A biological indicator for measuring and communicating local sea level rise captured in historic photographs.

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A biological indicator for measuring and communicating local sea level rise captured in historic photographs.

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Abstract

This paper explores a novel approach to collecting and communicating local site-specific data on recent sea level rise (SLR) using black zone biotic levels left on historic coastal stone structures by a stable community of cyanobacteria (blue-green algae) at the Royal Naval Dockyard in Bermuda. Photographs taken at the Dockyard in 1870, 2007 and 2017 show an upward shift in this living cyanobacterial community. A spatio-temporal digital twin computed from historic and contemporary photo assets was created to test the viability of these black zone lines as a proxy for sea level rise (SLR) measurements in Bermuda. Shifts in these black zone lines when analyzed through the digital twin demonstrate an average upward shift of 2.2 mm per year between 1870 and 2007 and 2.7 mm per year between 1870 and 2017, somewhat lower than the Global estimates from the Intergovernmental Panel on Climate Change Assessment Report predictions. However, the digital twin showed a dramatic upward shift of

8.8 cm between 2007 and 2017, or 8.8 mm per year, which coincided with Bermuda's highest recorded tidal extent since 1932. Black zone cyanobacteria are highly SLR sensitive and over long time scales comparative imagery of black zones could present a proper indicator of average sea level rise. At timescales less than 10 years the black zone may be best indicative of episodic tidal extent. As SLR will continue to shift supralittoral cyanobacteria upwards in Bermuda and in warm rocky intertidal zones worldwide, tidal monitoring and black zone assessments may prove to be a useful combination in documenting and communicating the reality, extent and possible acceleration of local SLR.

Keywords: sea level rise, black zone, cyanobacteria, change detection, historic photographs, spatiotemporal model synthesis, digital heritage, climate change communication, tidal flux, photogrammetry, digital twin.

1 Introduction

The 2015 Intergovernmental Panel on Climate Change (IPCC) Assessment Report shows that 95% of the world's oceans will experience a global mean sea level rise (SLR) of 0.51 m by the year 2100, although significant regional variability will exist (Stocker et al. 2013). Global Sea Levels have increased on average approximately 20 cm (1.7 mm/yr) over the last century and will continue to increase through temperature-induced expansion and the addition of new water mass through the melting of legacy ice (Stocker et al. 2013). The acceleration of the rate of global SLR, is of urgent interest as it has increased from 1.7 mm/yr in 1930 to 3.2 mm/yr in the 1990s to 3.6 mm/yr in the early 21st century (2006-2015) (Church et al. 2013; Clark et al. 2015; Nerem et al. 2018; Oppenheimer 2019). The increased volume of water in the world's oceans will interplay with regional differences in bathymetry, geography, currents, climate and weather patterns to create site-specific sea level rise effects in coastal areas around the globe.

Scientifically establishing local historic and ancient trends in SLR is critical in modeling the future rate and impact of Relative Sea Level Rise (RSLR) for specific regions and locations. Local models will be the basis for the development of strategies to manage impacts and adaptations. Determining how a particular area has responded to, or been impacted by, the most recent rise in sea level is of key importance in assessing, developing and communicating site specific adaptive strategies for near future SLR impacts. Planning policies and effective adaptive strategy development depend on predicting both the rate of future sea level rise and its effects in specific areas and, therefore, will be most effectively implemented nearer to the site or region where recent past or prologue sea level rise data has been collected and assessed. Data is especially applicable to the area in which it is collected.

Bermuda is a small limestone island chain in the middle of the North Atlantic sitting atop a volcanic seamount that formed 47–40 million years ago (Thomas 2004; Vogt et al. 2007). The islands are surrounded by a ring of fringing reef that protects the generally soft limestone coastline from erosion. Rising to only 76 m at its highest point, over 20% of the Bermuda land mass is less than 2 m above sea level, and with most of the islands at less than 3 km wide, the islands have an extensive coastline for their size (Vogt 2007). In 2016, Bermuda had a resident population of ca. 67,000 on a landmass 71.7 km^2, making it the country with the 3rd highest population density in the world. As the second most isolated inhabited archipelago in the world located 1,054 km east south east of North America at Cape Hatteras, North Carolina, Bermuda is uniquely important for the scientific investigation of remote ocean ecosystems and island environments. From the HMS *Challenger* expeditions in 1873, to the deployment of William Beebe's bathysphere in 1934 to a depth of 923 m, to the Bermuda Atlantic Time Series study, one of the world's longest continuous oceanographic studies

(Thomas 2004; Bates et al. 2014), Bermuda has long been a globally significant center for marine research.

Bermuda is well placed for the measurement and analysis of SLR. There is little island subsidence in the entire Bermuda platform and Bermuda is not on a tectonic margin as the active volcanic ridge that built Bermuda has long since shifted so that the island today is sitting on the eastern side of a tectonic plate. The crustal breach from which the original volcano emerged is presently non-active (Vacher and Rowe 2004), and there is little seismic activity making Bermuda ideal as an SLR point of reference.

Like all other small low elevation island states, Bermuda is especially vulnerable to the impact of climate change and in particular projected sea level rise. It was calculated in 2007 that even at the most conservative of Global SLR estimates by the IPCC of 0.59 m by 2050, Bermuda can anticipate that 186.6 ha or 1.87 km^2 of land will be inundated with sea water. With a 2 m rise Bermuda will lose 819.3 ha or 8.19 km^2, over 10% of Bermuda's landmass (Glasspool 2008). SLR, ocean warming and acidification, increased precipitation variability (droughts and rains), and extreme events such as hurricanes, coral bleaching episodes, etc., pose serious threats to islands' long-term inhabitability for human habitation (UNFCCC 2005; Nurse et al. 2014).

Bermuda began seriously researching local SLR after the discovery of a submerged endemic Bermuda cedar forest in 9 m of water off the Castle Harbor by world-renowned local ocean explorer Teddy Tucker in 1998.

This submerged coastal forest was found embedded in the seabed with well-preserved short pieces of trunk exposed above the sediment and complete root systems still embedded in remnant peat or soil beds beneath the coastal sand. The deepest of these was only recently found in 2012 at 17 m in the reef platform 12 km north of Bermuda. The uniqueness of these discoveries initiated the Bermuda Sea Level

Rise Project in 2001 led to the exploration and assessment of a number of well-preserved submerged forests and coastal habitats discovered by Mr. Tucker around the islands. Over the next decade, preserved organic material from these submerged forests and other ecological habitats from depths of 1–17 m were collected and analyzed. Radiocarbon dates retrieved from these former Pleistocene/Holocene forests ranged from 12,000–1,500 years ago and indicated that the pace of the disappearance of forests at different depths in these areas is entirely consistent with, and mirrors, the known rates of Prehistoric sea level change (unpublished data, S. Blasco). Bermuda's remnant submerged coastal forests can serve as a reliable biological reference base from which prehistoric SLR and its effects (inundation) can be documented.

The local communication value of this work has been significant. The tree roots recovered and the story of sea level rise as a prehistoric phenomenon was successfully shared across Bermuda through numerous newspaper stories, magazine op-ed pieces, talks, documentary films and large-scale permanent displays in local museums and public points of interest (Rouja 2009; Watson 2009). However, their utility as a data set for comparing the rise in sea level across sites and jurisdictions and reconstructing more detailed near-past data for use in modeling current SLR rates has limitations. As global awareness about SLR has increased so has the need to communicate to the public not just the history of rising sea levels, but also projections and impacts that will affect humanity in the short term. The need for tools that effectively communicate recent and ongoing SLR was seen as critical at this juncture.

1.1 Historic Evidence for RSLR

In 2007, the team began searching for evidence of historic sea level rise that could assist in determining and communicating the rate and impacts of SLR from the first habitation of Bermuda in 1609.   Early fortifications on Castle Island, the ruins of the oldest standing English fortifications in the New World, dating from 1612 (Madeiros et al. 2014) include a series of steps chiseled into the cliffs that descend into the ocean. These steps along with other early coastal structures were considered as possible reference points for establishing historic sea levels, however the inability to establish a frame of reference, through either a reliable measurable biologic indicator or accurate historical reference linked to their use or the location, made calculating sea level change at these exact spots difficult. The same difficulty applied to the many anecdotal references to recent shifts in sea level that local seamen, fishermen and marine contractors would regularly make reference to.

