REVEALING THE GEOMORPHOLOGIC IMPACTS OF HURRICANE IAN IN SOUTHWEST FLORIDA USING GEOSPATIAL TECHNOLOGY

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ABSTRACT:

Geospatial data were used to analyze changes to geomorphology of barrier islands and beaches in Southwest Florida resulting from Hurricane Ian in late September 2022. The hurricane generated high intensity winds and storm surge causing more than $112 billion in damages, along with massive sediment mobilization due to erosion and deposition. This study quantified net sediment loss and gain on specific barrier islands by storm surge (Sanibel, Naples, Fort Myers Beach, others, though this paper focuses exclusively on Sanibel) by comparing pre- and post-Ian topography generated by a drone-flown LiDAR sensor; changes in elevation were used to quantify spatial variation in sediment volume. Data were collected immediately after Hurricane Ian and compared against topographic data collected by NOAA in 2018. Digital elevation models (DEMs) were used to compare topography, shoreline positions (relative to Mean High Water), foredune position, and volumetric changes using GIS technology. In general, the shoreline position after Ian changed little, indicating that the incoming surge had little influence on the beach. The foredunes, however, were deflated and set back by surge overwash. The outgoing surge created a much more dramatic geomorphologic change. Erosional surge channels cut through the foredunes and upper beach berm along many regions of the coastline. The ebb erosion also caused extensive damage to physical structures when located immediately behind the foredune. Lastly, this work demonstrates the value of employing GIS and remote sensing technology to problems of beach and dune management, the restoration of coastal ecosystems, the enhancement of resilience capacity of both natural and developed infrastructure, and the development of new policy needed to contend with the effects of climate change.

1. INTRODUCTION

As the effects of climate change are perpetuated, coastal communities will be forced to contend with ever worsening conditions that negatively impact habitability, economics, and cultural heritage. Atmospheric and sea surface warming cause sea-level rise (SLR) rates to accelerate, through glacial ice melting and thermal expansion of liquid water, and storms, particularly tropical cyclones, to become more impactful. Tropical storms are likely to: intensify more rapidly (e.g., higher winds and storm surge; Balaguru et al., 2018; Knutson et al., 2021), have slower forward trajectories (Kossin, 2018), be larger in size, and deliver greater precipitation (Knutson et al., 2021). SLR exacerbates tidal flooding by placing storm surge and wave setup on top of a higher sea surface. Most coastal communities across the planet are assessing their vulnerabilities to these effects and are developing and implementing plans to enhance their resilience capacities.

Florida's vulnerability is particularly great. Florida boasts of its extensive coastline. Thirty-five coastal counties account for 825 linear miles of coastline bordering the Gulf of Mexico and the Atlantic Ocean (EDR, 2015). The State's economy depends heavily on its coastal environment. Florida's beaches and estuaries draw 19 million visitors annually (EDR, 2015). Most of the State's population resides along the coast and provides the services needed to foster its ecotourism. State government has made resources available to bolster coastal resilience through its Department of Environmental Protection's Office of Resilience and Coastal Protection and the competitive funds it provides local communities. It is, however, up to local government, municipalities and counties, to address their particular resiliency needs. This has left smaller jurisdictions disadvantaged, lacking the staff or the private and academic partners to develop foresightful and effective strategies. Having relatively inexpensive and effective methods to assess vulnerabilities is therefore essential.

On September 28, 2022, Hurricane Ian made landfall in Southwest Florida, severely impacting Lee and Collier Counties (Figure 1). The storm was responsible for at least 156 deaths and over $112B in damage to property and infrastructure (Bucci et al., 2023). Storm surge was particularly impactful; surge heights measured 3-4.6m along Fort Myers Beach and 1.8-2.7m along the length of Sanibel Island (Bucci et al., 2023). Despite its ravaging effects, the storm's impact on the coastal geomorphology provided insights for the region's vulnerability and resilience capacity. The hurricane provided valuable lessons with respect to storm processes and its differential effects along the reach of the two-county coastline. These processes and effects are currently being studied by our team at Florida Gulf Coast University's Water School, and we are sharing those insights to facilitate future planning by 3 city governments: Sanibel Island, Fort Myers Beach, and Naples. Remote sensing technologies (UAV-based LiDAR data collection) were employed to quantify the geomorphologic effects and to infer the processes responsible. In this paper, we demonstrate how remote sensing technology can be used to quickly assess change in geomorphology and inform management decisions concerning resilience. The data herein focus on the impacts to Sanibel Island, a municipality that is actively engaged in the work and one that is utilizing the results for restoration.

