Climate Risk Management 42 (2023) 100555

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Satellite monitoring for coastal dynamic adaptation policy pathways

Benjamin D. Hamlington [a,1,*], Anjali Tripathi [a,1], David R. Rounce [b], Matthew Weathers [b], Kyra H. Adams [a], Carmen Blackwood [a], Jamie Carter [e], Renee C. Collini [f], Laura Engeman [g], Marjolijn Haasnoot [c], Robert E. Kopp [d]

[a] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*
[b] *Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA, USA*
[c] *Deltares, Delft, Netherlands, Faculty of Geosciences, Utrecht University, Utrecht, Netherlands*
[d] *Dept. of Earth and Planetary Sciences, Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers Univ, New Brunswick, NJ, USA*
[e] *NOAA Office for Coastal Management, USA*
[f] *The Water Institute of the Gulf, Baton Rouge, LA, USA*
[g] *Scripps Institution of Oceanography and California Sea Grant, University of California San Diego, CA, USA*

ARTICLE INFO

Keywords:
Sea level rise
Satellite Data
Remote Sensing
Adaptation Pathways

ABSTRACT

Dynamic adaptation policy pathways provide a roadmap for coastal communities to establish a suite of sea level rise adaptation responses based on observation-driven signals of increasing risk. This adaptation approach relies heavily on iterative assessment of sea level rise observations and model projections. Remote sensing capabilities from satellites offer an opportunity to assess a consistent set of observational data indicators, around which adaptation pathways can be built. The large-scale nature and broad coverage of satellite observations provide the benefit of consistent monitoring capabilities across the globe, for regions with differing needs, resources, and monitoring capacities. In this study, we identify four categories of data indicators that can be monitored with satellites to support decision making in adaptation pathways: sea level rise, individual processes contributing to sea level rise, impacts of sea level rise, and impacts on implemented adaptation strategies. We review these categories in relation to existing adaptation pathway signposts and the available satellite data. As we highlight the opportunities for satellite-based contributions to sea level adaptation pathways, we also outline potential limitations, opportunities to overcome these limitations, and future steps that can be taken to integrate satellite observations into adaptation pathways.

1. Introduction

Sea level rise (SLR) is a present risk to many of the world’s coastal communities, and this risk is expected to increase in the coming decades (Fox-Kemper et al., 2021; Cooley et al., 2022). As a result, efforts are now underway for coastal communities to adapt to future sea level rise (Haasnoot et al., 2021). Such adaptation planning requires a foundation of scientific information about the timing and

---

* Corresponding author.
E-mail address: Benjamin.D.Hamlington@jpl.nasa.gov (B.D. Hamlington).

[1] B.D. Hamlington & A. Tripathi contributed equally.

https://doi.org/10.1016/j.crm.2023.100555
Received 15 February 2023; Received in revised form 25 August 2023; Accepted 26 August 2023

magnitude of future sea level rise. Complicating this, however, are the uncertainty and ambiguity in future estimates of sea level rise (Kopp et al., 2017), which can serve to limit or paralyze decision-making (Haasnoot et al., 2019). The magnitude of this uncertainty varies with time horizon making a "wait and see" approach an attractive adaptation option (Klein et al., 2014). However, this approach can limit future adaptation options and ultimately prove more costly than acting in a timelier manner (Haasnoot, 2013; Haasnoot, 2019; Haasnoot, 2021).

As a solution to these challenges, dynamic adaptation policy pathways (DAPPs or *adaptation pathways*) have been developed (Ranger et al., 2013; Haasnoot, 2013; Haasnoot, 2019; Smallegan et al., 2017; Obeysekera et al., 2020). Consisting of a sequence of adaptation actions with different lead times, DAPPs offer a framework for policy planning in the face of changing and uncertain conditions. DAPPs can be planned well in advance and aligned with development priorities for a particular location, leading to more effective adaptation planning, implementation, and response (IPCC, 2022). Adopted by some sea level rise adaptation plans (Ranger et al., 2013; Zandvoort et al., 2017, Barnett et al., 2014; Delta Programme, 2015; Lawrence and Haasnoot, 2017; Ramm et al., 2018; Toimil et al., 2021), DAPPs use a series of short-term (<5–20 years), low-regret actions that keep options open for the future (Barnett et al., 2014; Haasnoot et al., 2019) and longer-term (50–100 years) alternatives that may be needed as options narrow (Haasnoot et al., 2021). The dynamic aspect of this adaptive planning process is based on the evaluation of the plan's progress and performance, to adjust the sequence of actions as necessary. Dynamic monitoring (Haasnoot et al., 2018) of current trends (Haasnoot et al., 2013; Haasnoot et al., 2019) provides critically-needed assessment of the assumptions underlying a plan and offers guidance for when to maintain current actions, implement different actions, and respond to new information.

Underlying each DAPP, and its ability to inform the timely implementation or reassessment of adaptive plans, is a comprehensive monitoring system (Haasnoot et al., 2018, 2019; Stephens et al., 2018). At present, available resources and access to observations vary widely across the coastlines of the world, affecting the capacity of communities to effectively implement DAPPs. For example, in situ tide gauges can provide key data, and DAPPs developed to date (shown in Figure S1) have thus largely focused on locations that have tide gauges and detailed in situ observations. However, the temporal and spatial coverage of tide gauges is limited, especially in less developed regions (Hamlington and Thompson, 2015). By contrast, satellite observations of the land and ocean provide broad coverage that offers a potentially equitable complement to available in situ observations. The significant expansion of the satellite observational network over the past two decades (Ponte et al., 2019; Hamlington et al., 2020a; Melet et al., 2020; Laignel et al., 2023) creates an opportunity to develop a near-global, space-based monitoring system that meets the increasing interest in and reliance on DAPPs. With a range of measurement types (e.g. optical, radar, laser) and sampling capabilities in space and time, satellites can provide otherwise-missing data for a range of physical processes associated with rising sea levels and their coastal impacts.

Our objective is to explore the potential integration of satellite observations into DAPP monitoring systems. A main step in creating these systems is determining which quantities to track over time, to provide appropriate indications of when to change adaptation strategy. Unlike recent studies of sea level rise and coastal flooding DAPPs (e.g. Stephens et al., 2018), we focus on the underlying physical measurements that indicate when action is needed - hereafter referred to as data indicators (described in Section 2). To articulate how satellite observations can contribute to DAPP monitoring systems, we identify four categories of data indicators that can benefit from satellite observations: changes in sea level, changes in the processes contributing to sea level rise, observed impacts to natural and anthropogenic systems, and landscape changes resulting from adopted adaptation strategies. In Section 3, we describe these data indicators and the satellites that can provide key inputs. In Section 4, we conclude with a discussion of the limitations and opportunities for integrating satellite-based observations into DAPPs.

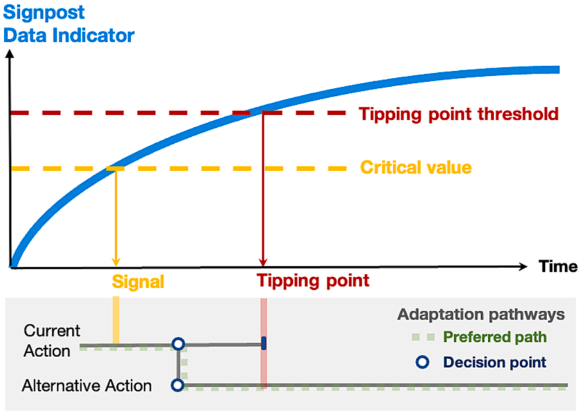

Fig. 1. DAPP Monitoring System Schematic. Upper: A signpost or data indicator can generate a signal to shift from a current action, with enough lead time to implement a new path, before the current action fails at the tipping point. Lower: A simplified adaptation pathways map, showing how a signal and tipping point translate into the adaptation pathway chosen.

2. Effective monitoring systems for dynamic adaptation policy pathways

2.1. Data indicators

Past studies (Haasnoot et al., 2013; 2018) have framed DAPP monitoring in terms of signposts, which track shifts in current and underlying physical conditions (environmental signposts) or in the performance of the current adaptation strategy (performance signposts) (Haasnoot et al., 2018). Regular monitoring of each signpost is essential to determine when it reaches a critical value, which generates a signal to change plans or to conduct more research to improve understanding. These signals must be generated with sufficient lead-time to augment an existing strategy or implement a different one. If this does not happen, a signpost can cross a threshold value, triggering an adaptation tipping point. Referred to as the "sell-by" date of actions (Haasnoot et al., 2013), an adaptation tipping point represents a breakdown in an adaptation pathway, when a current action is no longer sufficient to meet objectives (Kwadijk et al., 2010), necessitating revised adaptation pathways. The importance of tipping points is highlighted in the classification of signals as strong or weak (Haasnoot et al., 2018). Weak signals indicate that an adaptation tipping point may be approaching, while a strong signal indicates that a tipping point is likely to occur and action needs to be taken. As shown in Fig. 1, signals and tipping points correspond to the times for changing adaptation pathways, whereas critical and threshold values correspond to the conditions that prompt such change.

While decisions in a DAPP are guided by signpost values, what constitutes a signpost varies widely. A signpost like the number of flood days can be directly observed, whereas a signpost like future sea level relies on projections, shaped by current data and models. Based on the range of signposts needed for coastal adaptation planning, we adopt the DAPP monitoring system terminology of Haasnoot et al., 2018, and we introduce a new term, *data indicator*, to describe a measurable quantity that serves as the underlying data of a signpost. Better suited to available satellite observations, data indicators are the measurements of current conditions that feed into signposts - rather than the signposts themselves. Signposts may be more familiar to planners, whereas data indicators may be a step closer to the raw scientific data. The difference comes when describing a derived signpost like future sea level, which relies on data indicators such as the current rate of ice mass loss. By standardizing our starting point to be the observed data, we clarify the machinery underlying derived signposts and what physical changes are taking place. The value of data indicators is that they decompose signposts into foundational measurements that can be clearly tracked. Tracking changes in the data indicators can reduce uncertainties in the timing of adaptation pathway signals and improve responsiveness.

2.2. Satellite data as effective inputs

To serve as effective inputs for policy, signposts and data indicators must meet three criteria: salience, credibility, and legitimacy (Cash et al., 2003). Salient, or relevant, inputs are measurable, timely, reliable, and ideally, affordable (Haasnoot et al., 2018). Measurable inputs are sensitive enough to determine when a signal for action is generated, with sufficient location-specific information. Timely inputs provide information with enough lead time to respond to conditions and implement appropriate adaptation actions. Reliable inputs offer a low false alarm probability and continuity of accessible data because a system that goes offline may miss information and undermine credibility. Even when salient, a monitoring system's utility depends on how widely accepted the system is. Credible inputs match expectations and are derived from a trusted, authoritative source (Haasnoot et al., 2018). Legitimacy extends the notion of credibility to incorporate larger matters of perceived fairness and acceptability by stakeholders.