In 2007, in conjunction with the Bermuda Archives, we began searching through the early construction drawings made for and during the building of the Royal Naval Dockyard in an effort to find measurable historic sea level references. The Dockyard was built as a military fortification in western Bermuda on Ireland Island North, a hard limestone rock formation that is the last in the westerly chain of now connected islands that collectively make up Bermuda. Designed and built at a time of major expansion of the then “British Empire”, Bermuda was one of Britain’s most strategic outposts, its fortifications designed explicitly to maintain dominance of the British Empire that by the end of the 19th Century controlled a fifth of the world’s land and a quarter its population. Commenced in 1809 and functioning as an important military base for the next 139 years, the Dockyard was a major infrastructure project and investment by the British military. Many plans and documents from the Royal engineers detailing her construction and use remain in historical Bermuda Archives. Early drawings and plans for the Dockyard contained detailed references to high and low tide and the building of docks and slips of appropriate relative height to the projected use. These references were in many cases specific to the Works Tide Gauge that was used to manage the day-to-day uses of the dock – depths of boats, cargo type, etc.

The challenge of translating these archival tidal references to the actual dock and present day tide heights was compounded by the inability to rationalize the terms and measurement scales used and relocate the exact reference points used to make these calculations. Fortunately, the Bermuda Archives brought to our attention an album of the earliest historic military photographs taken of the Royal Naval Dockyard labeled between 1865 and 1870 (Barke and Harris 1994). These photographs were requested by the Colonial Office as part of the regular survey of British fortifications outside of the United Kingdom and as such are significant historic artifacts. The central command, ready to have actual images of their overseas facilities, rather than relying on artist's renderings used prior to then, were early adopters of photography and eagerly sent out teams of photographers to their major installations. Therefore, the images taken in Bermuda are some of the earliest photographs used to document British overseas military installations and as a consequence specifically document the buildings and functional parts of the military Dockyard. As a result, the photographs show in great detail elements of the construction and buildings including high quality images of the main docks and slipways of the Dockyard that served, and still serve, the Dockyard today. One image of the Royal Naval Dockyard in particular from 1870 (Fig. 1) showed a clear cyanobacterial (blue-green algal) black zone above the water at mid tide running the full length of the dock.

The black zone line in 1870 was uninterrupted, showing an unexpected consistency in relative height to the surface of the water and the top of the wall itself, running parallel to both. A visit to the Dockyard in 2007 after seeing that image confirmed that the same uninterrupted black zone could be seen along the entire dock face (Fig. 2). We quickly noted that there was one significant difference – the black zone sat approximately one full course of block higher than it did in the 1870 photograph (Fig. 3). It was decided that an investigation on whether the Dockyard wall and associated black zone line could be used as a measure of RSLR from the time the picture was taken to today. The history of the Dockyard has been well documented and continues to serve as a fully functional working dockyard with active slips and machine shops still using originally constructed buildings demonstrating and confirming the quality of the initial work of 19th century Royal Naval engineers. The Royal Naval

Dockyard incorporated a series of islands and islets at the northwestern end of Ireland Island North overlooking the entire approach to the main inland harbors of Bermuda (Barke and Harris 1994). The Royal Naval Dockyard was an extensive military zone and was conceived to make Bermuda the Gibraltar of the west built to the highest standards. Constructed as a working port and highly defended fortification, the Dockyard was constructed from a particularly dense, hard form of Bermuda limestone known locally as Walsingham rock, the most consolidated limestone in Bermuda (Vacher et al. 1989; Rowe 1990). The innate strength of the structures and their continued industrial usefulness coupled with a dynamic and sustained heritage lobbying effort have resulted in the intact preservation of much of its original stone structures over the past 160 yr. The dock face has remained level over the ensuing century and local civil engineers have confirmed there is no subsidence in any area indicating the dock's relative stability. Consultations with Bermuda's chief land surveyor revealed just how stable this area of the Dockyard is considered. In 1963, the Directorate of Overseas (DOS) conducted an extensive leveling network survey of the Island and placed a rivet, set in the coping stone in the southwestern corner of the Dockyard slip, as the Fundamental Bench Mark (FBM) elevation for Bermuda adjacent to the spot that contained the original Island Works Tide Gauge from the 1800's. This rivet, presently buried under concrete, is in fact opposite the wall where we are assessing the shift in the black zone cyanobacteria.

The dock face in the 1870 photograph (Fig. 1) was determined to be an excellent canvas for measuring SLR in Bermuda, and it was decided to test if the movement of the upper supralittoral black zone line was a useful indicator of changes in sea level. As the initial working year/point, we selected the date of the earliest photograph to show the black zone, 1870 (Fig. 1). We theorized that if the level of the dock and slipway shown in this photograph had remained stable and the line on the dock was caused by continuous and consistent marine processes, then the black zone line could provide a firm identification of tide height in 1870 allowing for a comparison with the same line in 2007, when we first discovered the archival photographs.

In March 2007, a series of photographs of the same Dockyard area as shown in 1870 were taken to compare with the archival photograph. Comparisons between black zone upper line height on the dock face between 1870 and 2007 were initially analyzed by selecting a particular spot where the black zone line was sharply defined in the archival photograph and then taking a series of pictures of the same area in 2007. From the ensuing comparisons it was immediately evident that the upper limit of the black zone had shifted upwards completely engulfing an entire course or row of the stone making up the face of the dock. In 1870 there were five mortar lines, or rows of stone, above the upper limit of the black line and below the capstone of the dock face, and in 2007 there were only four (Fig. 3). From this rather superficial method, we were able to gauge a change in height of the black zone above the water and along the wall indicating a rise of approximately 33-41 cm in the intervening 150 years.

This initial measurement was compared with the IPCC predictions and the rates of SLR that we had assessed from other resources for the Bermuda project. The relative change in height of the black zone mark on the wall, if taken to be between 33 and 41 cm, averages at 2.4–3.0 mm/yr, at the upper end on par with the with the global average calculated by the IPCC of 3.1 mm/yr and at the lower end closer to the average observed by the St. George’s (Bermuda) Tide Gauge of 2.17 mm/yr (Fig. 4). Thus, we had produced a local rough estimate as to how the global phenomenon of climate change and its associated SLR had impacted Bermuda minimally in this particular location.

It was decided that the potential for black zone lines providing much needed evidence of local ranges and impacts of SLR on other coastal communities needed to be explored further prior to sharing the observation. A more precise analysis and understanding of the phenomenon would expand on our initial simple use of the line as a rough local confirmation of known rates of SLR. We therefore set out to assess whether black zone marks created under the same environmental conditions could be an indicator of sea level on the coast used to physically observe and communicate timescale change. In order to achieve this, we explored how to best describe and assess both the biology of the black zone mark and create a spatiotemporal model of the seawall to measure change in the black zone marks on the seawall at Dockyard over time. Our intent as outlined above was to increase the availability of this unique communication tool and hypothesize the potential usefulness of measuring coastal black zone marks over time as an actual gauge of local SLR on much shorter time scales than 150 yr.

The first evaluation was made in 2007 at the time of the discovery of the 1870 Dockyard photograph when a number of pictures of the wall and its black zone line were taken for comparison. This suited our initial exploratory assessment and communications purposes. However, by the time the full team came together to complete the analysis described here huge advances had been made in photographic data analysis and the functionality and availability of unmanned aerial vehicles, UAVs or drones, to complete high-resolution large-area photographic surveys. This allowed for the collection of 267 additional detailed images capturing the present condition of the entire seawall and surroundings. These images could then be methodically compared with the rescanned 1870 photograph. As part of this initial exercise, the pictures taken in 2007 were included as a distinct dataset, and upon quick comparison with the 2017 images, it was clear that in the intervening 10 years the black zone line had continued to shift upwards. This opened the possibility of comparing two high-resolution image sets taken ten years apart and assessing the potential to use cyanobacterial black zone upper margins to measure RSL change on a much shorter timescale. How the black zone forms and how this is tied to and reflects local structural and wider climactic and sea level conditions is material to testing the value of this idea.