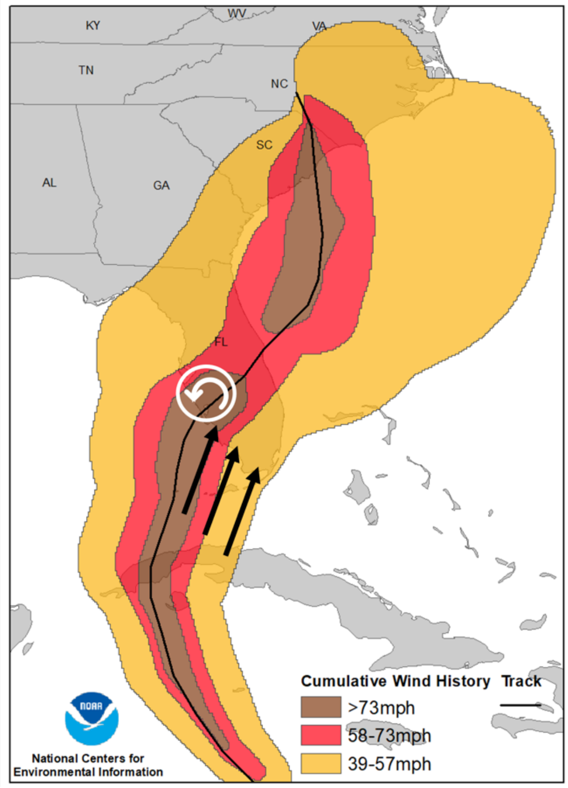


Figure 1. Hurricane Ian's path and wind field, showing counterclockwise rotation (white circular arrow) and direction of surge (black arrows). Modified from NOAA.

2. METHODOLOGY

The methodology employed follows a logical path (Figure 2) beginning with LiDAR (light detection and ranging). LiDAR is a technique which sends light in different wavelengths from a sensor, and based on the time and distance traveled by the returning light, elevations are acquired (Disney, 2019). Elevation data were collected following Hurricane Ian, starting from October 2022 and continuing through June 2023 using a Velodyne HDL 32B LiDAR infrared sensor onboard an unmanned aircraft.

Pre-Ian elevation data for our study area were downloaded from the National Oceanic Atmospheric Administration's (NOAA) Digital Coast Data Access Viewer (https://coast.noaa.gov/dataviewer/#/) as Digital Terrain Models (DTMs), or more commonly known as Digital Elevation Models (DEMs), with a spatial resolution of 0.5 m. The most recent data available from the NOAA website were from 2018. There were no significant storms from 2018 until Hurricane Ian impacted the Southwest Florida region. Hence, we can assume the 2018 elevation represents the pre-Ian elevation. All the data were then brought to a common vertical datum - NAVD88 (North American Vertical Datum of 1988) in meters.