On the basis of these criteria, satellite-based observations are well-suited inputs for DAPP monitoring systems. Satellite-based data indicators provide measurable indicators of change over time. The near constant flow of data, with records spanning decades, makes these observations a timely source of information, even considering acquisition and processing times. With publicly available data,

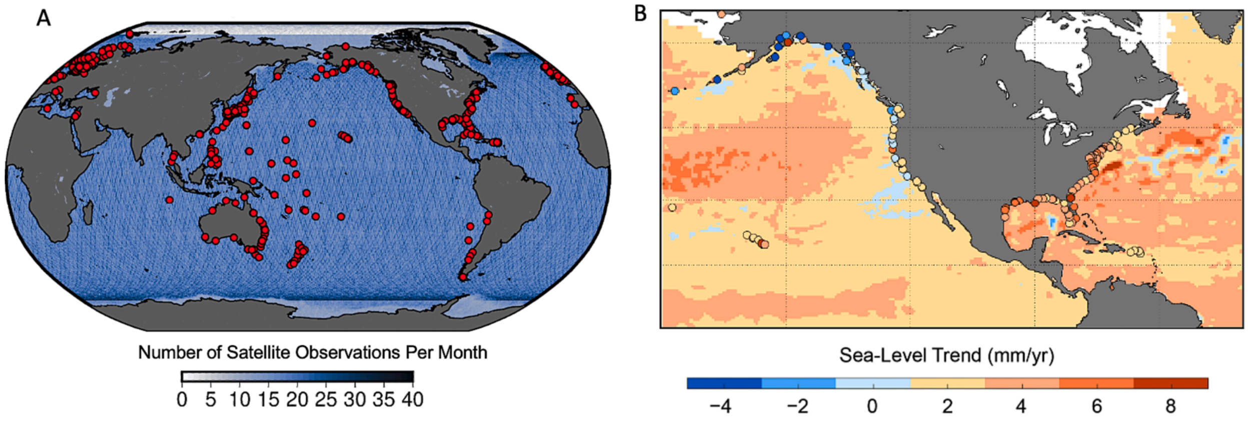

Fig. 2. (A) Satellite sea level observations (blue tracks) extend worldwide, beyond coastal tide gauge coverage (red circles). The sampling of global water bodies is shown as of July 2023 and includes the sampling of the SWOT mission. (B) Sea level trends computed from satellite sea level observations are shown with estimates from available tide gauges (circles), for the United States region.

satellite observations can also meet the affordability criterion. These satellite-based data are the product of international research collaborations, providing a neutral, trusted source of information, scoring high on both credibility and legitimacy metrics. Additionally, satellite-based systems have relatively no preference in terms of the location of measurements, as shown in Fig. 2A, and thus provide more equitable data access for communities, regardless of resources.

3. Satellite-based data indicators for sea level rise DAPPs

In recent decades, the satellite observing network of the coastal zone and processes relevant for changes at the coast has expanded. Reviewing the data available to coastal communities for monitoring, analysis, and evaluation of sea level rise, we identify four categories of satellite-based data indicators, shown in Fig. 3. The first two - sea level rise and the processes contributing to sea level rise - are connected to the physical changes of sea level. The second two - impacts of sea level rise and the impacts on implemented adaptation strategies - are grouped given their relation to the performance of a particular DAPP over time. Table 1 connects the data indicators that we discuss in subsequent sections to the associated satellites, both on-orbit now and planned in the near future.

3.1. Indicators of sea level rise

The amount and rate of future sea level rise are central to coastal management and planning, but uncertainty in these values leads to a range of possibilities for decision-makers (Garner et al., 2023). Available projections of sea level rise are tied to future shared socioeconomic pathways (SSPs, e.g. Fox-Kemper et al., 2021), which impart an uncertainty and ambiguity in future sea level rise. Alternatively, sea level scenarios are defined by targeted amounts of sea level rise in the future that span a scientifically plausible range, providing an alternative risk-based framing (e.g. Sweet et al., 2022; see Kopp et al., 2019 for explanation of projections vs. scenarios). In the near-term, there is relatively little divergence in different projections or scenarios. The range of plausible sea level rise in 2050 has narrowed in recent years as scientific understanding has evolved (IPCC AR5 vs. AR6; Slangen et al., 2023; Sweet et al., 2017 vs. Sweet et al., 2022). Beyond 2050, ambiguous information on future emissions and the processes causing sea level rise leads to a significant range of possible sea level rise, which can expand to multiple meters beyond 2100. As shown in Fig. 4, Sweet et al. (2022) found that future sea level scenarios will diverge and be statistically distinguishable from neighboring scenarios, with global mean sea level (GMSL) rise in 2100 ranging from 0.3 m to 2 m.

Planners must choose from projections and scenarios according to their planning horizon and risk tolerance. Low-regret adaptation strategies can be integrated into DAPPs with confidence and be supported by near-term (pre-2050) signals. Conversely, long-term projections can benefit from additional time, model advances, and accompanying observations to refine the relevant signals. Observations play a key role in targeting the sources of uncertainty and providing early indications that a shift may be occurring. For coastal adaptation DAPPs, the satellite record of GMSL can serve as a highly informative data indicator for future sea level rise. On both global and regional scales, satellite observations provide a comparison for projections and place in situ observations in context. Beyond informing the amount of future sea level rise, comparing observations of recent sea level to changes that have occurred in the past, or trends in physical processes affecting sea level, can be helpful in anticipating shifts in the rate of sea level rise.

3.1.1. Total sea level change

Beginning with the TOPEX/Poseidon satellite in 1992, satellite radar altimeters have provided a continuous record of high accuracy and near-global measurements of sea level. Continued by the Jason-1 (2001), Jason-2 (2008), Jason-3 (2016), and Sentinel-6A/Michael Freilich (2020; Donlon et al., 2021) satellites, conventional altimeters (e.g. Stammer and Cazenave, 2017) have enabled wide-ranging advances in our understanding of sea level change. This record of reference missions has been augmented by several

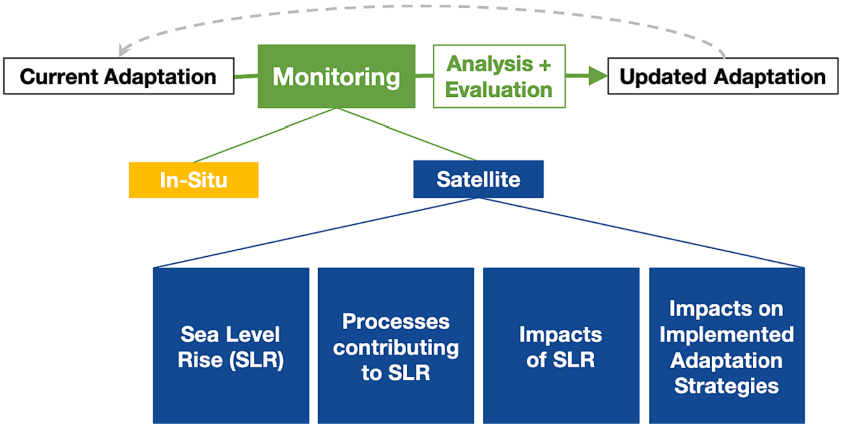

Fig. 3. Framework for integrating satellite-based data indicators into a DAPP monitoring system. The upper arrow represents iterative monitoring and assessment for dynamically choosing adaptation pathways.

Table 1
Examples of satellite data that can serve as data indicators for sea level DAPPs.

Data Indicator	Satellite (Current)	Satellite (Future)	Technique	Category
Global Mean Sea Level Change	Sentinel-6/MF, Jason-3, SWOT, SARAL, Sentinel-3A/3B	Sentinel-6B, Sentinel-6C	Radar Altimetry	Changes in SLR
Regional Sea Level Change	Sentinel-6/MF, Jason-3, SWOT, SARAL, Sentinel-3A/3B	Sentinel-6B, Sentinel-6C	Radar Altimetry	Changes in SLR
Ice Sheet and Glacier Change	GRACE-FO, ICESat-2, CryoSat-2	Mass Change (MC), CIMR, CRISTAL	Gravimetry, Laser Altimetry, SAR Altimetry	Changes in Processes Contributing to SLR
Sterodynamic Sea Level Change	Sentinel-6/MF, Jason-3, SWOT	Sentinel-6B, Sentinel-6C, CIMR, CRISTAL	Radar Altimetry, SAR Altimetry	Changes in Processes Contributing to SLR
Vertical Land Motion	Sentinel-1	NISAR, Surface Deformation and Change (SDC)	SAR	Changes in Processes Contributing to SLR
Flood Extent	Sentinel-1, Sentinel-2, Landsat-8, SWOT	NISAR	Optical, SAR, SAR Altimetry	Impacts of SLR
Flood Frequency	Sentinel-1, Sentinel-2, Landsat-8, SWOT	NISAR	Optical, SAR, SAR Altimetry	Impacts of SLR
Saltwater Intrusion	ECOSTRESS, MODIS, Landsat-9	Landsat-10, Surface Biology and Geology (SBG)	Radiometry, Optical	Impacts of SLR
Coastal Erosion	Landsat-8, Landsat-9, Sentinel-1, Sentinel-2	Landsat-10	Optical, SAR	Impacts of SLR
Groundwater Reinjection	Sentinel-1	NISAR, SDC	SAR	Impacts on Implemented Adaptation Strategies
Levee Monitoring	Sentinel-1	NISAR, SDC	SAR	Impacts on Implemented Adaptation Strategies
Beach Nourishment	Landsat-8, Landsat-9, Sentinel-2	Landsat-10	Optical	Impacts on Implemented Adaptation Strategies
Coastal Ecosystems	Landsat-8, Sentinel-2, ICESat-2, ECOSTRESS Landsat-9	Landsat-10, SBG	Optical, LiDAR, Hyperspectral	Impacts on Implemented Adaptation Strategies

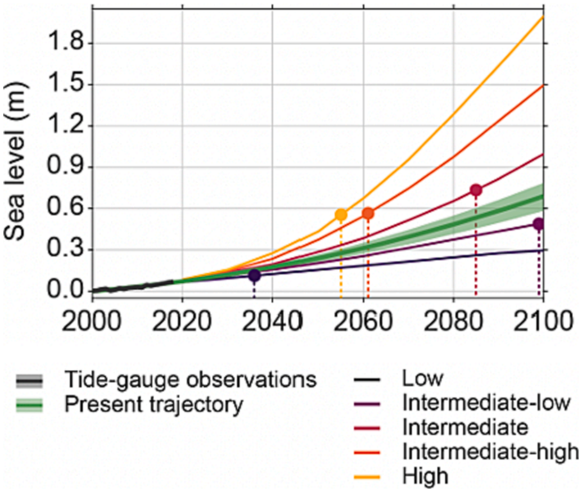

Fig. 4. Divergence of global mean sea level (GMSL) trajectory and scenarios from Sweet et al. (2022). The time series shows the observations (black), observation-based trajectory (green) and GMSL scenarios to 2100. Dots denote where each scenario deviates significantly (2 sigma) from the observation-based trajectory. Figure
adapted from Sweet et al. (2022)

other altimeters, including Envisat, SARAL/AltiKa, and Sentinel-3A/3B, to name just a few. The length of this observing record has allowed for an understanding of how GMSL is evolving as the climate warms, linking past and present sea level rise to inferences about the future. Year-to-year variations in GMSL are linked to changes in the global water cycle and large-scale natural variability like the El Niño-Southern Oscillation (ENSO). Over longer periods, however, rising GMSL is an integrative measure of warming oceans and melting ice. Changes in GMSL and in the rate of GMSL rise, or acceleration, provide the trajectory of ongoing sea level rise, and consequently, GMSL features in most coastal adaptation DAPPs through the choice of the ‘current best’ GMSL projection or scenario.

