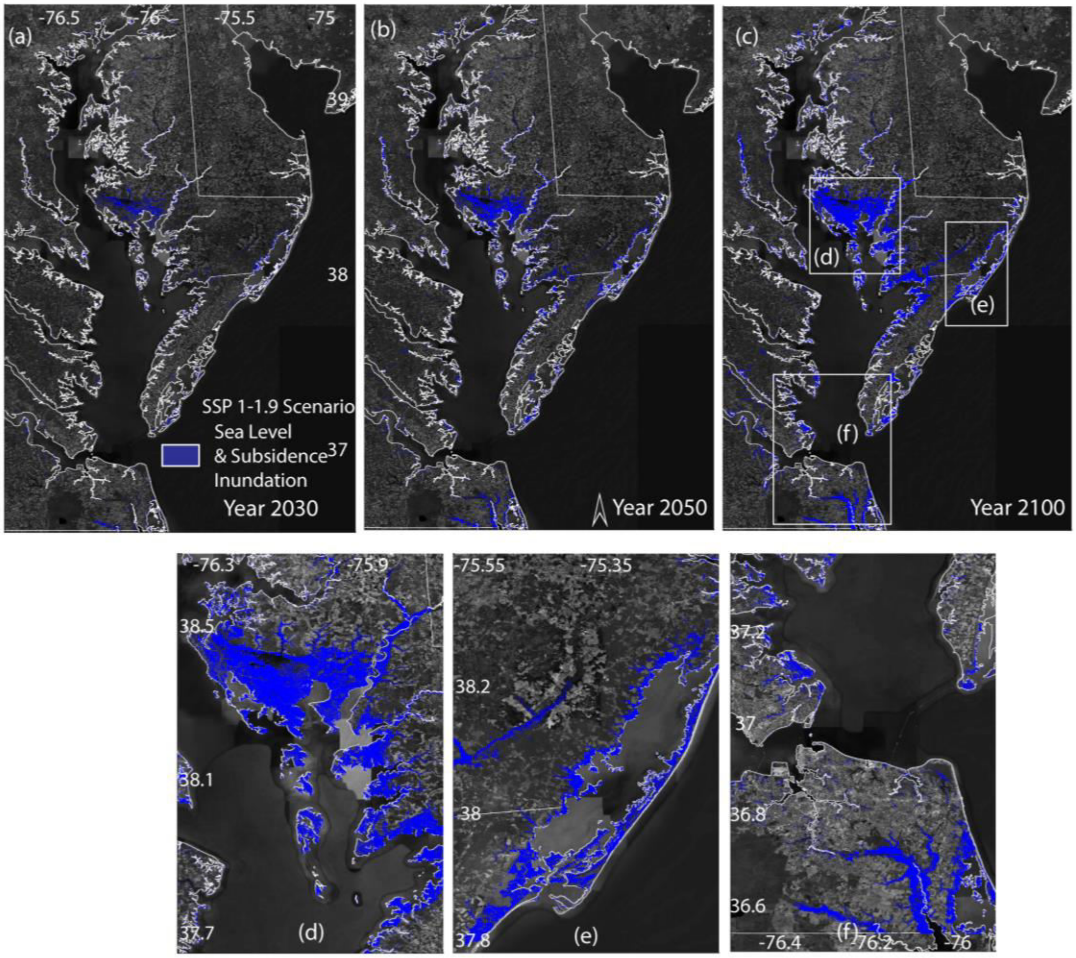

Figure 9. Projected Inundation area from both subsidence and SLR under Shared Socioeconomic Pathways (SSP) 1-1.9 at year 2030, 2050, and 2100 (top panels, panels **(a), (b), (c)** respectively). The bottom panel **(d), (e), (f)** highlights zoomed-in inundation from sea level and subsidence at 2100.