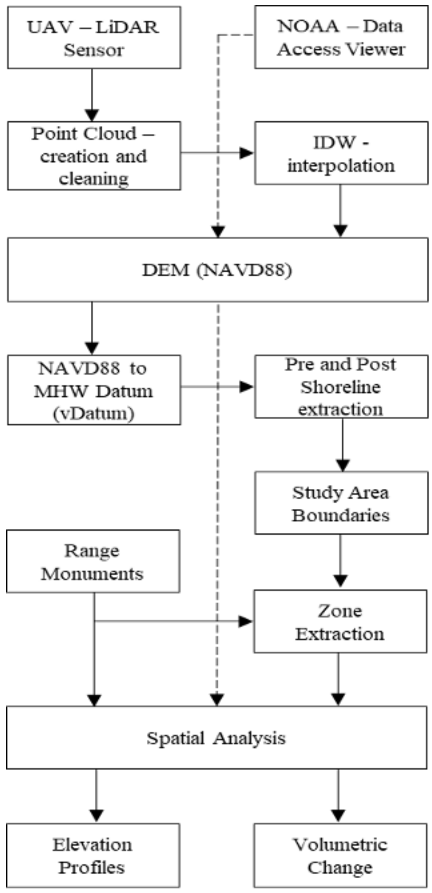


Figure 2. Flowchart showing the methodology adopted using ArcGIS Pro (ESRI) software to delineate shorelines and quantify volumetric changes.

The point clouds ("las" files) were cleaned using classification tools such as Classify LAS Ground, Classify LAS Noise, among others, and integrated with post Ian images collected by NOAA using ESRI's ArcGIS Pro software. Only the classified ground points were used to convert the elevation points into a digital elevation model using an inverse distance weighted interpolation technique since it is optimal for creating raster datasets from point clouds (Gares et al., 2006; Houser et al., 2008; Halls et al. 2018). This DEM was created with a spatial resolution of 1 m. The pre-Ian DEM was then aggregated to the common spatial resolution of 1 m, since this is in the ideal range for estimating volumetric changes of coastal features (Woolard and Colby, 2002; Halls et al., 2018).

The aggregated DEMs were converted from NAVD88 to Mean High Water (MHW) Datum using NOAA's VDatum

(Vertical Datum Transformation) software (https://vdatum.noaa.gov/). Elevation at 0 m for MHW Datum was used to delineate shorelines from DEMs derived from LiDAR data (Houser et al., 2008). Contour lines were created at 0 m elevation for the pre and post Ian DEMs. In some areas, the shoreline was not continuous, so a buffer of +/- 0.1 m was used to adjust for the shoreline discontinuity (-0.1 m and 0.1 m chosen as it is the smallest accuracy measure offered by the LiDAR sensors used to collect data). In rare cases, to find a proper connectivity between the shorelines, a least-cost path approach (Mitasova et al., 2011; Hardin et al., 2012; Wernette et al., 2018) was utilized.

This process gave seamless shorelines for pre- and post-Ian DEMs. Study area boundary was chosen based on certain criteria. For landward study area boundaries, sturdy structures such as roads and buildings, extent of an ebb surge channel, or a lagoon or waterbody were used to draw the polygon boundary. For seaward study area boundaries, whichever shoreline was the most landward was traced to complete the study area polygon. This eliminated the chances of any discrepancies in the volumetric change calculations. The study area boundary was used to clip the DEMs. The R monument data were imported into ArcGIS Pro software to create lines, both landward and seaward, based on the azimuth angles established by Florida Department of Environmental Protection (FDEP). These lines were then used to create inter-monument cells within the study area boundary. Each cell was labeled based on the ascending order of R monuments. These boundaries allowed analysis to be further divided by smaller segments of the beach. To calculate change in volume per pixel, pre-Ian DEM was subtracted from the post-Ian DEM. The new values were then used to calculate change in volume within each zone using a zonal statistics tool (i.e., a “cut and fill” analysis).

Elevation profiles were created along R monument lines for pre- and post-Ian DEMs and plotted.

3. RESULTS

Four regions of Sanibel Island can be delineated based upon differential impacts of Hurricane Ian. From west to east, they are: Santiva, Bowman’s Beach, Tarpon Bay Road Beach (TBRB), and Sanibel East (Figure 3). TBRB and Sanibel East experienced substantial erosion with numerous erosional channels cut across the dune field and beach (Figure 4B). This erosion developed more significantly on TBRB relative to Sanibel East. Santiva, at the western end of the island and adjacent to Blind Pass, experienced significant foredune deflation and set back but lacked channel erosion. Finally, Bowman’s Beach, a geomorphologically unique section of the island, bolstered by a multiple ridge and swale strandplain, remained relatively unchanged.