Satellite altimeters have revealed an increase in GMSL of 3.4 +/- 0.4 mm/year since 1992 (Beckley et al., 2017; Guérou et al., 2023), with indications of an increase in the acceleration of 0.08 +/- 0.025 mm/yearˆ2 (Nerem et al., 2018; Nerem et al., 2022; Guérou et al., 2023). Using the observed rate and acceleration as DAPP data indicators can provide key inputs driving reassessment of current plans and signposts. Consistency with a projected trajectory tied to a particular climate scenario can suggest that the current state of a

DAPP is still appropriate. However, if recent acceleration (computed over a predefined length of time) exceeds a value expected from a chosen projection, then the GMSL data indicator will signal a need to shift to a new adaptation strategy, conduct more research, or update the choice of sea level rise scenario that underlies the DAPP.

A preliminary example of this assessment is provided in Nerem et al. (2022), who extrapolated the rate and acceleration of GMSL to 2050 and compared them to modeled results. The conclusion was that the satellite observations are currently tracking near the IPCC AR6 SSP2-4.5 projection and between the Intermediate-Low and Intermediate scenarios from Sweet et al. (2022), although with significant overlap across all scenarios. An example of this type of analysis was conducted in Sweet et al. (2022) with results reproduced here in Fig. 4. Similar comparisons have been made in Slater et al. (2020) and Hamlington et al. (2022). Performing these comparisons regularly could enable policymakers to identify when observations are statistically different from the chosen ‘current best’ scenario and motivate an update to the assumptions associated with the DAPP.

3.1.2. *Regional sea level change*

Relevant to individual coastal communities and evident from the satellite altimetry observations are regional variations in the rate and acceleration of sea level rise, shown in Fig. 2B. Satellites offer near-global coverage of local sea level change, while tide gauges remain sparsely located along the coastlines of the world (Fig. 2A) but offer longer records than satellites. However, the dominant causes of sea level change shift over time (e.g. Frederikse et al., 2020), which result in the rate and acceleration computed over the full tide gauge record being unrepresentative of the changes occurring more recently. While the processes that lead to the regional pattern are generally known (see Hamlington et al., 2020a), there is uncertainty in the rates and acceleration, due to the presence of internal variability which can be substantial on regional levels (Hamlington et al., 2019; Hamlington et al., 2020b; Hamlington et al., 2022; Royston et al., 2018; Royston et al., 2022). Separating the contributions of forced climate-change drivers, which may persist into the future, from the contributions of internal variability, which impart an apparent rate or acceleration in short records, is a topic of ongoing research (e.g. Fasullo and Nerem, 2018; Richter et al., 2020; Royston et al., 2018; Royston et al., 2022; Hamlington et al., 2019; Hamlington et al., 2020b; Hamlington et al., 2021).

Recent studies have begun using regional observations to assess the near-term trajectory of sea level rise and subsequently compare them to modeled projections (Wang et al., 2021; Sweet et al., 2022; Hamlington et al., 2022). Similar to the analysis for GMSL data, these trajectories can provide an indication of how quickly sea level may rise and how appropriate a selected scenario might be at a given location. Sweet et al. (2022) used tide gauges to assess the near-term trajectory of sea level rise and compare to sea level scenarios for U.S. coastlines. For most regions, the observational trajectory to 2050 tracked the Intermediate-Low or Intermediate scenario for sea level rise, but the Eastern Gulf of Mexico region tracked the Intermediate-High to High scenarios. This information is important for decision-makers in the Eastern Gulf to reassess the assumptions in their adaptation plans and for researchers to improve their understanding of sea level rise and the processes contributing to it in the region.

Satellite observations of regional variations provide a complement to tide gauges that can be used as ongoing, near-global data indicators for local sea level rise. Through reprocessing of past observations (e.g. Cazenave et al. 2022) and launching new measurement capabilities, like the Surface Water and Ocean Topography (SWOT) mission, information on sea level change is also being provided closer to the coast than ever before. As a result, the utility of satellite observations for regional and local sea level change is expected to grow in the future.

3.2. *Indicators of the processes contributing to sea level rise*

Driven by an increase in satellite observations of the individual processes contributing to sea level change, recent studies have demonstrated the ability to fully explain – within uncertainty bounds – sea level change on both global and local scales (e.g. Harvey et al., 2021; Camargo et al., 2023). Contributing processes derive from changes in the cryosphere, ocean, and land. A new understanding of how individual processes may evolve can have direct consequences for both near-term and long-term sea level projections. These contributing processes have not traditionally been considered in adaptation planning. The availability of consistent satellite monitoring of these processes, which can occur locally or in remote parts of the Earth, makes it a source of valuable data indicators for capturing early warning of trends in the rate of sea level change and for fine tuning DAPPs.

3.2.1. *Ice sheet and glacier change*

Ice mass loss is a major contributor to sea level rise. Satellites have provided critical data for understanding ice sheet changes and how they may progress in the future (e.g. Aschwanden and Brinkerhoff, 2022; Box et al., 2022; Greene et al., 2022). Observations of ice sheets and glaciers have expanded in recent years, due to satellite missions like Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2), and CryoSat-2. These observations and efforts like the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE; The IMBIE Team, 2020) provide clear evidence of mass loss of mountain glaciers and ice sheets in recent decades, with rates of mass loss increasing (Hugonnet et al., 2021). There is also increased consensus regarding the behavior of many ice sheet processes.

As the climate warms, the future response of the ice sheets and some associated processes is still ambiguous (Fox-Kemper et al., 2021). Two specific processes, marine ice cliff instability (Deconto and Pollard 2016; Deconto et al., 2021) and marine ice sheet instability (Joughin et al., 2014; Waibel et al., 2018; Hoffman et al., 2019; Robel et al., 2019; Morlighem et al., 2020), could lead to rapid ice sheet loss over several decades, but when and if these instabilities could be triggered and how they would progress remain difficult to establish. These uncertainties and ambiguities have a direct impact on the range of land ice’s contribution to sea level rise across a set of projections or uncertainties. This is especially true for long-term (2100 +) projections, since the potential for rapid ice sheet loss was assessed to occur further in the future than previously thought (Deconto et al., 2021). For example, AR6 dealt with these possibilities by introducing a "Low Confidence" scenario and assessed that while high amounts of warming would be needed to trigger rapid ice sheet loss, the specific amount of warming remains unknown as does how sea level would respond should such a trigger happen. Sweet et al. (2022) similarly accounted for these processes in the updated sea level scenarios, with the Intermediate, Intermediate-High and High Scenarios all requiring contributions from this Low Confidence scenario to be constructed.

The wide range of projections for sea level rise at 2100 and beyond are heavily driven by process-based uncertainty with the ice sheets. This uncertainty represents one of the primary drivers of possible changes in projections in the future. Should a modeling advance or observational evidence emerge of a shift being triggered, the range across projections could be refined. The change from Sweet et al. (2017) to Sweet et al. (2022) provides an example of this. Because of the shift in timing of the potential for rapid ice sheet loss, the Extreme (2.5 m of GMSL rise by 2100) scenario was no longer viewed as plausible. Additionally, the range across the remaining five scenarios was assessed to be narrower in the near-term than in the previous report.

Ongoing monitoring of the ice sheets and glaciers is thus a critical data indicator for sea level DAPPs. GRACE-FO provides a measure of mass loss from the ice sheets and glaciers, indicating not just total mass loss but also which regions of the ice sheets and glaciers are losing ice most rapidly. GRACE-FO also provides a measure of changes in ocean mass, which represents the integrated contribution of all ice-mass loss to the ocean and thus is most directly tied to sea level rise. ICESat-2 measures ice loss and velocity changes through elevation data of ice-covered regions of the Earth. Cryosat-2 uses synthetic aperture radar (SAR) to monitor ice thickness changes on the ice sheets and mountain glaciers. Taken together, these and future satellites, like the Mass Change (MC) mission (Wiese et al., 2022), provide important information on how the ice sheets and glaciers are evolving and can be used to identify the onset of processes that could lead to a rapid increase in sea level rise, and thus trigger a change within a DAPP. The signal would be generated when either the projections have significantly changed due to an advance in the understanding of the processes driving change (e.g., instabilities of the ice sheets) or when the observation-based trajectory differs by more than some predetermined amount from the chosen scenario.

3.2.2. Sterodynamic sea level change

Essential to sea level rise and projections on regional scales are sterodynamic sea level changes, which arise from changes in the ocean's circulation (currents) and its density (temperature and salinity). Sea level rise associated with sterodynamic sea level change is the combination of global mean thermosteric rise associated with global ocean warming and local deviations from the global mean due to ocean dynamic processes. These processes can be small scale, particularly near the coast (Woodworth et al., 2019). On short timescales (annual to decadal), ocean dynamics dominate the pattern of sea level change, as has been visible over the course of the satellite altimeter record. While the spatial variability in the altimeter-derived sea level pattern has decreased as the record has lengthened, the pattern is still influenced by internal variability on interannual to decadal timescales, and these fluctuations are the dominant driver of decadal trend variations within the satellite record. Monitoring these shifts associated with internal variability can be relevant when planning horizons are short or when sea level rise is nearing a level that would trigger action within an adaptation pathway. This is connected to the example in Section 3.1.2 regarding sea level rise in the Eastern Gulf of Mexico region. While it is possible that the high rate and acceleration are driven by naturally occurring ocean variability, observations of the ocean provide some insight into how sea level may continue to rise at a high rate in the near-term. Another example of this is seen for the west coast of the United States, where the recent rate of sea level rise, as measured by satellite altimeters, has shifted over the past two decades (Hamlington et al., 2021). Monitoring as close as possible to the coast is critical to capture the small scale features and shifts that can directly influence the risk of flooding.

Ocean dynamics are a leading contributor to possible sea level change on longer timescales, in certain regions of the ocean. As an example, the Atlantic Meridional Overturning Circulation (AMOC) is an important component of global ocean circulation, transporting heat and carbon and affecting hydroclimate, hurricane activity, and coastal sea level. It is hypothesized from some proxy evidence that the AMOC has declined since the Industrial Revolution (Caesar et al., 2018). It remains uncertain whether observations support the anthropogenically forced weakening of the AMOC during the past four decades predicted by climate models (Jackson and Wood, 2020). Focusing on possible causes of long-term sterodynamic sea level changes for the coastlines of the United States, future changes in the AMOC are particularly relevant. A weakening AMOC will lead to an increase in sea level along the coastal Northeast and Southeast regions (Yin et al., 2009; Krasting et al., 2016). The IPCC AR6 (Fox-Kemper et al., 2021) determined that the AMOC is very likely to decline in the future, although there is still disagreement as to the extent of this decline.

Similar to monitoring of the cryosphere, consistent monitoring of the AMOC and other ocean dynamic signals is an important data indicator that can provide a constraint on the range of future sea level rise indicated by current projections and scenarios. McCarthy et al. (2020) discussed sustained observations of the AMOC, highlighting satellite altimetry along with complementary measurements of temperature and salinity, as important components of an AMOC observing system. If such observations could identify a clear slowdown in the AMOC, they could be immediately connected to projections of sea level in coastal regions of the Atlantic, serving as data indicators within a DAPP. Changes to the AMOC potentially have far broader impacts; Orihuela-Pinto et al. (2022) connected a slowdown in the AMOC to a nearer-term increase in La Niña-like conditions in the Pacific Ocean. La Niña is associated with lower sea levels in the eastern Pacific but dramatically higher sea levels in the western tropical Pacific, a region of the ocean that has experienced high rates of sea level rise during the past three decades (e.g. Hamlington et al., 2021).