1.2 The Black Zone in Bermuda

Throughout the world's oceans, the "black zone" of rocky intertidal environments is a stable community of cyanobacteria (blue-green algae) and often marine lichens that persists annually above the mean high water line (MHWL) in areas sprayed and splashed regularly by seawater (Lewis 1964; Stephenson and Stephenson 1972; Thomas 1985). In areas where the rocky intertidal is gradually sloping rather than a vertical face, the black zone can be extensive, covering wide areas, while on vertical surfaces the zone can be narrow and sharply defined as it is in this example at the Bermuda Dockyard. Rather than representing an average of the height of water on the dock facing at any time, the black zone community survives above the MHWL either by inundation with seawater in storms and spring high tides periodically throughout the year or by saltwater splash or spray for much of every lunar cycle by waters driven by wind or boat-produced waves. The species of cyanobacteria in the black zone live on, and in some cases burrow into, the limestone of many supratidal zones, particularly in tropical seas. Although there has been no extensive survey of the cyanobacteria that comprise the black zone in Bermuda, reports beginning after the turn of the 20th century listed over 30 species that were found on intertidal and supratidal rocks (Collins and Hervey 1917; Thomas 1985). Black crustose lichen species in the genus *Verrucaria* also occur in the black zone of Bermuda (Riddle 1918; Stephenson and Stevenson 1972), although they are not ubiquitous in all such areas within the islands. A recent look at the extent of species in the black zone showed this community is comprised of unicellular, colonial and filamentous cyanophytes that appear darkly pigmented in full sunlight due to their functional and protective phycobilin pigmentation. The species that live there, define distinct upper and lower boundaries, and thus are naturally produced, living evidence of tidal amplitude over time. Although these black zones are not caused by oil slicks settling on and staining marine walls, local folklore might think them caused by such pollution.

The microscopic cyanobacteria and macroscopic lichens that live within the black zone are subjected to widely varying conditions seasonally as well as daily, including desiccation, variation in water spray, splash or inundation, nutrient availability, frequent freshwater runoff and fluctuations in sunlight exposure and temperature. The species comprising the black zone are affixed to the rock substrate by mucilaginous sheaths (a polysaccharide matrix) extracellularly extruded through the outer membrane (De Philippis and Vincenzini 1998) and survive at times intense grazing activity when inundated by seawater (Stephenson and Stephenson 1972). For the attached forms living in the black zone, this hydrophilic matrix provides protection from desiccation of the cells during high temperatures especially when fully exposed to the atmosphere at low tide when the sun is at its zenith, but also during calm sea days with little atmospheric change, hence, little spray or wave splash. The mucilage is cement for stable attachment in this, at times, high-energy environment especially during storms and spring tides, a protection from being swept off the rock into the sea. The layer of cyanobacteria is often much less than 1 mm thick when exposed to air, swelling a bit thicker when inundated. Using their blue-green to black pigments, the cyanobacteria of the black zone can fully photosynthesize in periods of low tide, despite the intense radiation and heat they are subjected to daily for much of the year, in great part because of the mucilage sheaths that help them retain moisture when not inundated by seawater. In many species, there are pigments deposited in the mucilage as a protection from UV light (Dillon and Castenholz 1999), light that could otherwise severely affect metabolic processes and survival during low tide.

As is true of all of the marine biotic zones in Bermuda (Stephenson and Stephenson 1972), a change in the level of seawater would affect the ability of the organisms to survive the changing conditions. As sea level rises, the lower margin of the black zone would, over short time periods, decrease and eventually disappear due to biotic competition or herbivory by organisms that can now survive in the new upper intertidal zone or migrate twice daily to the upper reaches of the intertidal zone in search of food. Conversely, the upper margin would expand upwards approximately equal to the black zone loss in lower portions, now being sprayed higher by seawater, more frequently splashed and inundated by storm or spring tide waters. In both cases, such marginal shifts only occur over persistent change in the sea level, not daily shifts due to storms or high winds energizing wave action. As such, the black zone has migrated upwards in the 20th century reflecting a persistent rise in sea level over years and decades, as do all of the intertidal zones regulated by biotic and physical interactions in this extreme environment. Such zone shifts occur concomitantly with SLR as organisms cope or disappear from the margins according to their physical and competitive abilities. The black zone community in Bermuda today is no doubt substantially comprised of the same basic cyanobacterial community that was present in the supratidal 147 years ago, but it has shifted significantly higher due to the rising sea level in the intervening timeframe. This cyanobacterial community, therefore, provides a reliable biotic indicator of SLR. Growth factors that have remained biologically consistent over the recent biological history of the organism permit relative comparisons of its position on certain rock faces, such as the Dockyard, at different times in history and therefore can be accepted as accurate indicators of sea level change over time.

The south-facing dock and slipway in the 1870 photograph is oriented in such a way that 19th century boats could safely dock without encountering heavy wave action from wind or transient boat traffic. It is only exposed on its southern side to less than 50 m of the fetch that is framed by the opposite wall of the slipway. This area of water gets little anthropogenic- or weather-induced tidal accelerations. This accounts for the straight line formed by the cyanobacteria for nearly the entire length of the 100 m dock face that is neatly parallel to the top of the wall and the calm water below. The black zone on this south-facing wall is well nourished by water spray, and it is bathed with intense sunlight exposure. The horizontal line of the lower edge of the cyanobacteria in the black zone in this location accurately represents the meridional heat transport (MHT) level height for Bermuda, and the upper edge the approximate height of the spring high tides twice monthly. The design and orientation of this particular section of dock and slip make it perfectly suitable to evaluate the use of black zones as an indicator of SLR over time.

1.3 Bermuda Tidal Flux

Bermuda is an extremely remote island archipelago sitting atop a volcanic seamount arising steeply from the floor of the deep mid-Atlantic Ocean. As such this tiny island grouping generates limited geographically induced tidal factors and therefore exhibits a relatively limited tidal regime averaging 1.35 m (Stephenson and Stephenson 1972). Tidal waters in Bermuda do not approach the shore or accumulate in the same way they do on continental land masses such as the Atlantic Ocean coast of North America where the gradual rise in the continental shelf and the unbroken and variable continental barrier cause the tidal movement of water to accumulate to greater amplitudes and behave in a broad array of geographically unique ways that are not factors in Bermuda. The highest spring tide as a marker for sea level in Bermuda in any given year is therefore a reasonable reflection of the actual height of that mass of water coming towards and past Bermuda at that time. Bermuda's position in the mid-Atlantic, however, does expose it to larger ocean forces that can affect sea level amplitude and therefore the relative height of the tide in other ways. Bermuda tides in particular are subject to the effect of ocean fronts, maritime highs and lows, that move across the North Atlantic from west to east on nine month cycles that can, depending on their intensity, add or subtract significant height from Bermuda's tidal regime, up to 30 cm, sometimes for weeks at a time (McGillicuddy et al. 2007). In addition, spring tides are variable in their intensity depending in part on the moon's proximity to Earth such that on one particular cycle the lunar phase might add significant amplitude to a spring tide that may not be replicated or exceeded for years afterward even with rising sea level.

All of these variables, however, diminish over a longer timescale. Armed with an understanding of the biological processes that form and impact the black zone line, we are confident that our initial rough observations of historic sea level rise through the analysis of photographs taken 150 years apart reflect the change in SLR. The black zone line averages out these effects over time. Following this, could the cyanobacterial black zone be used to assess more recent changes in SLR over shorter timeframes, perhaps highlighting any acceleration that is presently taking place? Starting in 2017, we began recording the black zone line at the Royal Naval Dockyard in fine detail using digital imaging, data capture techniques in order to create a definitive baseline from which to model change over time.