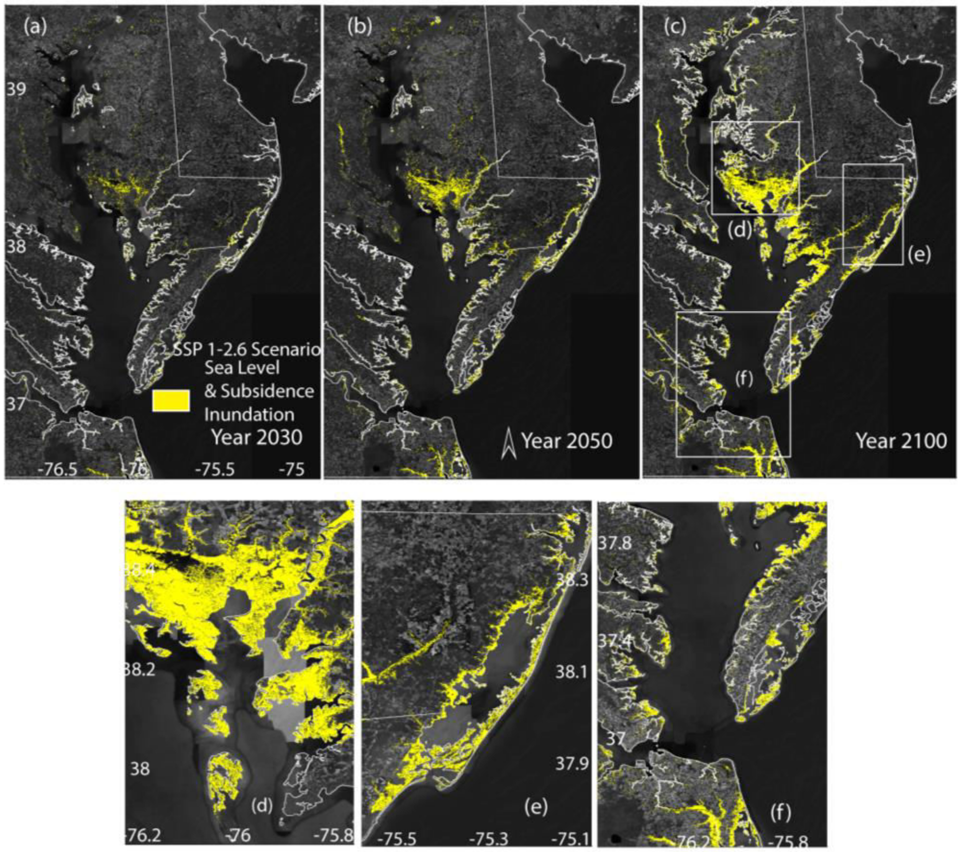

Figure 10. Projected inundation area both subsidence and SLR at Shared Socioeconomic Pathways (SSP) 1-2.6 for timescales 2030, 2050, and 2100 (top panels, panels **(a), (b), (c)** respectively). The bottom panels, **(d), (e), (f)** highlights zoomed-in inundation from sea level and subsidence at 2100.

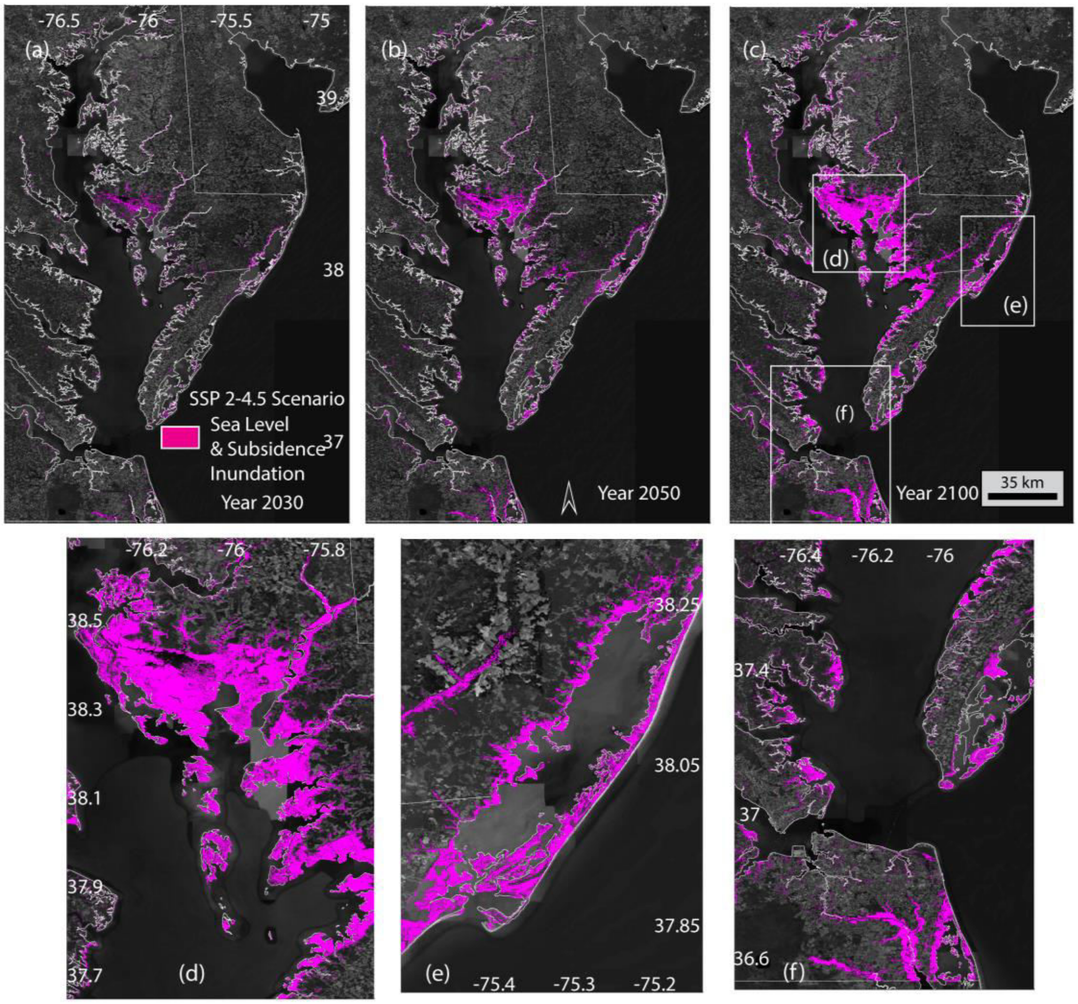

Figure 11. Projected inundation area from both subsidence and SLR at Shared Socioeconomic Pathways (SSP) 2-4.5 for timescales 2030, 2050, and 2100 (top panels, panels **(a), (b), (c)** respectively). The bottom panels **(d), (e), (f)** highlights zoomed-in inundation from sea level and subsidence at 2100.