3.2.3. Vertical land motion

Vertical land motion (VLM) is an important component of relative sea level rise because changes in surface elevation lead to changes in the height of the ocean relative to land (e.g. Nicholls et al., 2021). VLM is not a singular phenomenon but results from various processes that display different patterns in space and time. VLM in coastal settings is often complicated as these processes can operate at the same time and can serve to either increase relative sea level (subsidence) or decrease relative sea level (uplift). VLM is driven on local scales by both natural processes, such as compaction of river sediments, and anthropogenic processes, such as groundwater and fossil fuel withdrawal. On larger scales, subsidence is driven by tectonics and glacial isostatic adjustment (GIA).

VLM's contribution to relative sea level projections has typically been inferred from long-term tide gauge observations (e.g. Kopp et al., 2017; Fox-Kemper et al., 2021; Sweet et al., 2017; Sweet et al., 2022). In these projections, the assumption has been made that past estimates of VLM will persist linearly into the future – a reasonable assumption for long-term geological processes like sediment compaction and GIA, but less so for tectonic and anthropogenic processes. More accurate future projections of VLM could come from an understanding of and accounting for the underlying processes and the temporal and spatial scales on which they vary (Shirzaei et al., 2021; Fang et al., 2022).

Direct observations of VLM and how rates change over time could improve the information used in projections or provide an opportunity to assess assumptions made in these projections. One approach is to difference relative sea level measurements of tide gauges and sea level measurements from the nearest satellite altimetry data point (e.g. Wöppelmann and Marcos, 2016). In recent decades, GPS stations have provided estimates of VLM in coastal areas across the globe. While there is dense coverage along certain coastlines (e.g. Europe, North America, Japan), other areas that are vulnerable to sea level rise have little coverage. Moreover, subsidence can vary on small spatial scales in coastal regions, making it difficult to fully assess the rate of subsidence even in areas with good GPS coverage. Calibrated to land GPS station estimates, airborne and satellite-based interferometric synthetic aperture radar (InSAR) measurements of land elevation over time can provide higher spatial resolution measurements of VLM rates, for large swaths of coastlines (e.g., Blackwell et al., 2020; Shirzaei et al., 2021, Bekaert et al., 2017; Buzzanga et al., 2020). These higher-resolution assessments of VLM rates can help communities understand present-day VLM at fine scales (e.g., street block level) and provide guidance for how continued VLM will contribute to relative sea level projections.

The importance of ongoing monitoring for VLM is highlighted by cases where the rate of VLM has shifted, profoundly impacting projections of sea level rise. Tectonically active areas, like American Samoa, provide prime examples of VLM's impact on the future trajectory of sea level rise (Sweet et al., 2022). In 2009, the Samoa-Tonga Earthquake caused subsequent viscoelastic relaxation and subsidence that dramatically increased the rate of relative sea level rise in American Samoa (Han et al., 2019). Comparing the observation-based trajectory to modeled scenarios for the Pago Pago, American Samoa tide gauge reveals a clear mismatch that can be traced to an inadequate representation of the ongoing rate of subsidence within the model framework (Fig. 5A). Investigation of the nearby ASPA GPS station shows a dramatic shift in the VLM after 2009/2010 (Fig. 5B). The relaxation and related subsidence is expected to continue for decades. If the VLM shift is not accounted for, the projected sea level rise over the next several decades will be a significant underestimate. By using VLM as a data indicator, it can generate a signal to reassess and modify DAPP actions when a significant deviation is found, possibly earlier than a projection-based signpost.

3.3. *Indicators of the impacts of sea level rise*

The DAPP framework relies on consistent monitoring, but the impacts of sea level rise can be difficult to measure over large scales and to track effectively over time. Changes in experienced impacts can be anecdotal or hyper-local (e.g. at the location of a tide gauge). Compared to tracking sea level rise and its contributing processes, observing impacts directly may increase credibility since impacts are more consistent with perceived changes. Moreover, they can provide an assessment of the degree to which employed adaptation strategies are still effective.

Satellites can provide monitoring across entire regions, with broad coverage of global coastlines. The relative continuity of satellite and remote sensing data can provide longer lead times for action than might be possible with in situ monitoring. Observations can

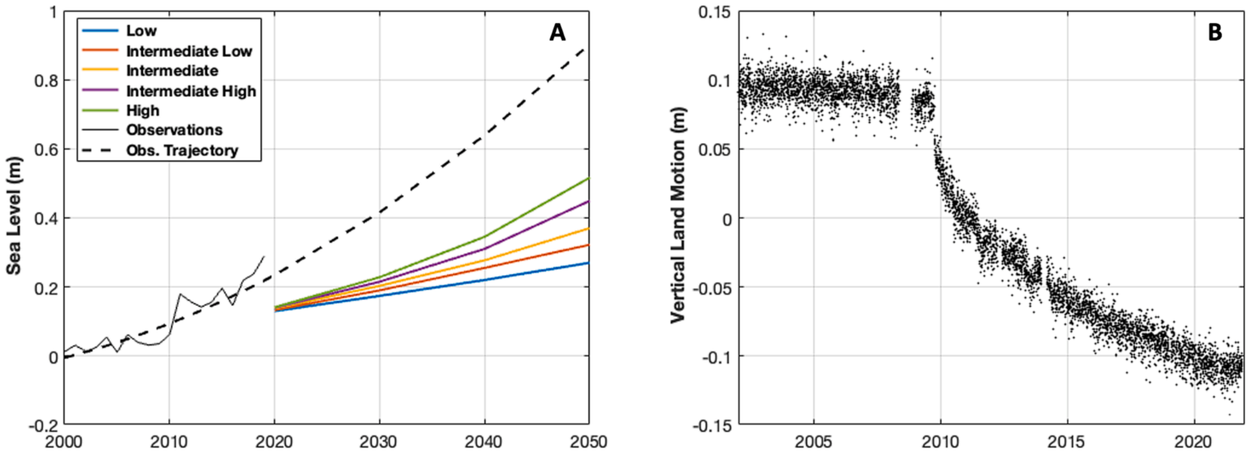

Fig. 5. Tide gauge measurements of relative sea level (A) and GPS measurements of vertical land motion (B) in Pago Pago, American Samoa reveal the 2009 Tonga earthquake's effect on sea level rise and the divergence from future sea level scenarios, from Sweet et al. (2022).
Adapted from Collini et al. (2022)

serve as performance-based data indicators for the impacts of sea level rise, illuminating both environmental effects and how well selected adaptation strategies are limiting undesired impacts.

3.3.1. Flood extent and frequency

As sea levels continue to rise across the globe, so does the severity and frequency of coastal flooding. Flooding at the coast can be driven by different factors. Storms can drive catastrophic flooding with storm surge that is exacerbated by increasing sea levels. High-tide flooding, on the other hand, is a more direct consequence of sea level rise. The combination of tides, naturally occurring sea level variability, and relative sea level rise can lead to flooding conditions (e.g. Sweet et al., 2022; Thompson et al., 2021) that may not be particularly damaging for any single event but can have a significant impact as the frequency and severity of the flooding builds over time. These higher frequency flood events may provide support for monitoring and projecting potential flooding events that are inherently less likely to occur (Stephens et al., 2018). In many coastal regions, compound flooding can arise from the concurrent contributions of precipitation, riverine flooding, and inundation from the ocean. Compound flooding can be longer in duration with impacts more widespread than flooding driven by the ocean alone.

Adaptation strategies are employed to account for all types of flooding, but determining the extent to which these strategies are effective on a regional level is challenging due to a lack of observations. Tracking the performance of these strategies over time can be difficult as in situ monitoring or anecdotal evidence is typically relied on, which can miss the full extent of flooding that has taken place. There are efforts to densely sample coastal regions with low-cost in situ networks, but they are limited to geographies with the capacity to install such networks.

Satellite monitoring of flood extent and frequency has been demonstrated over the past two decades (Laignel et al., 2023 for summary), and with additions to the satellite observing network, opportunities for such monitoring have increased in recent years. Optical satellite imagery from Landsat has formed the backbone of this monitoring for decades, continuing with the launch of Landsat 9 in 2021. Sentinel-2 also provides optical imagery from which water extent in coastal regions can be derived. While these optical satellites can be impeded by cloud cover, which is problematic for flood events that arise from storms or compound flooding, airborne and space-based synthetic aperture radar (SAR) platforms offer complementary monitoring that can penetrate cloud cover. Sentinel-1 has been collecting SAR data since 2014, and the SWOT mission launched in 2022. Future SAR missions include the NASA-ISRO SAR (NISAR) mission, launching in 2024, followed by the Surface Deformation and Change (SDC) mission, part of NASA's Earth System Observatory (ESO). Generating flood extent and frequency from these satellites can be expensive and labor-intensive. NASA's Observational Products for End-Users from Remote Sensing Analysis (OPERA) project provides an example of how to integrate available satellite data and generate timely surface water extent maps for planning and response.

Data indicators developed around flood extent and frequency would be based on monitoring the occurrence and prevalence of flooding in a particular region and assessing the degree to which those are evolving over time (e.g., Stephens et al., 2018). If a location is newly flooding or flooding more than anticipated or beyond a pre-assigned critical value, a shift in the DAPP could be necessary. This information would not replace on-the-ground metrics for tracking flood extent and frequency at specific locations, but understanding how flooding is changing over a larger region, covered by satellites, would be informative about persistent and larger-scale changes that are taking place and could be directly linked to increases in sea level rise.

3.3.2. Coastal erosion

A leading concern in many coastal regions is erosion, which threatens livelihoods and infrastructure, and is anticipated to increase in the future (Mentaschi et al., 2018). Coastlines around the world undergo constant changes caused by rivers, waves and nearshore currents. Sea level rise is increasingly contributing to coastal erosion in low-lying areas and indirectly exacerbating the other drivers of coastal erosion (Nicholls et al., 2010; Pilkey and Cooper, 2004). Because these changes can be gradual or more dramatic, due to extreme events like storms (Barnard et al., 2017; Borrero, 2005), shorelines must be monitored over time.

Coastal erosion can be highly local, so broad-scale, regional monitoring is critical. In situ or aerial observations, with cameras or lasers, have been relied upon to provide high-resolution data on coastal erosion over relatively small areas. Such observations can have limited spatial coverage or be inconsistent in time, in part due to the cost of maintaining these systems. As a solution, several studies have detailed the use of satellite imagery for surveying and monitoring changes in coastal erosion (Mentaschi et al., 2018; Borrero et al; 2005; Anthony et al., 2015; Luijendijk et al., 2020). Mentaschi et al. (2018) provides a detailed overview of monitoring coastal erosion on global scales, while Luijendijk et al. (2020) surveyed and classified the world's beaches with satellite observations. These studies have generally relied on optical remote sensing from Landsat and, more recently, Sentinel-2. Comparisons of observations can be made to assess changes occurring in one location relative to another and trends over time. A data indicator for DAPPs can be built around this monitoring of coastline changes and provide early identification of increasing coastal erosion that may trigger additional adaptation.