Comparisons of the pre- and post-Ian DEMs illustrate the storm’s geomorphologic effects. Pairs of DEMs are shown for portions of TBRB and Bowman’s Beach (Figure 4) as these two regions reacted most differently from one another. At TBRB, within the post-Ian DEM, the erosion channels are numerous, relatively wide, and crosscut the foredune ridge and upper beach (Figure 4B). Smaller tributary channels coalesce, and channel width increases from north to south in the seaward direction, collectively forming a drainage pattern that moved storm surge seaward. Base elevations within channels deepen seaward, also suggesting the ebb (return tide) surge current was responsible for erosion rather than the flood (incoming) surge.

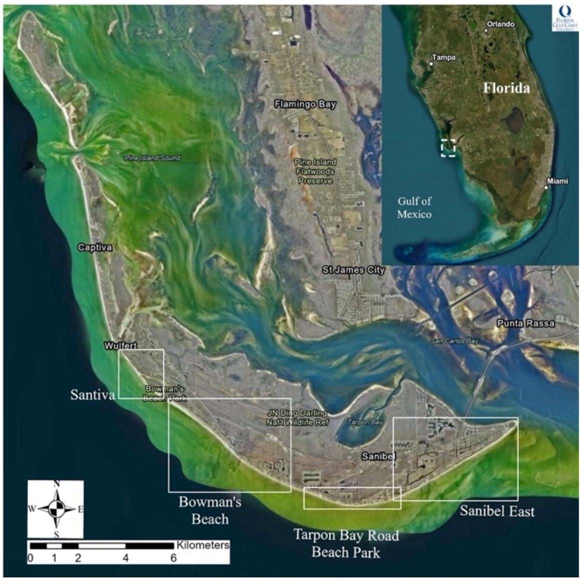


Figure 3. Study area showing location of Sanibel Island with respect to southern Florida (inset map). Four geomorphologic areas denoted in red: Santiva, Bowman’s Beach, Tarpon Bay Road Beach, and Sanibel East.

In contrast, Bowman’s Beach lacks erosional surge channels (Figure 4D). The pre- and post-Ian DEMs are very similar. The only obvious change is a slight reduction in elevation of the foredune. The pre- and post-storm beach profiles that were extracted from the DEMs show the unchanged nature. The positions and elevations of the ridges and swales across the strandplain are similar. Only the height of the foredune (i.e., the seaward-most ridge) exhibits deflation (Figure 5).

The mapping of the shoreline positions (herein defined as the contour representing Mean High Water [MHW]) further reveals the relative impact of the flood and ebb surge. Virtually everywhere in Southwest Florida, the shoreline position after Ian either shifted seaward or remained unchanged. This can be seen at TBRB on Sanibel (Figure 6). Here, and elsewhere on Sanibel, the shoreline extended seaward – the beach effectively widened. While there was net sediment loss associated with the foredune and the ebb surge channelization, the rest of the beach remained intact. Tide and wave setup was so high on the incoming flood surge that the beach remained unaffected while the foredune deflated and experienced overtop, landward erosion. The ebb surge, however, returned at a lower height, empowering the surge velocity to channelize the dune field and upper beach.