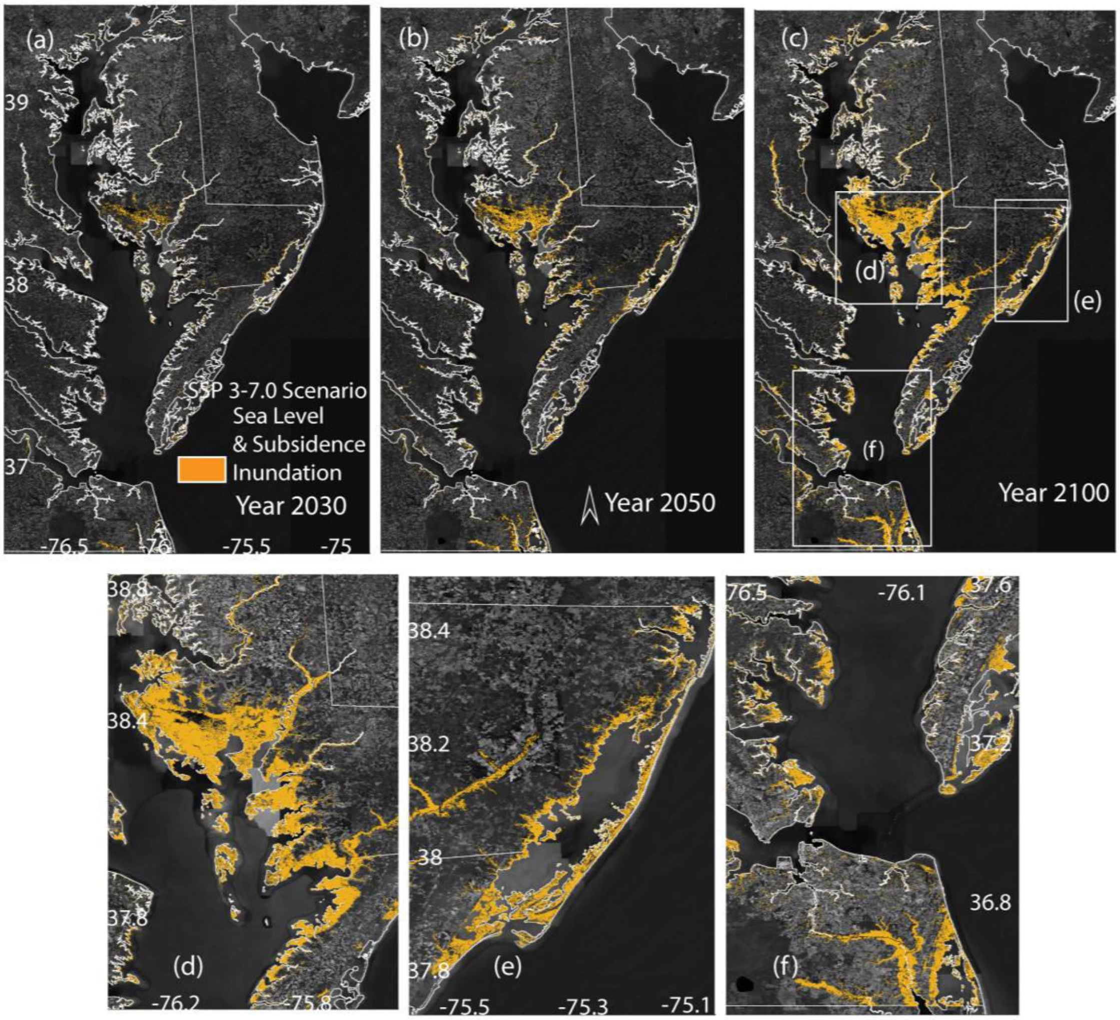

Fig.12. Projected inundation area from both subsidence and SLR at Shared Socioeconomic Pathways (SSP) 3-7.0 for timescales 2030, 2050, and 2100 (top panels, panels **(a), (b), (c)** respectively). The bottom panel **(d), (e), (f)** highlights zoomed-in inundation from sea level and subsidence at 2100.