3.3.3. Saltwater intrusion

Coastal populations are supported by underground infrastructure and fresh groundwater resources that flow through coastal aquifers, which host complex interactions between fresh groundwater and saline seawater. As sea level rises, the freshwater-saltwater interface moves inland and can lead to saltwater intrusion. While saltwater intrusion driven by sea level rise is expected to occur over several decades (Michael et al., 2013), it can also be driven by episodic high-tide or storm events (Yu et al., 2016; Cantelon et al., 2022) or coastal groundwater pumping (Michael et al., 2017). Saltwater intrusion can impact coastal populations through salt-damaging of essential infrastructure (Tansel and Zhang, 2022), by displacing terrestrial groundwater and causing inland groundwater flooding (e.g. McKenzie et al., 2021; Befus et al., 2020), or by altering the flux of groundwater discharge that influences coastal environments (Kim et al., 2011; Kim et al., 2017; Luijendijk et al., 2020; Correa et al., 2021). Saltwater intrusion is also a problem for fresh groundwater management, as freshwater is generally deemed non-potable even with ~ 2% salinization (Environmental Protection Agency, 1979). Salinization of freshwater can occur instantaneously, but recovery to fresh conditions can take months (Chui et al., 2011) to decades (Yang et al., 2015). With increasing sea levels and associated increases in high-tide flooding events, the saltwater intrusion problem is expected to increase in severity and rate.

In situ monitoring of subsurface salinity patterns is possible but difficult to conduct on large scales, and numerical models are difficult, if not impossible, to implement over continental scales (e.g., Befus et al., 2020). Satellite remote sensing does not provide an obvious solution to monitoring saltwater intrusion that is occurring subsurface. However, indicators and impacts of saltwater intrusion may be visible at the surface through vegetation and changes related to coastal freshwater processes. Studies have shown that saltwater intrusion impacts plant productivity and elevation gain in coastal wetlands and marshes (DeLaune and Pezeshki, 1994; Sutter et al., 2014; Tully et al., 2019; Charles et al. 2019; Solohin et al. 2020). Vegetation changes can be visible in optical satellite imagery through shifts in color (e.g., measured by the MODerate resolution Imaging Spectrometer (MODIS) aboard the Terra and Aqua satellites), and monitoring of coastal floodplain EVI (Enhanced Vegetation Index) has been shown to be useful in identifying regions undergoing long-term, low-level saltwater intrusion (White and Kaplan, 2021). Vegetation stress can also be measured using thermal imagery through temperature shifts related to water stress (e.g., measured by ECOSTRESS on the International Space Station and NASA's future Surface Biology and Geology (SBG) satellite). Monitoring coastal wetland elevation, inland groundwater flooding, or nearshore groundwater discharge variability using a combination of approaches and datasets (sea level, vegetation index, inundation extent, thermal imagery) could also provide useful ways to assess saltwater intrusion. These indirect observations of saltwater intrusion proxies have limited cases of demonstration to date but could serve as important signposts in a monitoring system. Data from such approaches may not be able to serve as early indicators but could inform when and where impacts associated with saltwater intrusion may be underway and subsequently increasing.

3.4. *Indicators of the impacts on implemented adaptation strategies*

Monitoring the performance of a DAPP requires measuring the impacts of sea level rise, as well as the changes and impacts on implemented adaptation strategies. Here we explore the natural continuation of the monitoring in the previous section – from flooding to levees, coastal erosion to beach nourishment, and saltwater intrusion to groundwater reinjection. While more commonly considered in the planning community, these data indicators involve less familiar uses of satellite capabilities.

3.4.1. *Groundwater reinjection*

Monitoring subsidence can be useful for understanding how implemented adaptation and mitigation strategies are evolving. Just as a reduction of groundwater pumping can serve to alleviate the subsidence being experienced at a particular location (e.g. Fang et al., 2022), so too can groundwater reinjection. One such effort, headed by the Hampton Roads Sanitation District, is the Sustainable Water Initiative for Tomorrow (SWIFT; https://swiftva.com), which aims to inject 90% (i.e., 135 MGD) of reclaimed wastewater, treated to potable quality, directly into the Potomac aquifer instead of releasing it downstream by 2030. This project aims to increase fresh groundwater availability, reduce or reverse saltwater intrusion, and contribute to a partial elastic rebound of the aquifer, thereby reducing the rate of land subsidence and the corresponding rate of relative sea level rise. Reinjection activities commenced in 2018, and it is anticipated that the rate of reinjection will continue to increase over the coming decade.

The monitoring plan for this effort involves a network of in situ systems that are designed to capture changes near the injection sites and also changes occurring farther afield with support from InSAR data. In Buzzanga et al. (2020), the use of InSAR was proposed to provide a wider view of the response to the reinjection and to detect a shift in subsidence from the other processes taking place. For the

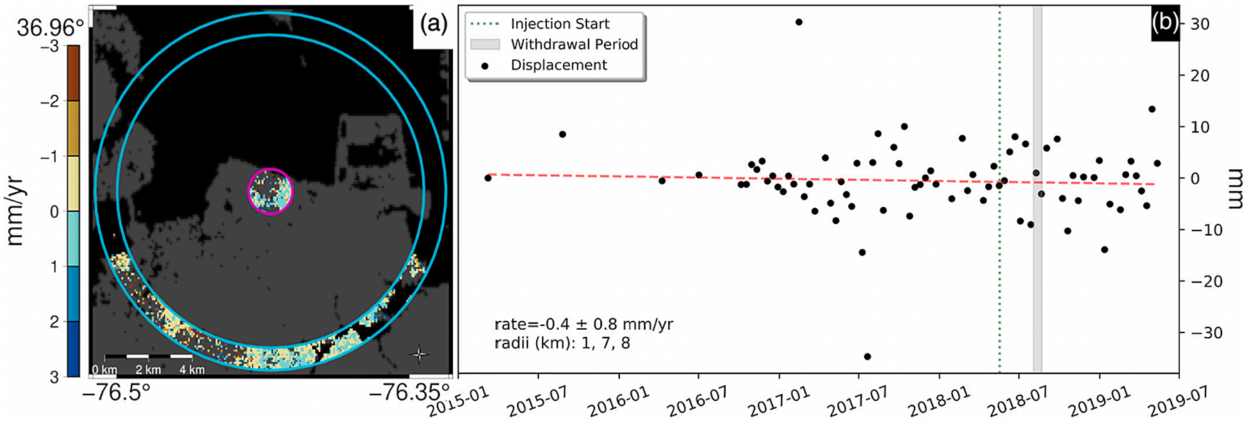

Fig. 6. (A) Map of vertical land displacement rates from InSAR data, used to assess the impact of wastewater reinjection in Hampton Roads, VA at its injection site (within magenta circle) relative to the surrounding area (cyan torus). (B) The vertical displacement history shows individual InSAR observations (black circles) and a linear fit to displacement rate (red dashed line), with reinjection effects on subsidence not yet detected. Vertical lines indicate the injection start time (green dashed line) and groundwater withdrawal period (gray region). From Buzzanga et al. (2020).

objective of alleviating subsidence, this monitoring could then be used to determine whether additional pumping is needed either by increasing the rates or adding additional injection sites. The data could also be used to determine how and if the reinjection affects the rate of subsidence. As seen in Fig. 6, there is no reduction in the rate of subsidence detected in the InSAR results, but this could change once reinjection rates increase. While this is a specific case, InSAR analysis can support a data indicator across any coastline and thus support monitoring of any similar efforts that may be undertaken.

3.4.2. *Levees*

Levees protect coastal populations and infrastructure from floods in many coastal regions worldwide. As sea level increases, a levee can become less effective, but if the levee itself degrades, this can accelerate the loss of performance and trigger the need for additional adaptation. Failure of a levee can lead to catastrophic flooding, and the potential impacts associated with levee failure have increased over time as a result of economic and demographic growth. Consequently, monitoring data indicators for levees is critical to ensuring adequate future performance. This monitoring has historically been done by visual inspection, which may not provide a clear picture of emerging problems and is difficult to conduct consistently over large scales. Studies have shown that monitoring through periodic inspection has not identified past levee failures in advance (Heyer, 2016). Additional monitoring techniques could be helpful in quantifying the changes that may be occurring and identifying problems before they lead to failure.

InSAR data may support the monitoring of flooding adaptation strategies such as levees. Airborne and space-based InSAR analysis can not only illuminate critical changes in the deformation of the levee over time, but also changes in land subsidence, which threatens levee stability. InSAR monitoring of levees has been demonstrated in a variety of locations, including the Netherlands (Özer et al., 2019) and New Orleans (Chung Nguyen et al., 2018), and can generally be used anywhere in the world, supported by coverage from Sentinel-1 and, in the future, NISAR. Monitoring of levees is a complementary signpost to that of VLM and flooding. As in the example of subsidence, it demonstrates the utility of satellite monitoring for multiple related data indicators.

3.4.3. *Beach nourishment*

Beach nourishment has been widely used as a management technique to combat coastal erosion. Off-site sand is used to increase the sand volume or width of the above-water beach (Dean, 2003; de Schipper et al., 2021). The ability to conduct beach nourishment varies by location and can be dictated by the availability of sand. The range of complexities associated with beach nourishment is detailed in de Schipper et al. (2021). Once completed, monitoring becomes important to track dispersed sand and evaluate the project performance and impacts, ideally encompassing changes both above and below the water, as well as neighboring coastal areas. de Schipper et al. (2021) recommend monitoring at least 500 m of adjacent coastline but suggest that more may be needed for larger projects and in areas with more complex coastal dynamics. They also note that monitoring needs to be consistent and with relatively short time gaps between observations, particularly following a storm. Similar to other performance signposts, monitoring is typically done in situ, which can be both labor intensive and expensive to perform consistently.

As noted in de Schipper et al. (2020), satellites have the potential to be “transformative” in the field of beach nourishment by providing continuous near-global coverage of sand. Satellites can be used to measure both the surface and subsurface that are relevant for ongoing beach nourishment efforts, with the accuracy required to evaluate performance. Optical imagery from Landsat can be used to measure changes occurring above the water, while laser altimetry from ICESat-2 can measure bathymetry near-shore. These complementary techniques can track the time evolution of beach nourishment and dictate when additional adaptation may be required.

3.4.4. *Coastal ecosystems*

Coastal ecosystems offer a range of ecosystem services such as wildlife habitat, carbon capture, and protection from coastal storms and erosion that are amplified by sea level rise (Buchanan et al., 2022). For example, salt marshes, mangroves, oyster beds, or coral reefs serve as natural barriers providing protection from flooding and erosion (Bongarts Lebbe et al., 2021; Mi et al., 2022). The active protection and restoration of coastal ecosystems are considered in the development of adaptation pathways for mitigating the impacts of sea level rise (Haasnoot et al., 2019, Powell et al., 2019). To assess the effectiveness of coastal ecosystems as protection from flooding and erosion, precise lidar measurements have been used to quantify their horizontal and vertical extent and general land classification (Buchanan et al., 2022), starting with 90-m resolution Shuttle Radar Topography Mission (SRTM) data (Schuerch et al., 2018) to more recent higher resolution NOAA coastal lidar data (https://coast.noaa.gov/digitalcoast/data/coastallidar.html). Using these data in combination with sea level rise projections, models allow for evaluating the long-term sustainability and effectiveness of proposed management solutions under different climate change scenarios.