2 Materials and Methods

2.1 Digital twin Creation

In order to identify and measure the change first captured by an archival photograph of the Bermuda Dockyard slipway, as well as create a correlation with current conditions captured in a new set of photographs, a spatiotemporal reference model of the target environment was required. This would allow for both the permanent documentation and archiving of data and the creation of a baseline for future study. As such, a digital twin of the seawall was constructed using UAV and still camera image survey data in combination with a distributed structure from motion (SfM) workflow, capturing seawall geometry and setting in respect to the surrounding environment, as it exists today. The digital twin allows the recreation of referenced objects in their real-world context within which to insert features, objects and additional models or data sets from a multitude of data sources. In this case data assets include photographs from different sources and time periods, some collected for the purpose of creating the detailed digital twin and others not collected for this purpose but containing features of interest captured in recent digital photographs and historic photographs. As part of the SfM workflow, intrinsic and extrinsic camera parameters were computed for each of the photographs contributing towards the creation of the final model, providing additional reference information that may be used towards the synthesis of photographic and other data assets as they emerge. The same workflow and baseline model were subsequently used for the synthesis of historic photographic records, assuming they provided sufficient resolution, correspondence and features, resulting in additional temporal 3D data layers, augmenting the baseline digital twin. Furthermore, the developed visual analytics framework allowed for the extraction of camera pose information for arbitrary viewpoints and as such supported visual co-registration of historic records for which features, resolution, sharpness, color, etc. were not sufficient for automatic alignment.

The spatiotemporal digital twin is currently based on multiple sets of image assets, including a high-resolution handheld photo survey of the seawall in 2017, a supplementary drone based aerial image set to extend the area covered, and a small image set from 2007 showing black zone coverage. The resulting SfM model is based on over 1,200 images, consists of dense point cloud with over 144 million points, as well as intrinsic and extrinsic camera parameters for all the contributing images, allowing the original images to be re-projected onto the point cloud using point-based data synthesis (Hess et al. 2015) and visual analytics techniques. Since the 2007 images were synthesized into the as-is structure from the motion model, they could subsequently also be reprojected onto the point cloud for analysis and comparison with the 2017 images. The approximate position and scale provided by the UAV's GPS was refined by adding constraints from the visible scale marker in the 2007 imagery. To co-register the historical 1870 seawall photo with the 3D point cloud, a prerequisite for taking measurements, first a high-resolution (23,000 x 12,000 pixel/in) ortho-projected reference elevation of the wall is generated from the as-is point cloud model. Horizontal boundary lines between blocks and the intersection line of the boat ramp floor with the wall were then found in both the reference and historical images (Fig. 5). Using these lines and other image features, such as the vertical block boundaries and horizontal block spacing pattern as guides, the historical image was then warped to match the reference orthoimage (Fig. 6). The resulting ortho-rectified image could then be draped back onto the point cloud using the projection already known for the reference image.

Other automated estimation procedures, using either detected or manually selected feature point correspondences yielded unsatisfactory results, possibly due to a paucity of sharp, unambiguous features in the historical image, or due to a mismatch between the imaging model for which parameters are being estimated for the actual historical camera that was used. This has motivated the exploration of alternative techniques, including optimization methods using line rather than point features, as well as subject matter expert supervised alignment techniques.

The user supervised co-registration varies in quality across the wall surface with vertical block boundaries coinciding in some parts, but offset in others, and horizontal boundaries approximately coinciding throughout, but is in general adequate to identify corresponding blocks between the reference model and the historical image, which allows us to make block-boundary-relative measurements in the rectified historical image, and then transform these by the known scale and position of the relevant block in the reference model.

2.2 Methods of Estimating Black Zone Change Across Image Sets.

The starting point was the perspective of the slipway dock wall in the 1870 photograph. Starting from the top of the wall, we noted a topmost single layer of dark blocks, the capstone, followed by five layers of lighter colored blocks, with visible horizontal boundaries separating the layers, and vertical boundaries separating blocks within each layer visible in some parts of the image, and blurred out or obscured in others (Fig. 6, red lines). No evidence of the black zone was seen in these lighter layers. Immediately below the first five block layers is a darker region, less clearly captured than the blocks above, and partially occluded by boats on the left (shallow side) of the ramp. For this analysis, we assumed that the black zone is within this darker region, and that the upper margin of the black zone coincides with the region's upper boundary.

To estimate the waterline, which is not visible on the dock wall, the visible ramp waterline was extended to intersect the ramp slope line (diagonal purple line, where the wall and the ramp meet), yielding a point on the wall that is at the water level. A reference line was then extended from this point and (roughly) parallel to the horizontal block boundaries above (as a proxy for 'level') to give a rough estimate of the wall waterline (Fig. 6, blue lines).

Using the modern-day digital twin, the overall geometry of the dock wall can be inspected. In cross-section, we see that the portion of the wall composed of the lighter blocks is roughly flat, and that it is lightly sloped, rather than vertical, with the topmost darker block, or capstone, faces being distinct from the others and closer to vertical. Next, estimated poses and intrinsic camera parameters, from the 2007 images, were used to reproject and drape them onto the more detailed and robust 2017 digital twin geometry to verify alignment and scale. It was observed that in a map view, the wall is not straight, but rather arcs outward toward the bay, however, this did not significantly affect the analyses presented here.

The horizontal boundaries of the dock wall blocks in both the 1870 2D image, and the 2017 3D site model were then digitized, and we manually placed line segments to coincide with the visible boundaries in the 2D image and the 3D point cloud, visually reviewing any deviations along the digitized lines. In the 3D case, deviations from linearity could have arisen due to reconstruction errors, or due to real-world boundaries actually not following straight lines. The resulting deviations were evaluated in a parallel-projected elevation view, showing that the digitized lines follow the boundaries reasonably well, staying within mortar joints between the blocks (which are generally 1–2 cm wide). In 2D, non-linear distortion in the 1870 photograph were not corrected and some deviation from linearity were seen and expected. To reduce the impact of these deviations across data sets, the region of the wall with modern coverage (for which linearity is a reasonable local approximation), were prioritized, showing that the digitized lines generally fall within the footprint of the visible boundaries (Fig. 6). As an additional check, the relative spacing of the boundary lines were computed, top-to-bottom, for both the 2D and the 3D line sets, and showed that the relative spacings match to within 3% between them.

The black zone margins in the 1870 image, the 2017 model, and within the 2007 images were then digitized and projected onto the 2017 geometry. For the 2017 3D model, the upper margin of the black zone (Fig. 5, green) was digitized, using draped original photographs for reference, and noted that neither margin appears to be level, with both increasing in altitude from left to right (shallow-to-deep). For the reprojected 2007 photographs, the upper margin was digitized (Fig. 7, purple line).

For the 1870 image, the darker lower region of the wall, presumed to contain the black zone, begins at or near the bottom boundary of the lowest lighter block layer. This block boundary, though digitized with reference to relatively few visible block edges, is consistent in terms of vertical spacing with the corresponding boundary in the modern 3D model. Since it also plausibly separates the lighter blocks above from the darker region below, we assumed that it happens to coincide with the black zone upper margin (Fig. 7, yellow line); note that the visual evidene, or rather the relative lack thereof in the relevant part of the photograph, does not exclude other plausible nearby upper margins, similar to that observed in 2017.

Finally, the relative upper extent of the black zone upper margins within the context of the 2017 site model was meassured. Transferring the black zone margin from its 1870 position on the wall to the 2017 model is particularly simple given that it coincides with a digitized block layer boundary (Fig. 7, purple line).