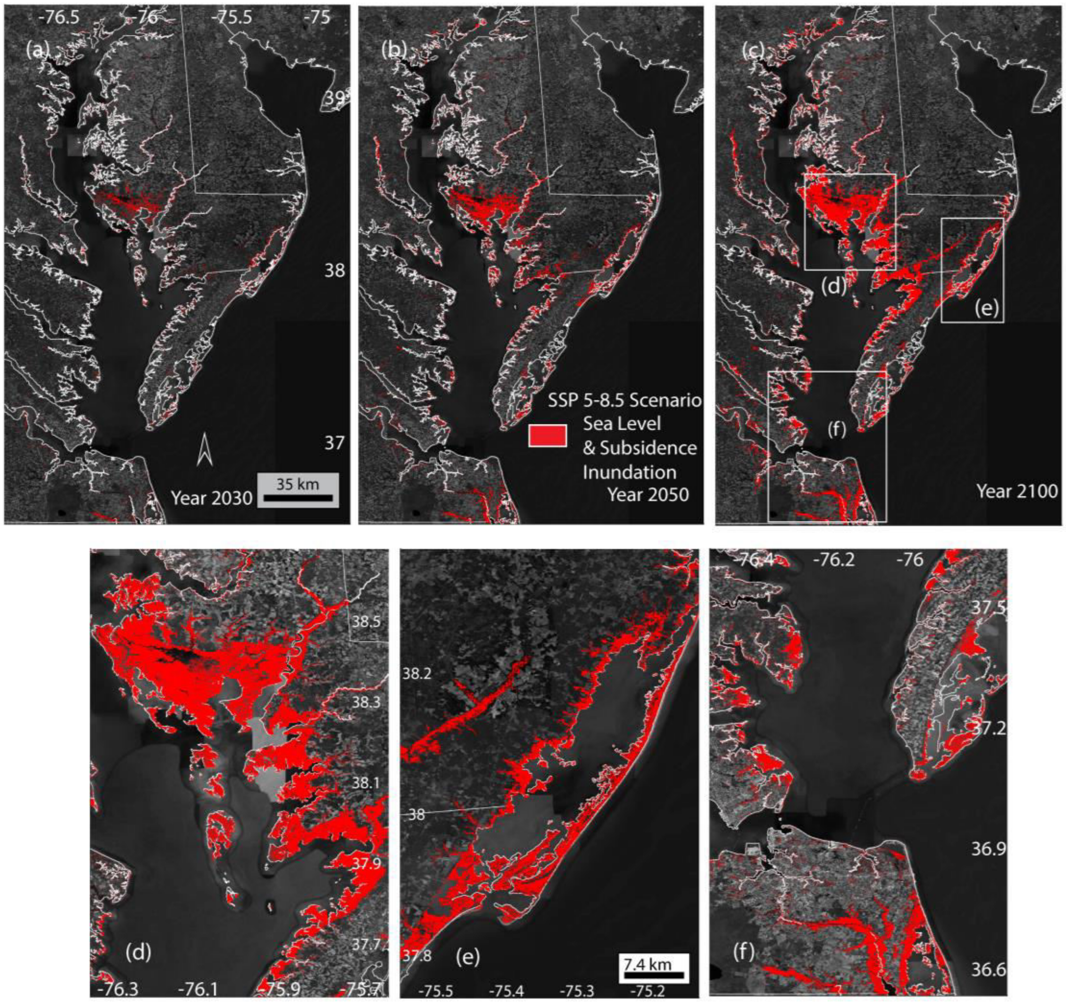

Figure 13. Projected inundation area from both subsidence and SLR at Shared Socioeconomic Pathways (SSP) 5-8.5 for timescales 2030, 2050, and 2100 (top panels, panels **(a), (b), (c)** respectively). Bottom panel **(d), (e), (f)** highlights zoomed-in inundation from sea level and subsidence in 2100.