Similar to monitoring beach nourishment efforts, satellite optical imagery from Landsat and laser altimetry from ICESat-2 can further enhance studies to monitor and evaluate the use of coastal ecosystem management and provide long-term consistency in the data record. At the same time, as more vegetation-monitoring instruments, such as ECOSTRESS, and satellites, such as the future SBG mission, come online, they will allow for not only evaluating the physical extent but also the overall ecosystem health of these coastal environments, which can influence the planning and adjustment of future adaptation pathways.

4. Discussion and conclusion

DAPPs offer coastal communities a roadmap to develop resilience to rising sea levels. To date, sea level DAPPs have been proposed or implemented for a handful of locations, as shown in Figure S1 and summarized in Table S1. Most of these are for areas with good coverage from in situ observations. Within these DAPPs, there are few examples of monitoring using satellite-based signposts, but many of the examples' signposts rely on data indicators that are the same as those covered in Section 3. Specifically, the vast majority of these DAPPs use sea level rise as an indicator, which is expected as projections for future sea level rise sit at the foundation of coastal planning. Other examples of overlap with the satellite-based indicators include flood frequency, subsidence, coastal erosion, beach width, and performance of implemented adaptation strategies. The lack of overlap with the other data indicators discussed is not surprising. For example, flood extent is difficult to monitor regularly using in situ observations. Similarly, monitoring the processes that are most relevant for future sea level change cannot be done locally in most cases due to the large-scale, global nature of those processes.

With the expanding satellite network, observations are available for many of the relevant parameters that could serve as data indicators within sea level DAPPs. While the preceding sections have explored which satellite observations are suited to DAPPs, it is important to understand the limitations and opportunities afforded by these data. We consider the criteria for effective inputs, described in Section 2.2, to evaluate the potential of these satellite-based indicators. Based on this evaluation, we recommend steps to integrate satellite data into monitoring systems for sea level DAPPs.

4.1. Limitations

Satellites enable observations of coastlines across the globe, but their spatial coverage can affect their effectiveness and require further solutions. One challenge is the inability of radar altimeters to measure at the coast. Traditionally, they have been unable to provide useful measurements within 20 km of the coastline due to the presence of land in the altimeter and radiometer footprint. Other sensors are capable of coastal measurements, but, as in the case of optical imaging, some can be limited by cloud cover. To overcome these limitations, there are dedicated efforts to reprocess the along-track altimeter measurements near the coast. This effort has shown great promise in connecting open ocean sea level change to that occurring at the coast. Moreover, new satellite technologies have been developed and deployed to fill the coastal gap, including the radar interferometer launched on the 2022 SWOT mission. SWOT is providing high-resolution measurements of sea level within hundreds of meters of the coast, closer than any altimetry satellite to date, offering the potential to shift the paradigm in terms of coastal sea level monitoring. Both reprocessing and technology developments must continue in the future to generate usable satellite-based information at the coast.

Another challenge can come from satellite sampling times. The frequency of observations for a given location is determined by the satellite's orbit, and return times can range from a few days to months. Even with increasing observations, gaps can still persist and are compounded by the finite lifetime of satellites, which are usually designed with a lifespan of a few years, although some will continue to function for years beyond. Every Earth-observing satellite will eventually stop collecting data, and this can be problematic for reliable monitoring within a DAPP, as a signpost that is reliant on satellite observations could become obsolete when the satellite fails. Efforts have been made to ensure continuity in some satellite records (e.g. the satellite altimeter reference mission), but this is not a given. Even if continuity is planned or intended, gaps may occur between records (e.g. GRACE and GRACE-FO). Relatedly, for short observational records, detecting relevant signals through the variability occurring across a range of timescales can be challenging and often only remedied through lengthening of the record. Strategies and approaches must be devised to overcome such signal-to-noise challenges.

A fundamental challenge for satellite observations is that the data are not in a form that is immediately usable for monitoring by planners. In many cases, additional analysis needs to be done. Relatedly, some of the most needed information to support adaptation lies at the intersection of different satellite observations and requires dedicated effort to synthesize useful information. This analysis is done ad hoc in many cases, but there are still relatively few formal efforts to do so in a systematic way. Most coastal communities and stakeholders will not have the technical capacity to convert raw satellite observations into a usable form for monitoring within a DAPP. Projects like OPERA, based in the United States, and Copernicus Services, in Europe, provide a solution to this challenge by providing equal access to derived satellite observational products to all communities, but similar projects are not widespread and may not span the full extent of what is ultimately needed by coastal communities. As the need continues to grow, focused effort will be critical to build capacity for transitioning satellite observations into useful information to support planning.

4.2. Opportunities

Some of the limitations associated with satellite support of DAPPs have been and will increasingly be overcome based on future plans (Ponte et al. 2019). The reference altimeter mission is a programmatic success story as the satellite record of sea level has now surpassed 30 years in length. With Sentinel-6B planned for launch in the coming years, this record should extend beyond four decades. The series of Landsat satellites extends back even further, continued most recently by Landsat-9. Other satellite missions relevant to sea level and coastal zones, such as ICESat-2, GRACE-FO, and SWOT, have lengthened temporal records and spatial coverage in recent years, albeit with gaps. With a growing need to maintain these critical records, continuity is a focus of new satellites and future missions, such as NISAR, MC, SDC and SBG, which are expected to fill gaps in the observational network. NISAR will complement and extend SAR observations currently being made by Sentinel-1 and enable accompanying InSAR analyses. As a general statement, significant investment is being made on an international scale to continue and expand upon the available satellite network of relevant land and ocean observations (Ponte et al., 2019). Critically for coastal communities and planners, these observations are publicly available and thus more affordable than the extensive in situ monitoring that is currently relied upon in some locations.

As discussed for some of the data indicators in this study, observations have the potential to provide key information for evaluating and improving model-based projections. Observations can be used directly to constrain projections (e.g. Aschwanden and Brinkerhoff, 2022) or can be used alongside projections to assess whether physical processes are being adequately captured and represented in the future (e.g. Sweet et al., 2022; Hamlington et al., 2022). Satellite observations, in particular, have the potential to assess large-scale variability and signals in a way that is challenging for in situ observations.

4.3. Steps to integration for satellite data and coastal monitoring for DAPPs

Building off of recent discussions (e.g. Benveniste et al., 2019), a goal of this study was to outline how satellites can provide an observational backbone enabling DAPPs to be used at any location across the globe. We did not, however, define the details of implementing such integrated monitoring systems. It can be difficult to determine how to select and establish satellite observations as DAPP monitoring components, in part because needs and resources to undertake adaptation can vary dramatically across the globe. Nevertheless, we offer two suggestions to build capacity for satellite-based DAPP monitoring.

First, similar to the Delta Programme in the Netherlands (Haasnoot et al. , 2018), signal groups should be established, where the capacity exists. Each signal group would consist of a group of technical experts, who initially identify a suite of relevant data indicators and then monitor and interpret them to issue signal alerts when adaptation actions are needed. This human-powered monitoring system depends on available expertise, so initial signal groups could be considered for larger, regional scales, rather than individual communities. On these scales, these signal groups would track indicators that are consistent across different DAPP implementations, such as changes in sea level and the underlying processes that contribute to these changes. For the United States, this signal group could be composed of members from the relevant federal agencies and coupled to the in situ observations that are abundantly available along U.S. coastlines. Given the global scope of satellite observations, something similar could be established on an international basis, convened by organizations with a global purview. As with the DAPP monitoring framework, signal groups would need to output regular assessments, to be utilized in dynamic adaptation planning.

Second, investment should continue to be made in progressing satellite observations beyond initial stages and into forms that are more immediately useful for stakeholders and coastal communities, rather than technical experts only. For signposts that may pull from multiple satellites, this translation is particularly important and needed. OPERA and Copernicus Services are specifically designed to provide a significant push to get over the first hurdle of working with low-level satellite data and deliver products derived from this data those that need it. These projects are making strides in transitioning satellite observations into information that is useful for coastal stakeholders, indicating a promising future for the use of satellite data in coastal management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. D.R.R. and M.W. were supported by the Gulf Research Program of the National Academies of Sciences, Engineering, and Medicine under award number 2000013282. The content is solely the responsibility of the authors and does not necessarily represent the official views of the Gulf Research Program or the National Academies of Sciences, Engineering, and Medicine.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2023.100555.

References

Anthony, E.J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., Nguyen, V.L., 2015. Linking rapid erosion of the mekong river delta to human activities. Sci. Rep. 5 (1), 1–12.

Aschwanden, A., Brinkerhoff, D.J., 2022. Calibrated mass loss predictions for the greenland ice sheet. Geophys. Res. Lett. 49 (19) e2022GL099058.

Barnard, P.L., Hoover, D., Hubbard, D.M., Snyder, A., Ludka, B.C., Allan, J., Kaminsky, G.M., Ruggiero, P., Gallien, T.W., Gabel, L., 2017. Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. Nat. Commun. 8 (1), 1–8.

Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E., Hurlimann, A., 2014. A local coastal adaptation pathway. Nat. Clim. Chang. 4 (12), 1103–1108.

Beckley, B.D., Callahan, P.S., Hancock Iii, D.W., Mitchum, G.T., Ray, R.D., 2017. On the "Cal-Mode" correction to TOPEX satellite altimetry and its effect on the global mean sea level time series. J. Geophys. Res. Oceans 122 (11), 8371–8384.

Befus, K.M., Barnard, P.L., Hoover, D.J., Finzi Hart, J.A., Voss, C.I., 2020. Increasing threat of coastal groundwater hazards from sea-level rise in California. Nat. Clim. Chang. 10 (10), 946–952.

Bekaert, D.P.S., Hamlington, B.D., Buzzanga, B., Jones, C.E., 2017. Spaceborne synthetic aperture radar survey of subsidence in hampton roads, virginia (USA). Sci. Rep. 7 (1), 1–9.

Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio-Marc, L., Shah, R., Almar, R., Wöppelmann, G., 2019. Requirements for a coastal hazards observing system. Front. Mar. Sci. 6, 348.

Blackwell, E., Shirzaei, M., Ojha, C., Werth, S., 2020. Tracking California's sinking coast from space: Implications for relative sea level rise. *Science*. Advances 6 (31), eaba4551.

Bongarts Lebbe, T., Rey-Valette, H., Chaumillon, E., Camus, G., Almar, R., Cazenave, A., Euzen, A., 2021. Designing coastal adaptation strategies to tackle sea level rise. Front. Mar. Sci. 1640.

Borrero, J.C., 2005. Field data and satellite imagery of tsunami effects in banda aceh. Science 308 (5728), 1596.

Box, J.E., Wehrlé, A., van As, D., Fausto, R.S., Kjeldsen, K.K., Dachauer, A., Ahlstrøm, A.P., Picard, G., 2022. Greenland Ice sheet rainfall, heat and albedo feedback impacts from the mid-august 2021 atmospheric river. Geophys. Res. Lett. 49 (11) e2021GL097356.