3 Results

Changes in the upper-level height of the black zone line over 147 years are in keeping with documented changes in global and local sea levels and the increasing global rate of SLR, which has almost doubled from 1932 to 1990, from 1.7 to 3.2 mm/yr (Church et al. 2013; Stocker et al. 2013; Clark et al. 2015; Nerem et al. 2017). According to our analysis the upper cyanobacterial line at the Royal Naval Dockyard slipway has moved 31.2 cm upwards from 1870 to 2007, and an additional 8.8 cm from 2007 to 2017 for a total of 40 cm from 1870 to 2017. The Bermuda Tide Gauge data managed by NOAA shows an average annual SLR rate of 2.17 mm from 1932 to 2019 (Fig. 4; NOAA 2020 https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=2695540).

The distance of 31.2 cm between black zone lines at the Dockyard in 1870 to 2007 yields an average shift of 2.28 mm/yr, 5% above, but close to the Bermuda tide gauge data average SLR rate of 2.17 mm calculated at the Bermuda tide gauge. The distance between black zone lines at the Dockyard from 1870 and 2017 is 40 cm, an average shift of 2.72 mm p/yr., and 25% higher than the 2.17 mm average. The increase can be attributed to the upward shift of 8.8 cm we documented between digital photosets taken in 2007 and 2017. This represents an average upward shift of 8.8 mm/y over ten years, 305.5% higher than the average annual SLR rate of 2.17 mm calculated by NOAA at the Bermuda tide gauge.

4 Discussion

Through the comparison of historic and recent photographs, we have demonstrated that cyanobacterial indicators of the black zone in Bermuda offer a stable, yet adaptable, biotic community to understand recent SLR consequences *in situ*. It can be useful for interpreting the local effects of regional and globally predicted SLR allowing adjustments to SLR models and action plans accordingly for more local circumstances.

The application to Bermuda of the IPCC 2013 prediction of 51 cm by 2100 (Stocker et al. 2013) has certain limitations because it represents an average of a prediction that leaves the regional variability unaccounted for. Bermuda may experience a regional sea level rise 1–30% above the global mean (to as much as a 67 cm increase), and this should be considered conservative as the most recent IPCC 2019 Special Report on the Ocean and Cryosphere in a Changing Climate reports accelerations in the annual average rate of SLR to 3.6 mm p/yr from 2006 to 2015 (Oppenheimer, 2019). The average rates of SLR from 1870 to 2007 and 1870 to 2017 suggested by our research is significantly lower than 3.6 mm/yr but comes close to matching the 2.17 mm average documented by the St. George's tide gauge data from 1932 to 2020 (Church et al. 2013; Clark et al. 2015; Nerem et al. 2017). The 2007 to 2017 increase in SLR of 8.8 cm as indicated by the black zone line, suggests a sea level rise rate of nearly 9 mm/yr. This is inconsistent with the average of the data collected at the St. George's tide gauge over that same time period and while it also exceeds the most recent IPCC 2019 GMSL calculations of 3.6 mm/yr between 2006 and 2015 it does correspond with the significant acceleration represented. The 2007 to 2017 increase also coincides with the St Georges Tide Gauge measuring the highest monthly mean sea level ever recorded in Bermuda since it was deployed in 1932. The shift observed in the black zone line over a decade beginning in 2007 has acted a reliable indicator in the shorter term of the highest tides recorded. In addition, it may allow some insight into how changes in sea level express themselves. If Bermuda is experiencing an average SLR rate of 2.17 mm/yr using the St Georges Tide Gauge average then our measure of a change in the black zone line of 8.8 cm at Dockyard from 2007 to 2017 suggests a local impact factor, in the calmest conditions, 6.6 cm over the anticipated increase of 2.17 cm. If we use the most recent estimation of GMSL calculated from 2006 to 2015 of 3.6 mm p/yr (IPCC 2019) then our measure of change in the black zone line is 5.2 cm or 144.4% above the anticipated increase.

Our analysis has clear limitations. We have used a photogrammetric methodology to test the value of rigorously documenting shifts in black zones but our comparisons remain largely observational in their quality. This rigorous observation has substantially refined our initial rough estimate of changes in the black zone line from an estimated average SLR rate of 3 mm/yr from 1870 to 2007 to 2.28 mm/yr much closer to the Bermuda tide gauge data of 2.17 mm/yr. Black zone lines over the longer timescale can reflect real verifiable local and global changes in SLR.

The impact of SLR is not limited to its average extent, but rather how it presents itself locally at the uppermost range of the tidal reach. In this domain, comparative assessments of black zone lines for shorter timeframes may have another function in documenting, assessing and anticipating dangerous episodic tidal impacts. Averages may mask significant trends in changing amplitudes that can also have significant effects, with episodic extreme tide driven coastal flooding occurring more frequently and with greater penetration moving them above “nuisance” thresholds (Sweet 2014). In fact the most noticeable impact from SLR is the increasing frequency of high tide flooding (Sweet 2019). Additionally, it is important to remain open to the possibility that an anomaly may express the start of acceleration or a “new normal”. Amalgamating long data sets to express annual SLR average rates could mask more recent shifts and significant accelerations in SLR.

The in-depth assessment of the cyanobacteria black zone line today, using digital photogrammetry, also allowed us to capture, with intent, a baseline that will allow for detailed comparative temporal measurements in the future that could provide more accurate and perhaps much shorter SLR comparisons going forward, and importantly could highlight any new or sudden shifts or accelerations in SLR. The use of cyanobacteria biological markers when captured using photogrammetry also offers the potential to develop a low-cost protocol for monitoring SLR that can be rapidly applied in many jurisdictions. Tailoring or interpreting SLR models to suit specific local circumstances will be critical in adapting and managing the effects of rising sea level. Other biological markers for climate change could exist. Recent use of video footage of roadside growth in Belgium gathered by chance over 30 yr while filming an annual bicycle race showed significant roadside changes in leaf-out and flowering that could be linked to climate shifts, demonstrating both the analytical and communications value of highly local imagery when used to assess and communicate climate change (DeFrenne et al. 2018). We anticipate that all coastal areas will require in depth analysis of regional recent past and current SLR. Developing an understanding of more recent sea level rise patterns and the varying degree and impact of rising seas in different coastal contexts is especially important in Bermuda as any increase in sea level is compounded by the effects of extreme weather events, hurricanes, that greatly amplify the regular impact of any incremental rise in sea level.

Perhaps the most significant value of identifying the black zone as an interpretive tool for SLR is in its explanatory power. The elucidation of highly visible, clear, site-specific indicators of recent historic examples of SLR data could be very effective in communicating the need to implement intelligent policies and take immediate action to mitigate the effects of SLR now and in the future.

Declarations.

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Conflict of interest/competing interests

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Data Statement

Historic Imagery used in the article is available from the Bermuda Archives. Imagery and data collected and used for Photogrammetry to create the digital twin of the slip wall at the Dockyard will be made available on the Bermuda 100 website as an interactive model - http://bermuda100.ucsd.edu/ - and the baseline data set can be made available upon request.

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Figures and Captions

Figure 1. Archival photograph of the Royal Naval Dockyard in Bermuda 1865/1870, view of Commissioners house and slip.

Figure 2. View of the Royal Naval Dockyard Slip and Commissioners house in 2017.

Figure 3. Close-up of the 1870 photograph showing the upper limit of the black zone line with 5 mortar lines and the matching image in 2017 clearly showing only 4 mortar lines.

Figure 4: Tide Gauge St. George's 1932–2020.

Figure 5: Reference ortho-image of the 2017 dock wall image set with horizontal block boundaries and ramp marked in red.

Figure 6: Reference ortho-image of the 1870 dock wall image with horizontal block boundaries in red, upper extent of black zone in yellow and water level at wall and ramp marked in blue.

Figure 7. Black zone line progression left to right: 2017 green line, 2007 purple line, 1870 yellow line, with ortho-measured differences between levels displayed in upper right box.