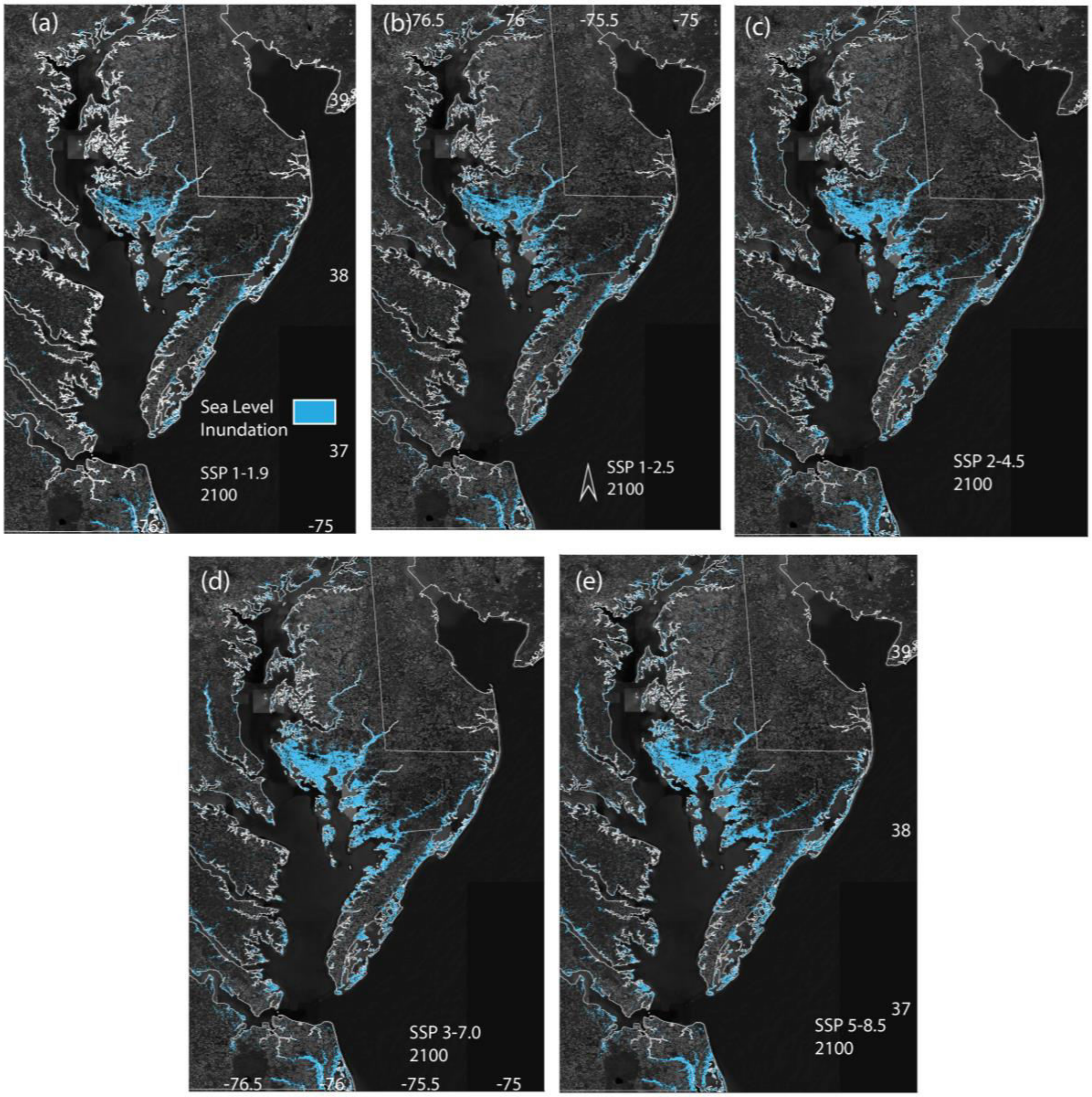

Figure 14. Projected inundation area from SLR for time 2100 all SSPs, 1-1.9, 1-2.5, 2-4.5, top panels **(a), (b), (c)**, bottom panels **(d), (e) are** 3-7.0, and 5-8.5 respectively for the Chesapeake Bay.

At SSP 3-7.0 and 5-8.5 in 2100 time-period, we observed more inundation from only sea-level rise ranging from 587 and 627 km^2 in contrast to while including VLM effect in the projection resulting in 571 and 600 km^2 showing the result of non-linear VLM and role of uplift pixels in the overall inundation area (Fig. 15, Table 3). The combination of the storm surge scenario from Hurricane Sandy in October 2012, with the SLR showed an inundated area of 578-1087 km^2, respectively, from 2030 to 2100 (Fig.16A) in SSP 5-8.5 and 599-1232 km^2 when incorporating Hurricane Isabel of September 2003 (Fig. 16B). Further, an amalgamation of all three components SLR, VLM, and Strom surge, projected inundation of 739-1032 km^2 and 588-1117 km^2 for Hurricane Sandy and Isabel, respectively.