Buchanan, M.K., Kulp, S., Strauss, B., 2022. Resilience of US coastal wetlands to accelerating sea level rise. Environmental Research Communications 4 (6), 061001.

Buzzanga, B., Bekaert, D.P.S., Hamlington, B.D., Sangha, S.S., 2020. Toward sustained monitoring of subsidence at the coast using InSAR and GPS: An application in hampton roads, virginia. Geophys. Res. Lett. 47 (18) e2020GL090013.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., Saba, V., 2018. Observed fingerprint of a weakening atlantic ocean overturning circulation. Nature 556 (7700), 191–196.

Camargo, C.M., Riva, R.E., Hermans, T.H., Schütt, E.M., Marcos, M., Hernandez-Carrasco, I., Slangen, A.B., 2023. Regionalizing the sea-level budget with machine-learning techniques. Ocean Sci. 19 (1), 17–41.

Cantelon, J.A., Guimond, J.A., Robinson, C.E., Michael, H.A., Kurylyk, B.L., 2022. Vertical saltwater intrusion in coastal aquifers driven by episodic flooding: A review. Water Resour. Res. 58 (11) e2022WR032614.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. 100 (14), 8086–8091.

Cazenave, A., Gouzenes, Y., Birol, F., Leger, F., Passaro, M., Calafat, F.M., Benveniste, J., 2022. Sea level along the world's coastlines can be measured by a network of virtual altimetry stations. Communications Earth & Environment 3 (1), 117.

Charles, S.P., Kominoski, J.S., Troxler, T.G., Gaiser, E.E., Servais, S., Wilson, B.J., Rudnick, D.T., 2019. Experimental saltwater intrusion drives rapid soil elevation and carbon loss in freshwater and brackish everglades marshes. Estuar. Coasts 42, 1868–1881.

Chui, T.F.M., Low, S.Y., Liong, S.-Y., 2011. An ecohydrological model for studying groundwater–vegetation interactions in wetlands. J. Hydrol. 409 (1–2), 291–304.

Collini, R.C., Carter, J., Auermuller, L., Engeman, L., Hintzen, K., Gambill, J., Johnson, R.E., Miller, I., Schafer, C., Stiller, H., 2022. Application Guide for the 2022 Sea Level Rise Technical Report. National Oceanic and Atmospheric Administration Office for Coastal Management, Mississippi–Alabama Sea Grant Consortium (MASGP-22-028), and Florida Sea Grant (SGEB 88).

Chung Nguyen, D.D., Bennett, V., Jones, C., Abdoun, T., Zeghal, M., O'Meara, K., 2018. pp. 516 – 525.

Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Ito, S.I., Yool, A., 2022. Oceans and coastal ecosystems and their services. IPCC AR6 WGII. Cambridge University Press.

Correa, R.E., Cardenas, M.B., Rodolfo, R.S., Lapus, M.R., Davis, K.L., Giles, A.B., Santos, I.R., 2021. Submarine groundwater discharge releases CO2 to a coral reef. ACS ES&T Water 1 (8), 1756–1764.

de Schipper, M.A., Ludka, B.C., Raubenheimer, B., Luijendijk, A.P., Schlacher, T., 2021. Beach nourishment has complex implications for the future of sandy shores. Nature Reviews Earth & Environment 2 (1), 70–84.

Dean, R.G., 2003. Beach nourishment projects as large scale experiments in nature. In: Coastal Engineering 2002: Solving Coastal Conundrums. World Scientific, pp. 3649–3661.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea level rise. Nature 531 (7596), 591–597.

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D.M., Ashe, E.L., 2021. The Paris Climate Agreement and future sea level rise from Antarctica. Nature 593 (7857), 83–89.

DeLaune, R.D., Pezeshki, S.R., 1994. The influence of subsidence and saltwater intrusion on coastal marsh stability: Louisiana Gulf coast, USA. J. Coast. Res. 77–89.

Delta Programme, 2015. Delta Program 2015, Working on the Delta. The Decision to Keep the Netherlands safe and liveable, The Ministry of Infrastructure and the Environment, The Ministry of Economics.

Donlon, C.J., Cullen, R., Giulicchi, L., Vuilleumier, P., Francis, C.R., Kuschnerus, M., Simpson, W., Bouridah, A., Caleno, M., Bertoni, R., 2021. The Copernicus Sentinel-6 mission: Enhanced continuity of satellite sea level measurements from space. Remote Sens. Environ. 258, 112395.

Environmental Protection Agency, 1979. National Interim Primary Drinking Water Regulations; Control of Trihalomethanes in Drinking Water. Fed. Reg. 44 (231), 68624.

Fang, J., Nicholls, R.J., Brown, S., Lincke, D., Hinkel, J., Vafeidis, A.T., Shi, P., 2022. Benefits of subsidence control for coastal flooding in China. Nat. Commun. 13 (1), 6946.

Fasullo, J.T., Nerem, R.S., 2018. Altimeter-era emergence of the patterns of forced sea level rise in climate models and implications for the future. Proc. Natl. Acad. Sci. 115 (51), 12944–12949.

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. and Coauthors, 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, and Coeditors (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 1211 1362 10.1017/ 9781009157896.011.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Wu, Y.H., 2020. The causes of sea-level rise since 1900. Nature 584 (7821), 393–397.

Garner, A.J., Sosa, S.E., Tan, F., Jie Tan, C.W., Garner, G.G., Horton, B.P., 2023. Evaluating knowledge gaps in sea-level rise assessments from the united states. Earth's Future e2022EF003187.

Greene, C.A., Gardner, A.S., Schlegel, N.-J., Fraser, A.D., 2022. Antarctic calving loss rivals ice-shelf thinning. Nature 609 (7929), 948–953.

Guérou, A., Meyssignac, B., Prandi, P., Ablain, M., Ribes, A., Bignalet-Cazalet, F., 2023. Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty. Ocean Sci. 19 (2), 431–451. https://doi.org/10.5194/os-19-431-2023.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Chang. 23 (2), 485–498.

Haasnoot, M., Brown, S., Scussolini, P., Jimenez, J.A., Vafeidis, A.T., Nicholls, R.J., 2019. Generic adaptation pathways for coastal archetypes under uncertain sea level rise. Environmental Research Communications 1 (7), 071006.

Haasnoot, M., van 't Klooster, S., van Alphen, J., 2018. Designing a monitoring system to detect signals to adapt to uncertain climate change. Glob. Environ. Chang. 52, 273–285.

Haasnoot, M., Winter, G., Brown, S., Dawson, R.J., Ward, P.J., Eilander, D., 2021. Long-term sea-level rise necessitates a commitment to adaptation: A first order assessment. Clim. Risk Manag. 34, 100355.

Hamlington, B.D., Gardner, A.S., Ivins, E., Lenaerts, J.T.M., Reager, J.T., Trossman, D.S., Zaron, E.D., Adhikari, S., Arendt, A., Aschwanden, A., 2020b. Understanding of contemporary regional sea-level change and the implications for the future. Rev. Geophys. 58 (3) e2019RG000672.

Hamlington, B.D., Frederikse, T., Thompson, P.R., Willis, J.K., Nerem, R.S., Fasullo, J.T., 2021. Past, present, and future pacific sea-level change. Earth's Future 9 (4) e2020EF001839.

Hamlington, B.D., Chambers, D.P., Frederikse, T., Dangendorf, S., Fournier, S., Buzzanga, B., Nerem, R.S., 2022. Observation-based trajectory of future sea level for the coastal United States tracks near high-end model projections. Communications Earth & Environment 3 (1), 1–11.

Hamlington, B.D., Thompson, P.R., 2015. Considerations for estimating the 20th century trend in global mean sea level. Geophys. Res. Lett. 42 (10), 4102–4109.

Hamlington, B.D., Fasullo, J.T., Nerem, R.S., Kim, K., Landerer, F.W., 2019. Uncovering the pattern of forced sea level rise in the satellite altimeter record. Geophys. Res. Lett. 46 (9), 4844–4853.

Hamlington, B.D., Frederikse, T., Nerem, R.S., Fasullo, J.T., Adhikari, S., 2020a. Investigating the acceleration of regional sea level rise during the satellite altimeter era. Geophys. Res. Lett. 47 (5) e2019GL086528.

Han, S., Sauber, J., Pollitz, F., Ray, R., 2019. Sea level rise in the Samoan Islands escalated by viscoelastic relaxation after the 2009 Samoa-Tonga earthquake. J. Geophys. Res. Solid Earth 124 (4), 4142–4156.

Harvey, T.C., Hamlington, B.D., Frederikse, T., Nerem, R.S., Piecuch, C.G., Hammond, W.C., Blewitt, G., Thompson, P.R., Bekaert, D.P.S., Landerer, F.W., 2021. Ocean mass, sterodynamic effects, and vertical land motion largely explain US coast relative sea level rise. Communications Earth & Environment 2 (1), 1–10.

Heyer, T., 2016. Reliability assessment of levees based on failure investigations. Vodohospodářské Technicko-Ekonomické Informace 58 (3), 28–33.

Hoffman, M.J., Asay-Davis, X., Price, S.F., Fyke, J., Perego, M., 2019. Effect of subshelf melt variability on sea level rise contribution from thwaites glacier, antarctica. J. Geophys. Res. Earth 124 (12), 2798–2822.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Kääb, A., 2021. Accelerated global glacier mass loss in the early twenty-first century. Nature 592 (7856), 726–731.

IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 10.1017/9781009325844.

Jackson, L.C., Wood, R.A., 2020. Fingerprints for early detection of changes in the AMOC. J. Clim. 33 (16), 7027–7044.

Joughin, I., Smith, B.E., Medley, B., 2014. Marine ice sheet collapse potentially under way for the thwaites glacier basin. West Antarctica. *Science* 344 (6185), 735–738.

Kim, K.H., Heiss, J.W., Michael, H.A., Cai, W.J., Laattoe, T., Post, V.E., Ullman, W.J., 2017. Spatial patterns of groundwater biogeochemical reactivity in an intertidal beach aquifer. J. Geophys. Res. Biogeo. 122 (10), 2548–2562.

Kim, G., Kim, J.S., Hwang, D.W., 2011. Submarine groundwater discharge from oceanic islands standing in oligotrophic oceans: Implications for global biological production and organic carbon fluxes. Limnol. Oceanogr. 56 (2), 673–682.

Klein, R.J.T., Midglev, G.F., Preston, B.L., Alam, M., Berkhout, F.G.H., Dow, K., Shaw, M.R., 2014. Climate change 2014: Impacts, adaptation, and vulnerability. IPCC Fifth Assessment Report, Stockholm, Sweden.

Kopp, R.E., DeConto, R.M., Bader, D.A., Hay, C.C., Horton, R.M., Kulp, S., Strauss, B.H., 2017. Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. Earth's Future 5 (12), 1217–1233.

Kopp, R.E., Gilmore, E.A., Little, C.M., Lorenzo-Trueba, J., Ramenzoni, V.C., Sweet, W.V., 2019. Usable science for managing the risks of sea-level rise. Earth's Future 7 (12), 1235–1269.

Krasting, J.P., Dunne, J.P., Stouffer, R.J., Hallberg, R.W., 2016. Enhanced atlantic sea level rise relative to the Pacific under high carbon emission rates. Nat. Geosci. 9 (3), 210–214.