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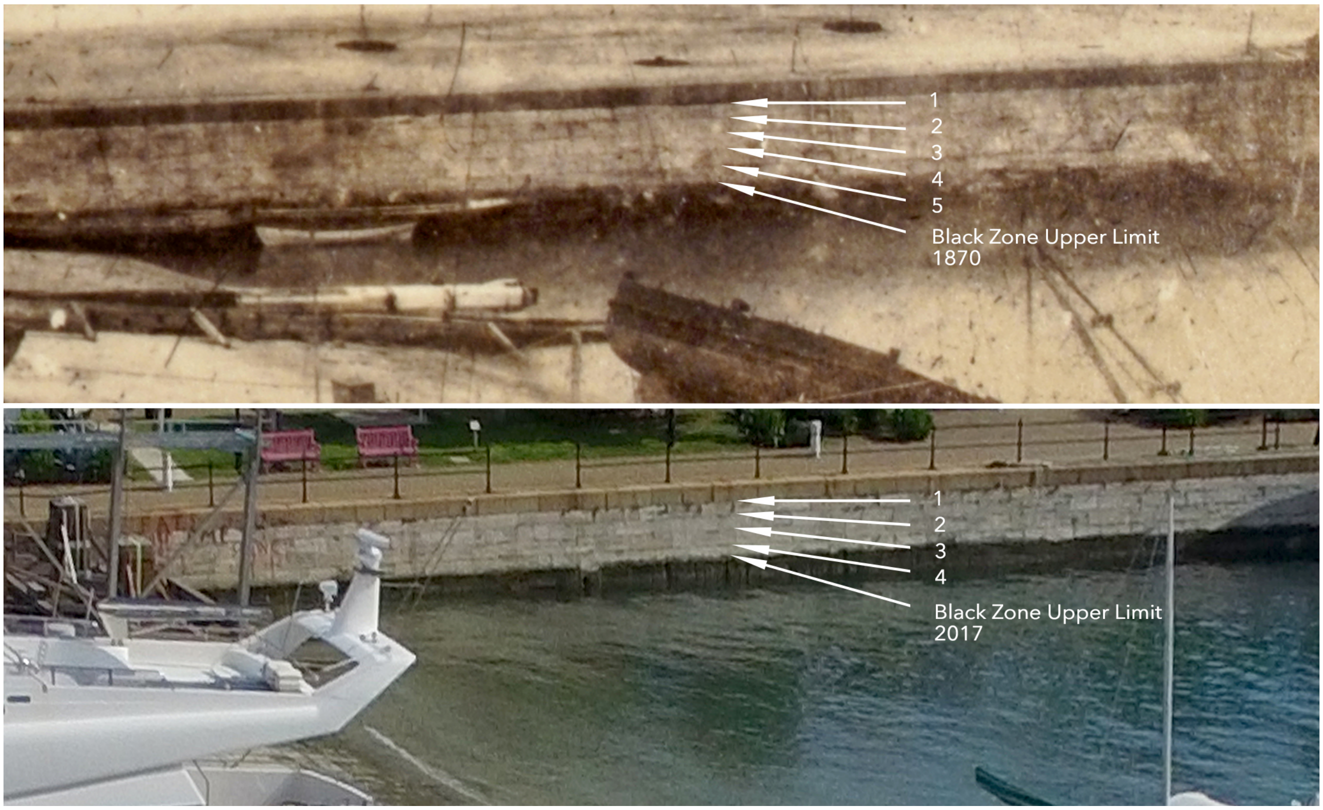

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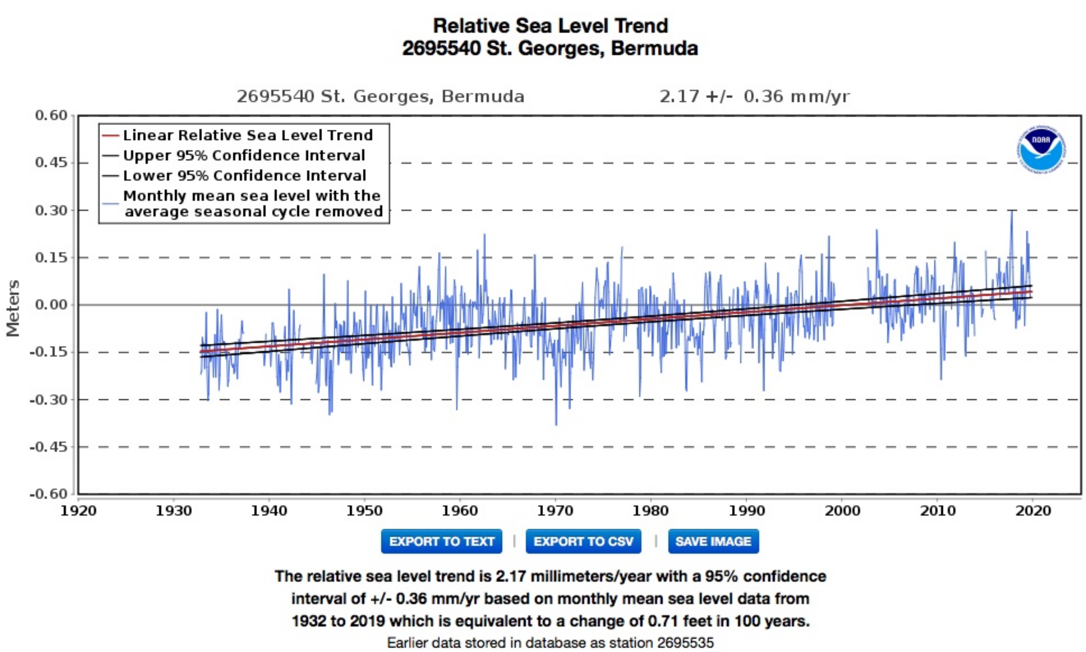

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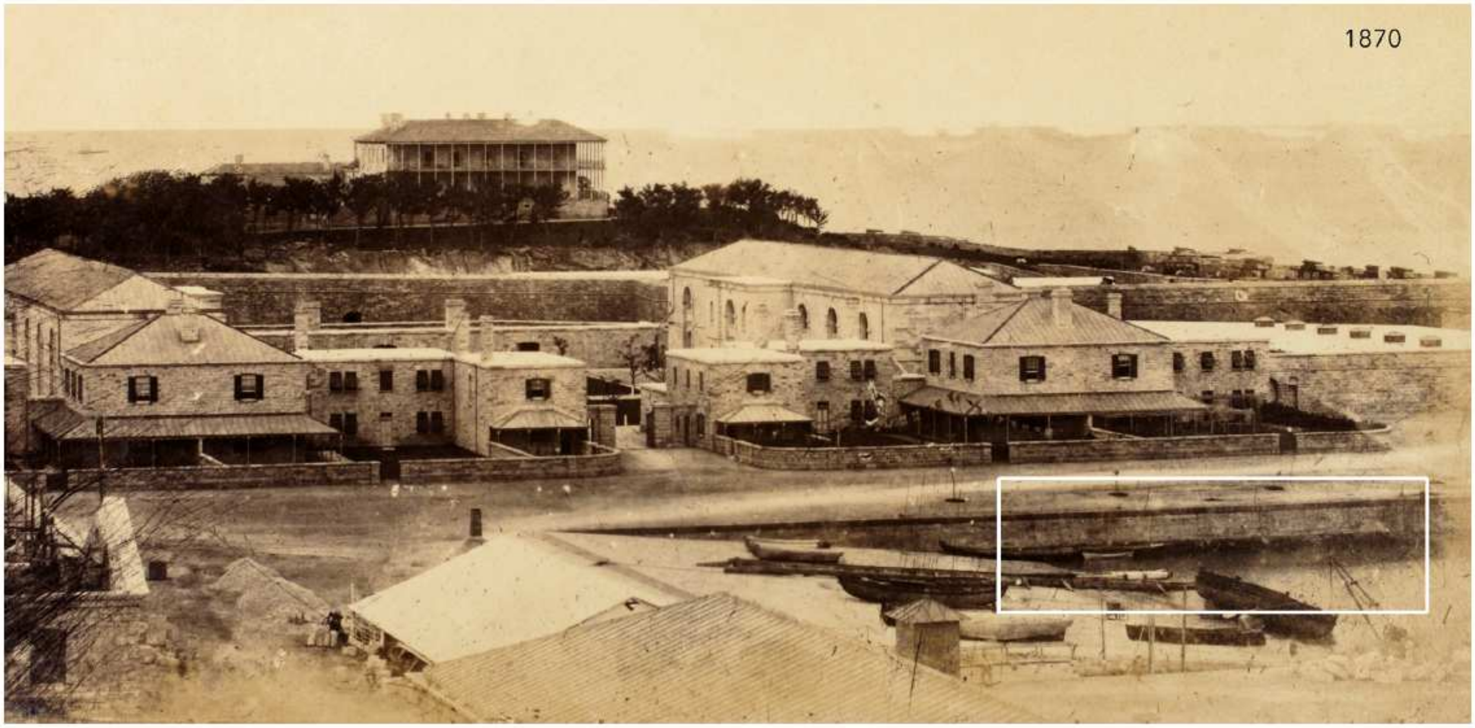
Figures