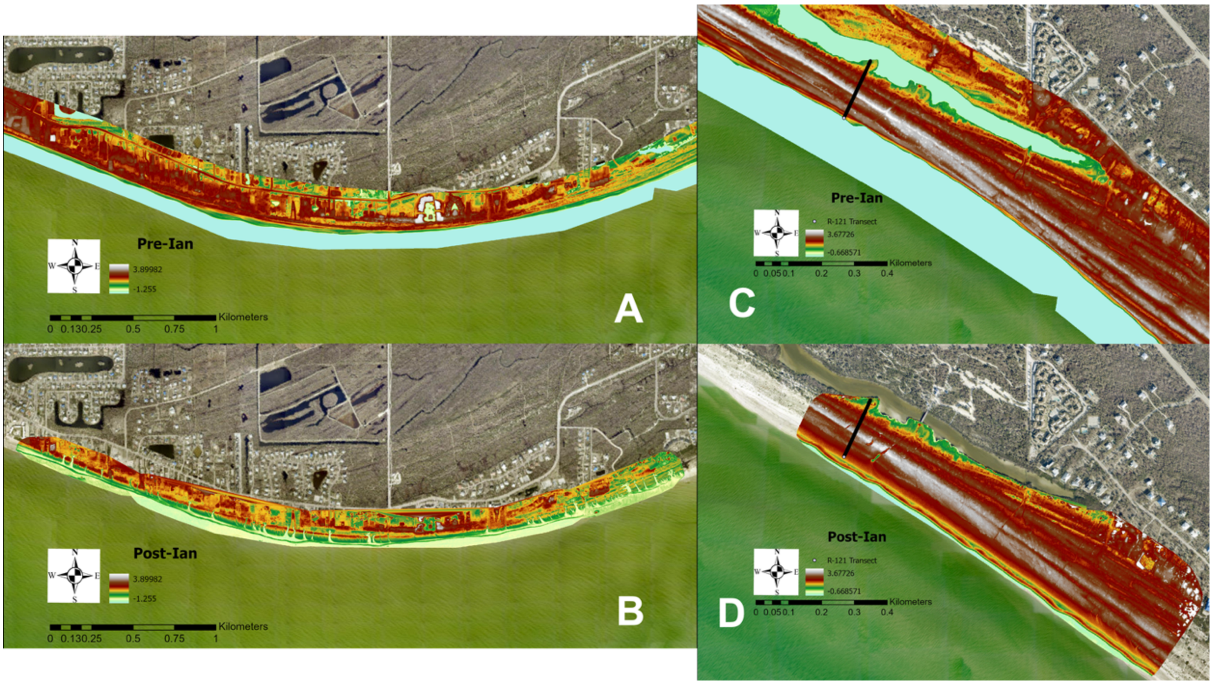


Figure 4. Pre- (A,C) and post-Ian (B,D) DEMs for Tarpon Bay Beach Road (A,B) and Bowman's Beach (C,D). Color contours show elevation in meters above NAVD88. Parts C & D show position of the extracted beach profiles shown in Figure 5.

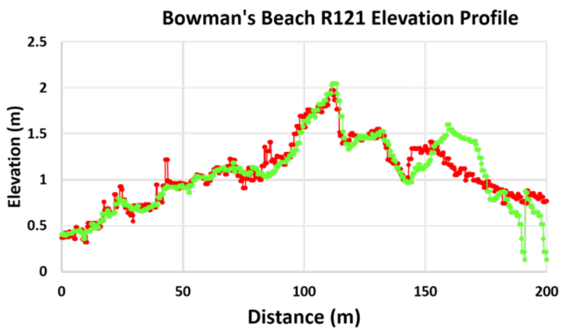


Figure 5. Beach profiles extracted from the Bowman's Beach DEMs located at monument R121 (location noted in Figure 4 C,D). Transects run from landward (at 0 m) to seaward (at 200 m); pre-Ian profile is in green, the post in red. Elevations in meters relative to NAVD88.

Cut and fill analysis allows the quantification of the relative effects of flood and ebb surge on each region's sediment budget. A comparison of sediment budgets between TBRB and Sanibel East demonstrates how the pattern varies spatially (Figure 7) and how powerful the cut and fill GIS-analysis tool is. TBRB exhibits significant erosion with, for the region shown in Figure 7A, over 60,000 m^3 of sand lost. The total sediment lost quickly declines eastward with the region of roughly equal area in Sanibel East (Figure 7B) losing approximately 18,000 m^3. When the locations of erosion and deposition are compared within an inter-R-monument cell, another spatial disparity exists. At TBRB areas of deposition are few in number and small in extent, and they occur as foredune overtop. Alternatively, in Sanibel East the area of deposition has a larger footprint with much more extensive overtop deposition behind multiple ridges. These spatial differences exist despite the net sediment loss for both regions.