Kwadijk, J.C.J., Haasnoot, M., Mulder, J.P.M., Hoogvliet, M.M.C., Jeuken, A.B.M., van der Krogt, R.A.A., van Oostrom, N.G.C., Schelfhout, H.A., van Velzen, E.H., van Waveren, H., de Wit, M.J.M., 2010. Using adaptation tipping points to prepare for climate change and sea level rise: A case study in the Netherlands. WIREs Clim. Change 1 (5), 729–740.

Laignel, B., Vignudelli, S., Almar, R., Becker, M., Bentamy, A., Benveniste, J., Verpoorter, C., 2023. Observation of the coastal areas, estuaries and deltas from space. Surv. Geophys. 1–48.

Lawrence, J., Haasnoot, M., 2017. What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. Environ Sci Policy 68, 47–57.

Luijendijk, E., Gleeson, T., Moosdorf, N., 2020. Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. Nat. Commun. 11 (1), 1260.

McCarthy, G.D., Brown, P.J., Flagg, C.N., Goni, G., Houpert, L., Hughes, C.W., Hummels, R., Inall, M., Jochumsen, K., Larsen, K.M.H., 2020. Sustainable observations of the AMOC: Methodology and technology. Rev. Geophys. 58 (1) e2019RG000654.

McKenzie, T., Habel, S., Dulai, H., 2021. Sea-level rise drives wastewater leakage to coastal waters and storm drains. Limnol. Oceanogr. Lett. 6 (3), 154–163.

Melet, A., Teatini, P., le Cozannet, G., Jamet, C., Conversi, A., Benveniste, J., Almar, R., 2020. Earth observations for monitoring marine coastal hazards and their drivers. Surv. Geophys. 41 (6), 1489–1534.

Mentaschi, L., Vousdoukas, M.I., Pekel, J.-F., Voukouvalas, E., Feyen, L., 2018. Global long-term observations of coastal erosion and accretion. Sci. Rep. 8 (1), 1–11.

Mi, J., Zhang, M., Zhu, Z., Vuik, V., Wen, J., Gao, H., Bouma, T.J., 2022. Morphological wave attenuation of the nature-based flood defense: A case study from chongming dongtan shoal. China. Science of the Total Environment 831, 154813.

Michael, H.A., Russoniello, C.J., Byron, L.A., 2013. Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. Water Resour. Res. 49 (4), 2228–2240.

Michael, H.A., Post, V.E., Wilson, A.M., Werner, A.D., 2017. Science, society, and the coastal groundwater squeeze. Water Resour. Res. 53 (4), 2610–2617.

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., 2020. Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the antarctic ice sheet. Nat. Geosci. 13 (2), 132–137.

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T., 2018. Climate-change–driven accelerated sea level rise detected in the altimeter era. Proc. Natl. Acad. Sci. 115 (9), 2022–2025.

Nerem, R.S., Frederikse, T., Hamlington, B.D., 2022. Extrapolating empirical models of satellite-observed global mean sea level to estimate future sea level change. Earth's Future 10 (4) e2021EF002290.

Nicholls, R.J., Cazenave, A., 2010. sea level rise and its impact on coastal zones. Science 328 (5985), 1517–1520.

Nicholls, R.J., Lincke, D., Hinkel, J., et al., 2021. A global analysis of subsidence, relative sea-level change and coastal flood exposure. Nat. Clim. Chang. 11, 338–342. https://doi.org/10.1038/s41558-021-00993-z.

Obeysekera, J., Haasnoot, M., Lempert, R., 2020. How are decision-science methods helping design and implement coastal sea-level adaptation projects. US CLIVAR Variations 18 (3), 1–7.

Orihuela-Pinto, B., Santoso, A., England, M.H., Taschetto, A.S., 2022. Reduced ENSO variability due to a collapsed atlantic meridional overturning circulation. J. Clim. 35 (16), 5307–5320.

Özer, I.E., van Leijen, F.J., Jonkman, S.N., Hanssen, R.F., 2019. Applicability of satellite radar imaging to monitor the conditions of levees. J. Flood Risk Manage. 12 (S2), e12509.

Pilkey, O.H., Cooper, J.A.G., 2004. Society and sea level rise. Science 303 (5665), 1781–1782.

Ponte, R.M., Carson, M., Cirano, M., Domingues, C.M., Jevrejeva, S., Marcos, M., Zhang, X., 2019. Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level. Front. Mar. Sci. 6, 437.

Powell, E.J., Tyrrell, M.C., Milliken, A., Tirpak, J.M., Staudinger, M.D., 2019. A review of coastal management approaches to support the integration of ecological and human community planning for climate change. J. Coast. Conserv. 23 (1), 1–18.

Ramm, T.D., Watson, C.S., White, C.J., 2018. Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. Environ Sci Policy 87, 92–101.

Ranger, N., Reeder, T., Lowe, J., 2013. Addressing 'deep'uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. EURO Journal on Decision Processes 1 (3–4), 233–262.

Richter, K., Meyssignac, B., Slangen, A.B.A., Melet, A., Church, J.A., Fettweis, X., Marzeion, B., Agosta, C., Ligtenberg, S.R.M., Spada, G., 2020. Detecting a forced signal in satellite-era sea level change. Environ. Res. Lett. 15 (9), 094079.

Robel, A.A., Seroussi, H., Roe, G.H., 2019. Marine ice sheet instability amplifies and skews uncertainty in projections of future sea level rise. Proc. Natl. Acad. Sci. 116 (30), 14887–14892.

Royston, S., Watson, C.S., Legrésy, B., King, M.A., Church, J.A., Bos, M.S., 2018. Sea-level trend uncertainty with Pacific climatic variability and temporally-correlated noise. J. Geophys. Res. Oceans 123 (3), 1978–1993.

Royston, S., Bingham, R.J., Bamber, J.L., 2022. Attributing decadal climate variability in coastal sea level trends. Ocean Sci. Discuss. 1–21.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., Brown, S., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561 (7722), 231–234.

Shirzaei, M., Freymueller, J., Törnqvist, T.E., Galloway, D.L., Dura, T., Minderhoud, P.S.J., 2021. Measuring, modelling and projecting coastal land subsidence. Nature Reviews Earth & Environment 2 (1), 40–58.

Slangen, A.B., Palmer, M.D., Camargo, C.M., Church, J.A., Edwards, T.L., Hermans, T.H., van de Wal, R.S., 2023. The evolution of 21st century sea-level projections from IPCC AR5 to AR6 and beyond. Cambridge Prisms: Coastal Futures 1, e7.

Slater, T., Hogg, A.E., Mottram, R., 2020. Ice-sheet losses track high-end sea-level rise projections. Nat. Clim. Chang. 10 (10), 879–881.

Smallegan, S.M., Irish, J.L., van Dongeren, A.R., 2017. Developed barrier island adaptation strategies to hurricane forcing under rising sea levels. Clim. Change 143 (1), 173–184.

Solohin, E., Widney, S.E., Craft, C.B., 2020. Declines in plant productivity drive loss of soil elevation in a tidal freshwater marsh exposed to saltwater intrusion. Ecology 101 (12), e03148.

Stammer, D., Cazenave, A. (Eds.), 2017. Satellite altimetry over oceans and land surfaces. CRC Press.

Stephens, S.A., Bell, R.G., Lawrence, J., 2018. Developing signals to trigger adaptation to sea-level rise. Environ. Res. Lett. 13 (10), 104004.

Sutter, L.A., Perry, J.E., Chambers, R.M., 2014. Tidal freshwater marsh plant responses to low level salinity increases. Wetlands 34 (1), 167–175.

Sweet, W.V., Hamlington, B.D., Kopp, R.E., Weaver, C.P., Barnard, P.L., Bekaert, D., Brooks, W., Craghan, M., Dusek, G., Frederikse, T., 2022. Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along US coastlines. NOAA Technical Report.

Tansel, B., Zhang, K., 2022. Effects of saltwater intrusion and sea level rise on aging and corrosion rates of iron pipes in water distribution and wastewater collection systems in coastal areas. J. Environ. Manage. 315, 115153.

The IMBIE Team, 2020. Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature 579 (7798), 233–239. https://doi.org/10.1038/s41586-019-1855-2.

Thompson, P.R., Widlansky, M.J., Hamlington, B.D., Merrifield, M.A., Marra, J.J., Mitchum, G.T., Sweet, W., 2021. Rapid increases and extreme months in projections of United States high-tide flooding. Nat. Clim. Chang. 11 (7), 584–590.

Toimil, A., Losada, I.J., Hinkel, J., Nicholls, R.J., 2021. Using quantitative dynamic adaptive policy pathways to manage climate change-induced coastal erosion. Clim. Risk Manag. 33, 100342.

Tully, K., Gedan, K., Epanchin-Niell, R., Strong, A., Bernhardt, E.S., BenDor, T., Mitchell, M., Kominoski, J., Jordan, T.E., Neubauer, S.C., 2019. The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. Bioscience 69 (5), 368–378.

Waibel, M.S., Hulbe, C.L., Jackson, C.S., Martin, D.F., 2018. Rate of mass loss across the instability threshold for thwaites glacier determines rate of mass loss for entire basin. Geophys. Res. Lett. 45 (2), 809–816.

Wang, J., Church, J.A., Zhang, X., Chen, X., 2021. Reconciling global mean and regional sea level change in projections and observations. Nat. Commun. 12 (1), 1–12.

White Jr, E., Kaplan, D., 2021. Identifying the effects of chronic saltwater intrusion in coastal floodplain swamps using remote sensing. Remote Sens. Environ. 258, 112385.

Wiese, D.N., Bienstock, B., Blackwood, C., Chrone, J., Loomis, B.D., Sauber, J., Zlotnicki, V., 2022. The mass change designated observable study: overview and results. Earth Space Sci. 9 (8) e2022EA002311.

Woodworth, P.L., Melet, A., Marcos, M., Ray, R.D., Wöppelmann, G., Sasaki, Y.N., Merrifield, M.A., 2019. Forcing factors affecting sea level changes at the coast. Surv. Geophys. 40 (6), 1351–1397.

Wöppelmann, G., Marcos, M., 2016. Vertical land motion as a key to understanding sea level change and variability. Rev. Geophys. 54 (1), 64–92.

Yang, J., Graf, T., Ptak, T., 2015. Sea level rise and storm surge effects in a coastal heterogeneous aquifer: A 2D modelling study in northern Germany. Grundwasser 20 (1), 39–51.

Yin, J., Schlesinger, M.E., Stouffer, R.J., 2009. Model projections of rapid sea level rise on the northeast coast of the United States. Nat. Geosci. 2 (4), 262–266.

Yu, X., Yang, J., Graf, T., Koneshloo, M., O'Neal, M.A., Michael, H.A., 2016. Impact of topography on groundwater salinization due to ocean surge inundation. Water Resour. Res. 52 (8), 5794–5812.

Zandvoort, M., Campos, I.S., Vizinho, A., Penha-Lopes, G., Lorencová, E.K., van der Brugge, R., Jeuken, A.B., 2017. Adaptation pathways in planning for uncertain climate change: Applications in portugal, the czech republic and the netherlands. Environ Sci Policy 78, 18–26.

Sweet, W.V., Kopp, R.E., Weaver, C.P., Obeysekera, J., Horton, R.M., Thieler, E.R., Zervas, C., 2017. Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083.