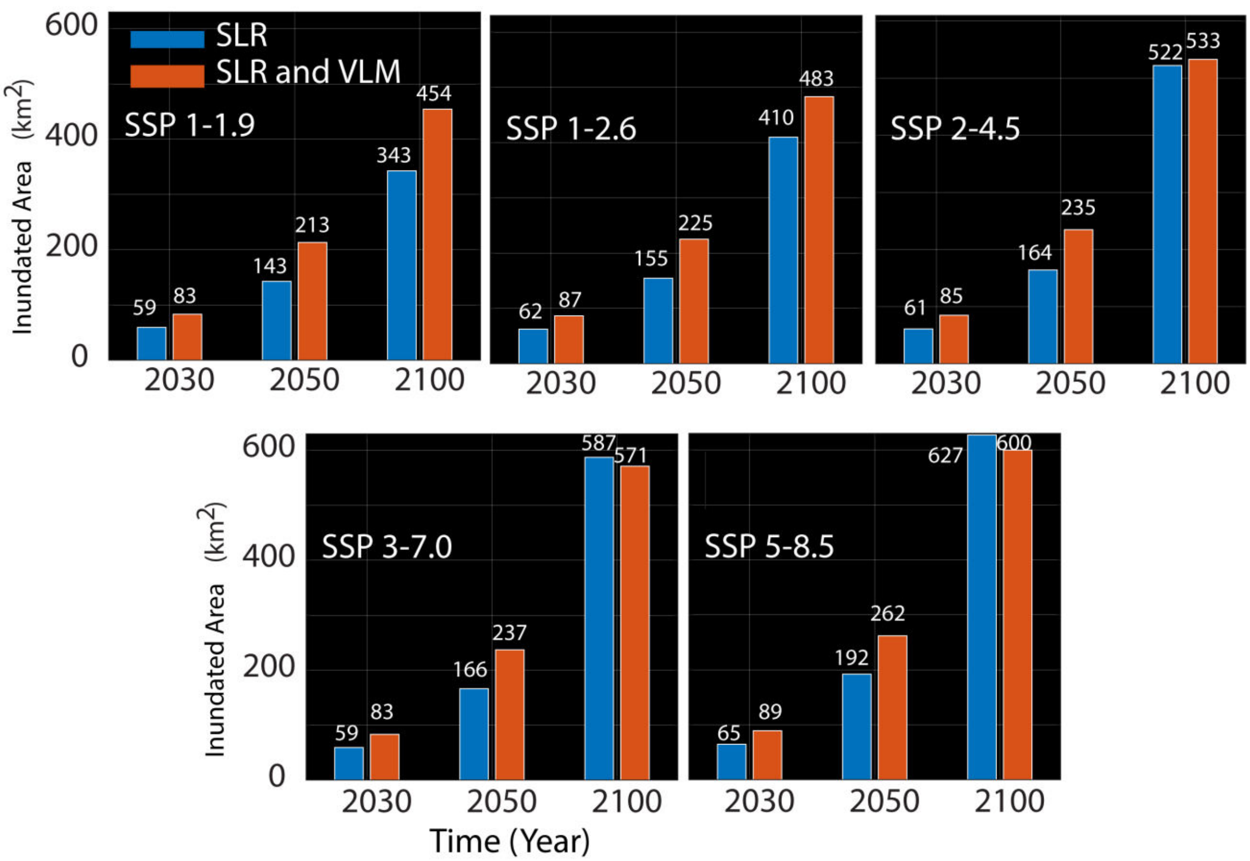

Fig. 15. Inundated Area from Subsidence and SLR (km^2) (in orange), and only SLR (in blue in km^2) at SSPs 1-1.9, 1-2.5, 2-4.5, 3-7.0, and 5-8.5 respectively.

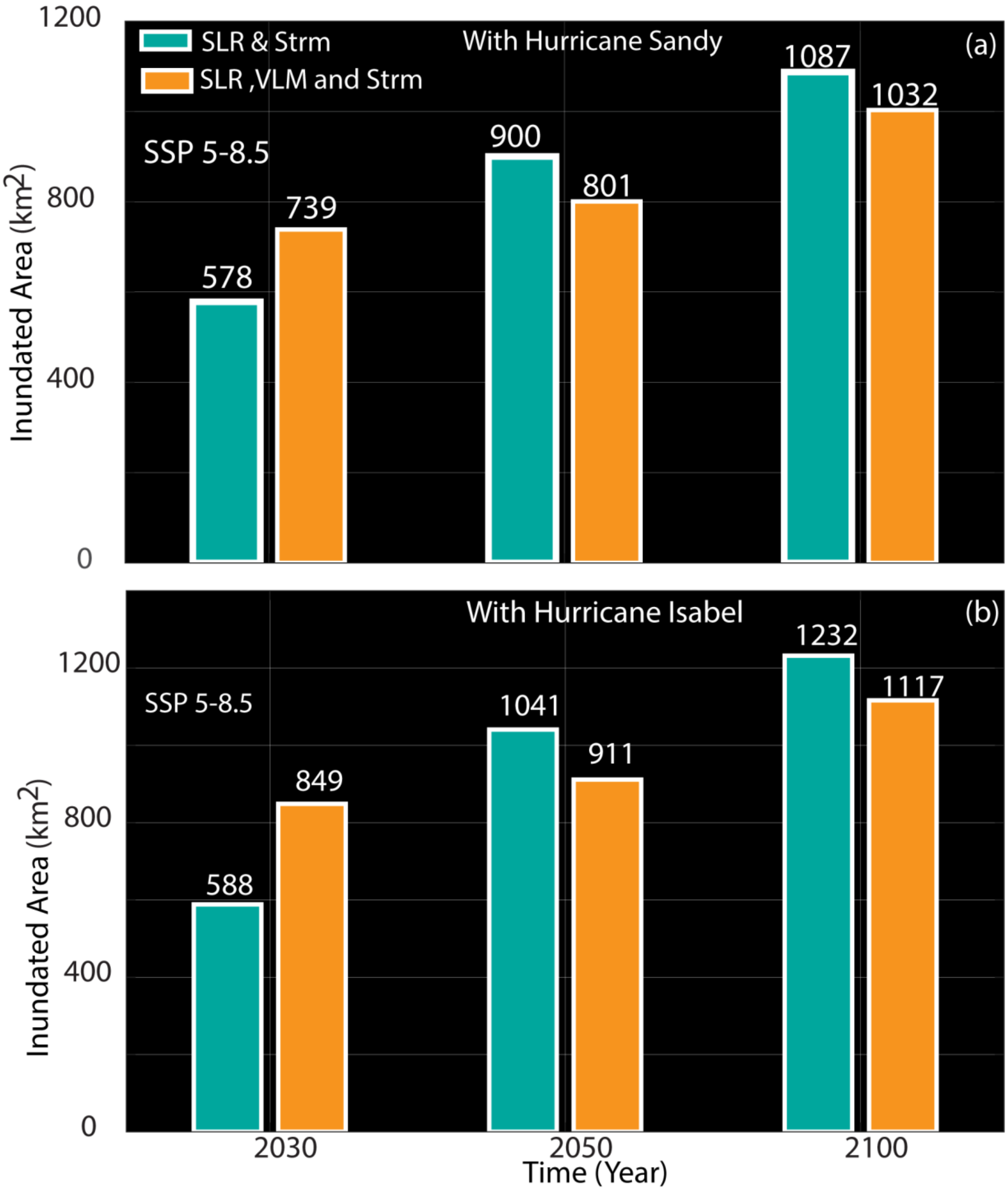

Fig.16. Inundation Area (km^2) from Storm surge based on **(a)** October 2012 Hurricane Sandy Datasets and **(b)** Hurricane Isabel recorded on 18-19 September 2003 from NOAA and SLR scenario of highest emission SSP 5-8.5 in km^2.