4. DISCUSSION

The results clearly demonstrate that Hurricane Ian's storm surge resulted in significant effects on Sanibel's coastal geomorphology, but that impact was location specific and varied along the island's west to east length. Both the relative position of the storm's wind field and intensity prior to and through landfall and the previous geomorphologic configuration of the coastal region influence process and effect. We see this expressed across the 4 regions of Sanibel Island.

Coastal managers must be made aware of these differential behaviors to best prepare for and to rebuild from a storm. Any resilience-enhancing strategy must be developed in concert with this knowledge. The City of Sanibel, for example, has raised a number of questions about its adaptation planning to future impacts of storminess and climate change. The Santiva and TBRB regions of the island have chronically suffered from storm-related damage. This work demonstrates that Ian's effects were most pronounced in these regions. Their management strategies should reflect this "hot spot" characterization. The City is also curious about the effectiveness of its development setback policy. Bowman's Beach demonstrates the resilience value of a strandplain. Hurricane Ian's effects reveal the high resilience capacity of ridge and swale systems (strandplains); consequently, management of strandplains should maintain their integrity. Finally, the City is interested in knowing how sustainable a restoration to the pre-Ian condition will be given the worsening nature of climate change. This is not a simple matter, but the documentation of the effects of historic events, like Ian, provide valuable data to address this complex matter.

Perhaps this study's greatest significance concerns the value revealed of employing remote sensing technologies for efficiently and effectively gauging a storm's impact for restoration and future adaptation planning. The resources required, both in time and dollars, required to map a coastal region with UAV-supported LiDAR and the geospatial post processing are modest. Typically. and immediately after a major storm, fixed-wing LiDAR is flown by a federal agency. These data, however, often require many months to be processed and quality checked before being released to the public. An inhouse drone-based alternative is more immediate and often provides greater spatial resolution.