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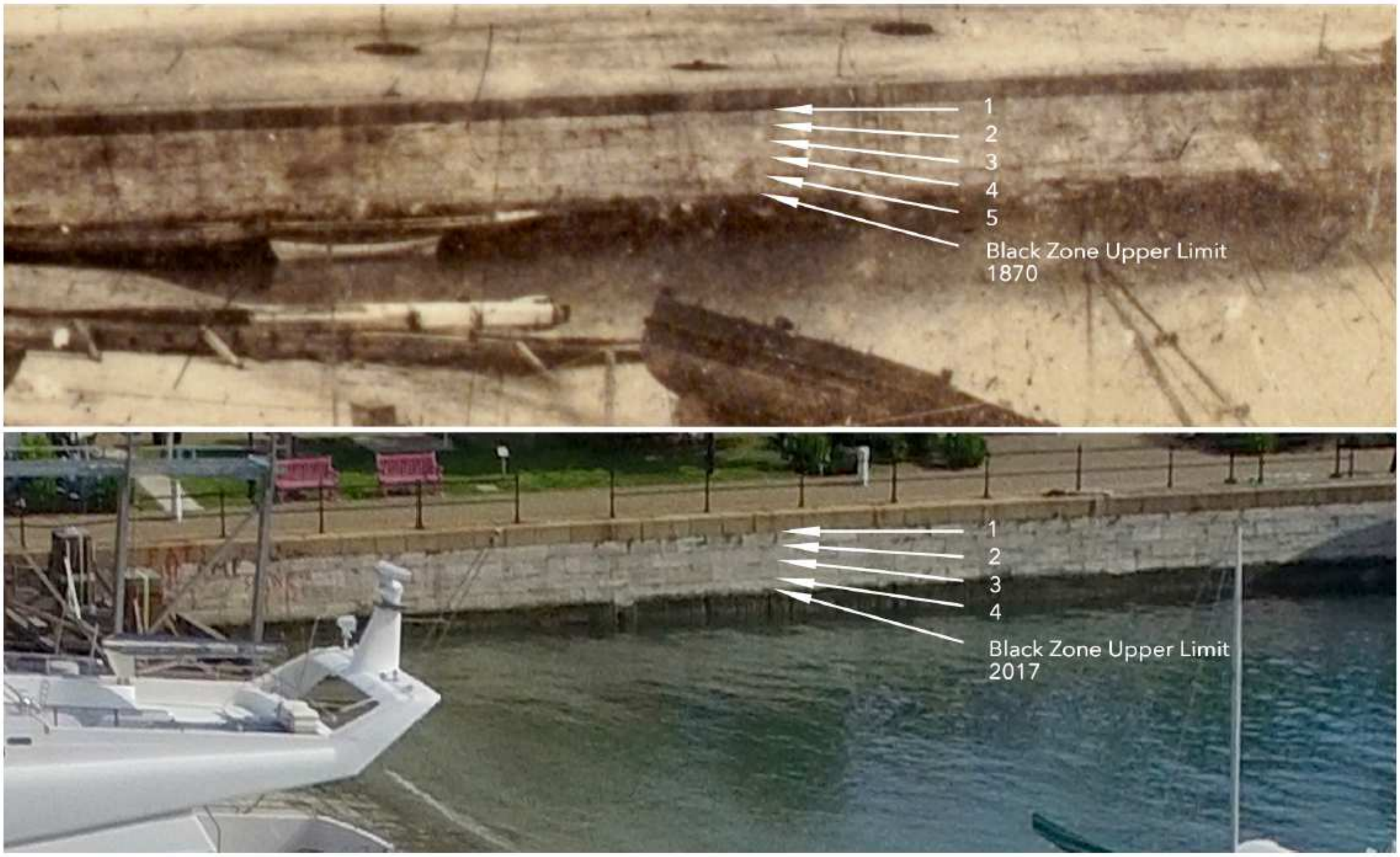

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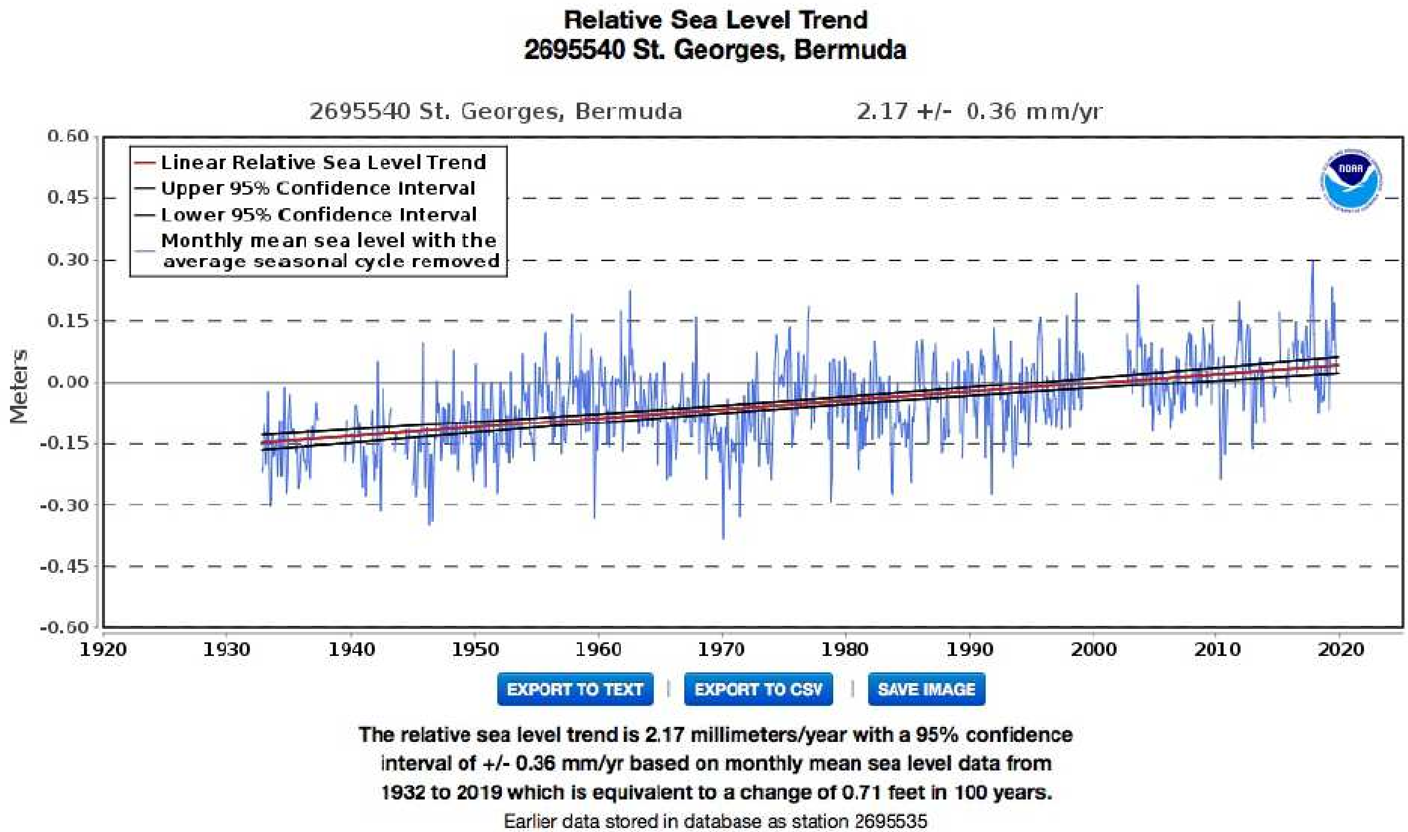