Table 3. Inundated area (km^2) modeled for five climate scenarios for Sea-Level Rise (SLR), Sea Level Rise and Subsidence from 2030 through 2100 and SLR, storm surge and VLM incorporating Hurricane Sandy of October 2012 and Hurricane Isabel of September 2003, for high reference scenario with no additional climate policy, SSP 5-8.5 from 2030 to 2100.

Content		***Year***		
		2030	***2050***	***2100***
	IPCC Climate Scenarios	***Area (Km^2)***	***Area (Km^2)***	***Area (Km^2)***
Sea Level Rise	SSP 1-1.9	59	143	342
	SSP 1-2.6	62	155	410
	SSP 2-4.5	61	164	522
	SSP 3-7.0	59	166	587
	SSP 5-8.5	65	192	627
Sea Level Rise and Subsidence	SSP 1-1.9	83	213	454
	SSP 1-2.6	87	225	483
	SSP 2-4.5	85	235	533
	SSP 3-7.0	83	237	571
	SSP 5-8.5	89	262	600
Sea Level Rise and Storm Surge (Hurricane Sandy)	SSP 5-8.5	578	900	1087
Sea Level Rise, Storm	SSP 5-8.5	739	801	1032

Surge, and VLM (*Hurricane Sandy*)				
Sea Level Rise and Storm Surge (Hurricane Isabel)	SSP 5-8.5	588	1041	1232
Sea Level Rise, Storm Surge, and VLM (*Hurricane Isabel*)	SSP 5-8.5	849	911	1117

4. Discussion and Conclusion

The Chesapeake Bay area, the largest estuary in the United States, is home to 15 wildlife refuges (Ernst, 2003; Ray & McCormick-Ray, 2009). The urban Hampton area encompasses the world's most extensive naval base and a dense population of more than 1.7 million people (U.S. Census Bureau, 2020). Accurate estimation of VLM and flooding coming from sea level change allows flood mitigation. A recent study on the region has highlighted increasing regional sea-level changes in the Chesapeake Bay area (Bekaert et al., 2017; Buzzanga et al., 2020; Harvey et al., 2021; Karegar et al., 2017). Here we provide accurate high-resolution observations and estimate changes in local processes driving relative sea-level change and inundation projection until 2100, encompassing factors contributing to sea level.

Combining ALOS and Sentinel-1 datasets with GNSS measurements allows obtaining robust estimates of long-term VLM at management-relevant resolution (10s m) for the period 2007-2020, suitable for investigating natural and anthropogenic drivers and relative sea-level rise and inundation hazards. To perform our analysis, we assumed that the VLM rates were steady during the observation period and we ignored the gap from 2011 to 2014 between the two satellite acquisition periods. Thus, a decadal change in VLM rates may affect the estimated long-term trends. However, a comparison with independent GNSS measurements yields a good agreement, suggesting our assumptions are reasonable and decadal VLM rate variations are of 2nd order importance. Forward projections of VLM are crucial for assessing future flooding and inundation hazards. Following earlier studies (Fox-Kemper et al., 2021; Miller & Shirzaei, 2021; Manoochehr Shirzaei & Bürgmann, 2018), we assumed a linear functional model for future estimates. However, this assumption might only be valid for the GIA effect, and most anthropogenic factors, such as contributions from aquifer compaction, are likely non-linear and change over time (Manoochehr Shirzaei et al., 2021). The Chesapeake Bay region, particularly Hampton Roads, injects treated wastewater into the underlying aquifer to mitigate subsidence from aquifer compaction. A recent study by Buzzanga et al. (2020) on Hampton reported an overall subsidence rate of -3.6 ± 2.3 mm/year with considerable spatial variability and no significant effects of groundwater injection. Despite its importance, thus far little research has focused on scenario-based projections of coastal VLM that account for various socioeconomic and climate forcing factors to obtain values comparable to that of SLR projections.

Using a VLM-adjusted high resolution (1x1 m grid) lidar topographic dataset alongside IPCC AR6 sea level scenario and two Hurricanes, Sandy and Isabel, allowed estimation of flood and inundation extent in the Chesapeake Bay throughout 21st century. Overall, subsidence increases the hazards, except at a few locations, where some uplift is observed due to aquifer recharge and wetlands elevation gains. These results highlight the disruptive role of VLM in defending against and adapting to climate change in coastal areas.

In the United States, almost 29% of the US population live along the coastline, with more than 41 million people living on the Atlantic coast, including a minority population, and are vulnerable to hurricanes alongside an increase in sea level (US Census Bureau, 2021). A study by Neumann et al. (2015) has projected the global coastal population to surpass one billion people this century. Flooding and inundation hazards can displace a large proportion of the population (Hauer et al., 2020). This further influences human migration due to permanent, irreversible inundation of low-elevation areas, which, under SLR, renders unavailable for livelihoods and ultimately land uninhabitable (Hauer et al., 2020). In Hampton Roads, flooding impacts low-income, socially vulnerable areas such as portions of Newport News, Norfolk, and Portsmouth, and some outlying rural areas in the counties of Gloucester and Surry. The most recent Census data lists the City of Norfolk as having 19.7% of its population living in poverty, Portsmouth as having 17.2%, and Newport News as having 15.5% (U.S. Census Bureau, 2021) and an increase in future flooding risk will disproportionately impact Black communities while remaining concentrated on the Atlantic and Gulf coasts. Our findings of current and future coastal hazards in the Chesapeake Bay, driven by climate and solid Earth changes, provide critical information for hazard and risk management and have a significant societal relevance as they induce considerable adaptation needs for disaster resilience.

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Data Availability Statement

SAR datasets are available at the Alaska satellite facilities https://vertex.daac.asf.alaska.edu/. GNSS velocities information is obtained from the Nevada Geodetic lab (http://geodesy.unr.edu/). Tide gauge datasets are found on the NOAA website https://tidesandcurrents.noaa.gov/map/index.html. The LiDAR dataset is a contribution from USGS and can be found at https://coast.noaa.gov/htdata/raster2/elevation/Chesapeake_Coned_update_DEM_2016_8656/.

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Supplementary online materials for

Disruptive Role of Vertical Land Motion in Future Assessments of Climate Change-Driven Sea Level Rise and Coastal Flooding Hazards in Chesapeake Bay.

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Table S1. Acquisition dates of ALOS L-band, Sentinel-1A/B, C-band SAR images acquired in ascending orbit geometry of paths 134, 135, 136,137,138 for ALOS and paths 106 and 04 for Sentinel used for estimating vertical land motion for Chesapeake Bay. Acquisition dates of the data are provided in YYYYMMDD format. Beam modes are Polarimetric mode (PLR) and interferometric wide swath (IW) mode for ALOS PALSAR and Sentinel-1 respectively.

Satellite	**Paths**	**Frames**	**Acquisition Date (YYYYMMDD)**	**Look Direction**	**Look Angle (θ)**	**Wavelength λ (cm)**	**Beam Mode**	**Flight Direction**
ALOS	134	750	20070804 20070919 20071220 20080921	Ascending	34.5	24.6	PLR	347

			20081222 20090924 20091225 20100327 20100512 20100627 20100812 20101112 20101228 20110212					
		760	20070804 20070919 20071220 20080921 20081222 20090924 20091225 20100327 20100512 20100627 20100812 20101112 20101228 20110212	Ascending	34.5	24.6	PLR	347
		770	20070919 20071220 20080921 20081222 20090924 20091225 20100327 20100512 20100627 20100812 20101112 20101228 20110212	Ascending	34.5	24.6	PLR	347
ALOS	135	740	20080523 20080708 20090711 20100111 20100226 20100529	Ascending	34.5	24.6	PLR	347

			20100714 20100829 20101014 20101129 20110114					
		750	20080523 20080708 20090711 20100111 20100226 20100529 20100714 20100829 20101014 20101129 20110114					
ALOS	136	720	20061205 20071208 20090728 20100315 20100430 20100615 20100915 20101031 20101216 20110131	Ascending	34.5	24.6	PLR	347
		730	20061205 20071208 20100315 20100430 20100615 20100915 20101031 20101216 20110131	Ascending	34.5	24.6	PLR	347
		740	20061205 20071208 20100315 20100615 20100915 20101031 20101216	Ascending	34.5	24.6	PLR	347

			20110131					
		750	20061205 20071208 20090728 20100315 20100430 20100615 20100915 20101031 20101216 20110131	Ascending	34.5	24.6	PLR	347
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		770	20061205 20071208 20090728 20100315 20100430 20100615 20100915 20101031 20101216 20110131	Ascending	34.5	24.6	PLR	347
ALOS	137	720	20061222 20070924 20080626 20080926 20090814 20100401 20100517 20100702 20100817 20101002	Ascending	34.5	24.6	PLR	347

	20101117 20110102					
730	20061222 20070924 20080626 20080926 20090814 20100401 20100517 20100702 20100817 20101002 20101117 20110102 20110217	Ascending	34.5	24.6	PLR	347
740	20070924 20100702 20100817 20101117	Ascending	34.5	24.6	PLR	347
750	20061222 20070924 20080626 20080926 20090814 20100401 20100517 20101002 20101117 20110102 20110217	Ascending	34.5	24.6	PLR	347
760	20061222 20070924 20080626 20080926 20090814 20100401 20100517 20100702 20100817 20101002 20101117 20110102	Ascending	34.5	24.6	PLR	347

			20110217					
		770	20061222 20070924 20080626 20090814 20100401 20100517 20100702 20100817 20101002 20101117 20110102 20110217	Ascending	34.5	24.6	PLR	347
Sentinel-1/A	106	118	20170411 20170423 20170505 20170517 20170529 20170610 20170622 20170704 20170716 20170809 20170902 20170914 20170926 20171008 20171020 20171101 20171113 20171125 20171207 20171219 20171231 20180112 20180124 20180205 20180217 20180301 20180313 20180325 20180406 20180418 20180430	Ascending	38.4	5.547	IW	347

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