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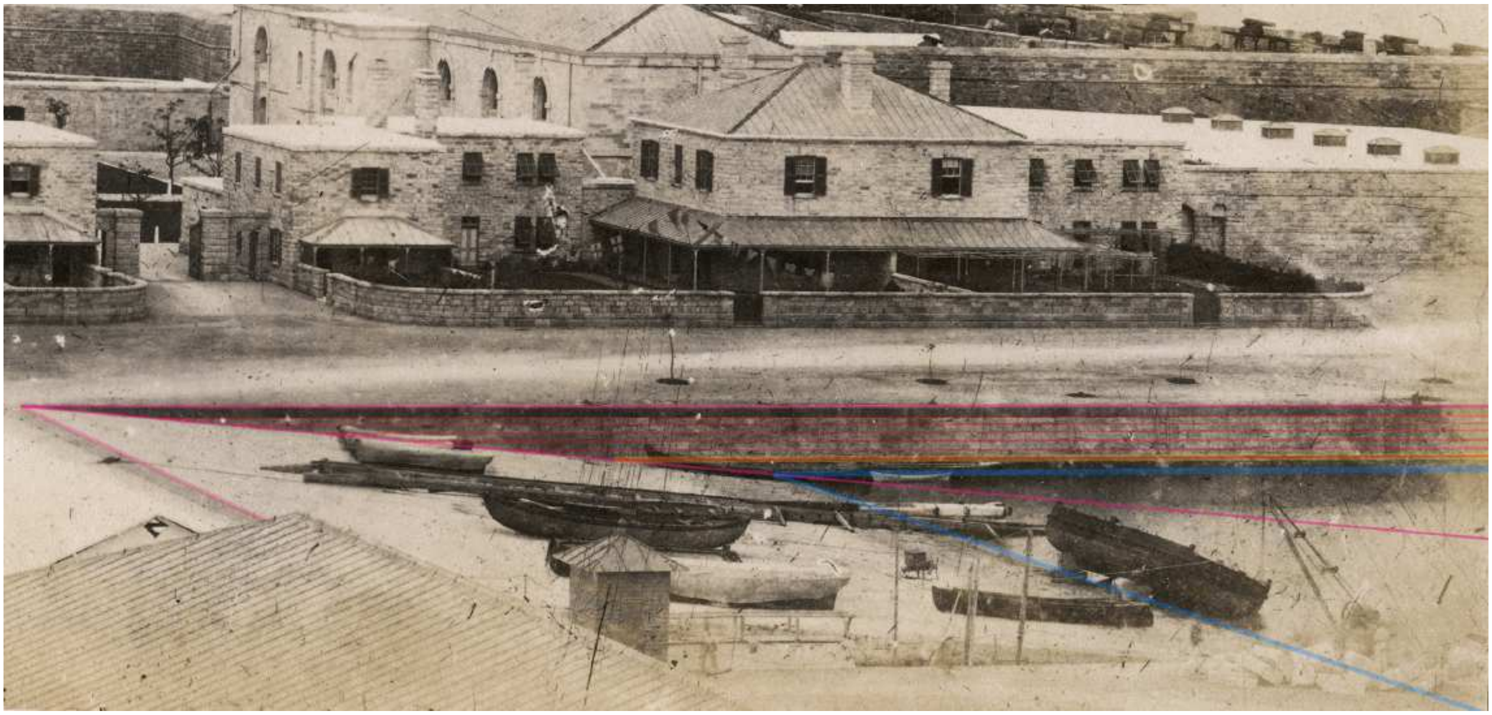

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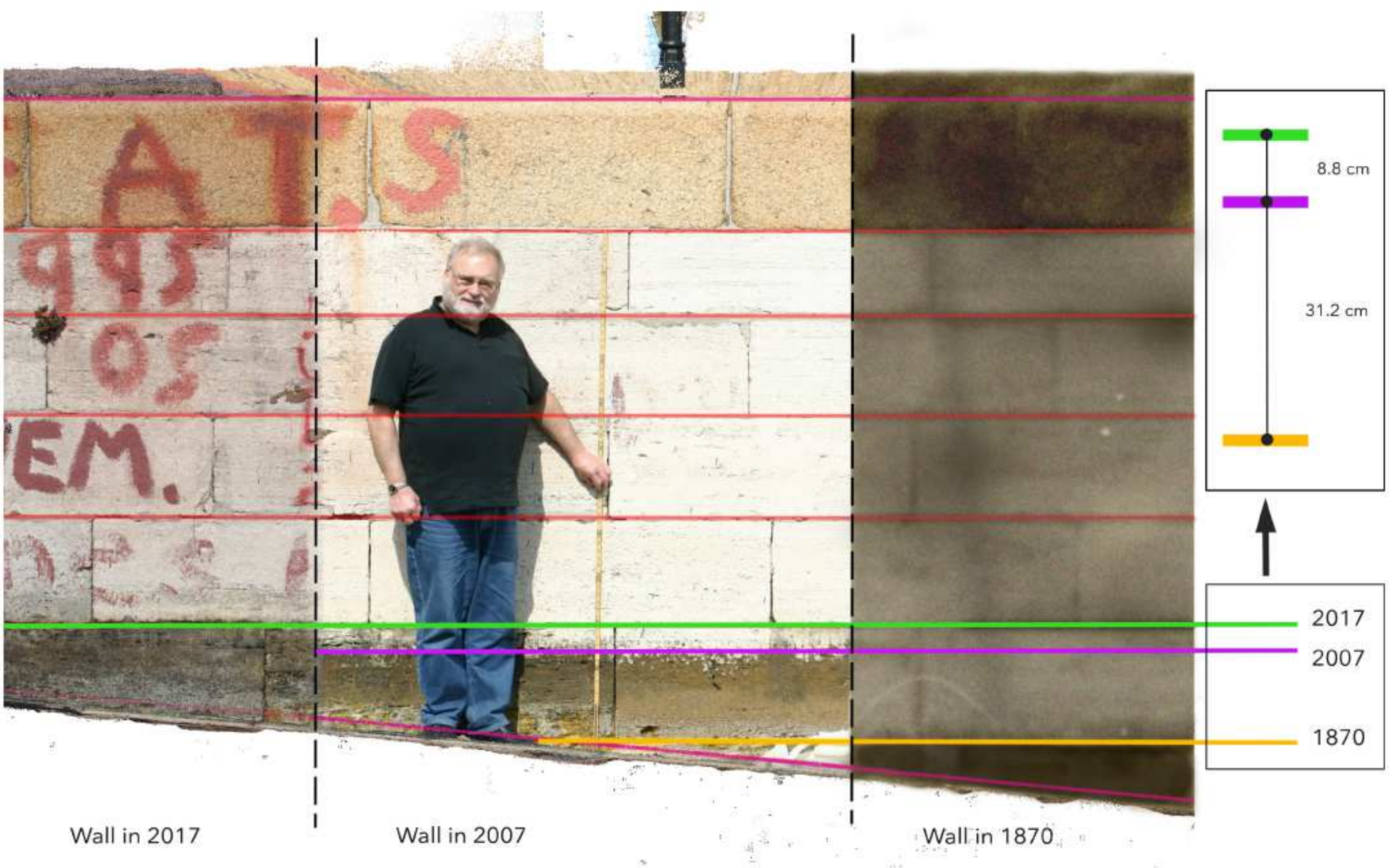

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