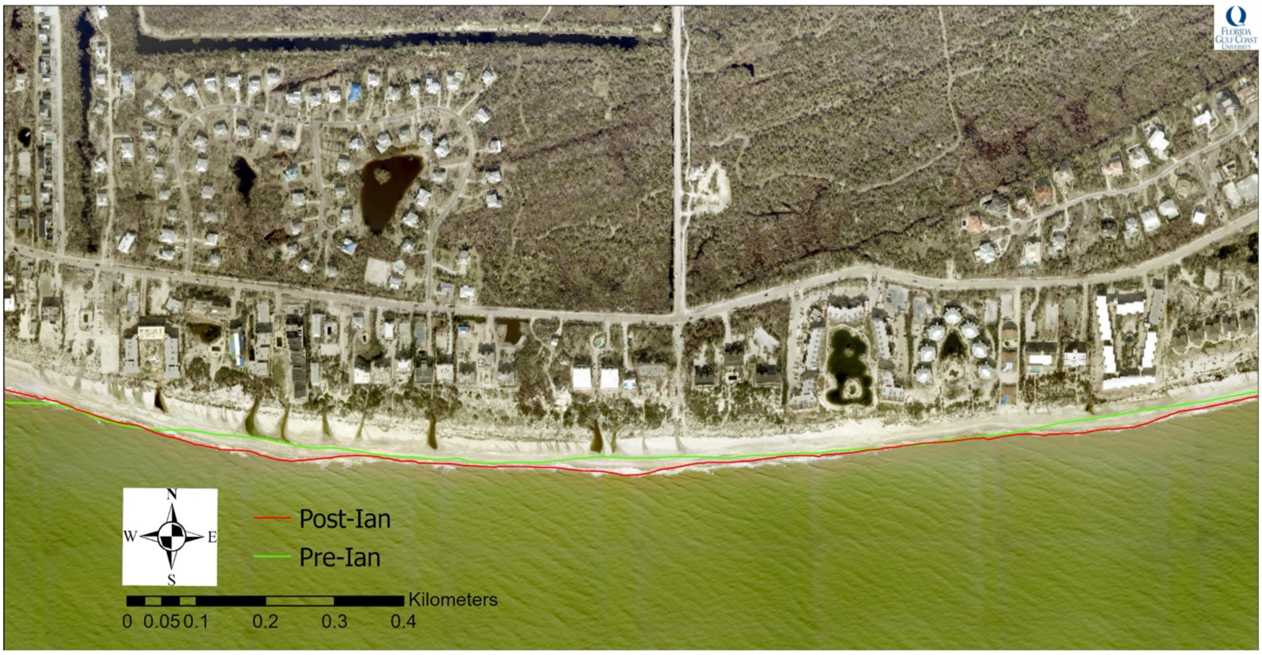
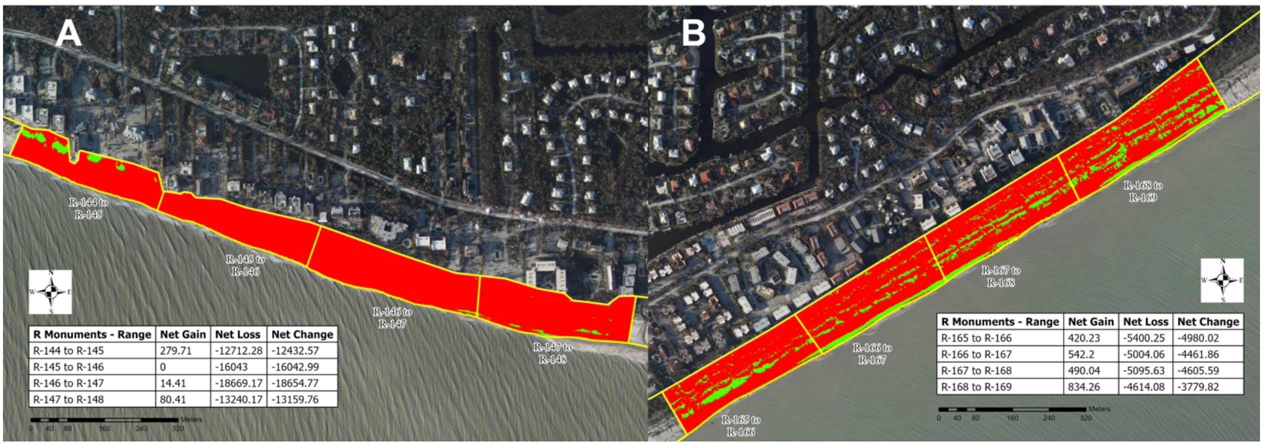


Figure 6. The positions of the shoreline, defined as the Mean High Water (MHW) contour, at Tarpon Bay Road Beach for both the pre- (green) and post-Ian (red) condition.



R Monuments - Range	Net Gain	Net Loss	Net Change
R-144 to R-145	279.71	-12712.28	-12432.57
R-145 to R-146	0	-16043	-16042.99
R-146 to R-147	14.41	-18669.17	-18654.77
R-147 to R-148	80.41	-13240.17	-13159.76

R Monuments - Range	Net Gain	Net Loss	Net Change
R-165 to R-166	420.23	-5400.25	-4980.02
R-166 to R-167	542.2	-5004.06	-4461.86
R-167 to R-168	490.04	-5095.63	-4605.59
R-168 to R-169	834.26	-4614.08	-3779.82

Figure 7. Cut and fill analysis for western Tarpon Bay Road Beach (A) and western Sanibel East (B). Analyses differentiate the net gain, loss, and total change for each of 4 inter-monument cells (outlined in yellow) after the impact of Hurricane Ian. Cells are 1000 ft long and vary slightly in width. Monuments are maintained by Florida Department of Environmental Protection. Inset tables show the values for each cell. Areas mapped red experienced erosion, green deposition. Volume in cubic meters.

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REFERENCES

Balaguru, K., Foltz, G.R., and Leung, L.R., 2018. Increasing magnitude of hurricane rapid intensification in the Central and Eastern Tropical Atlantic. *Geophysical Research Letters*, 45, pp. 4238-4247.

Bucci, L., Alaka, L., Hagen, A., Delgado, S., Beven, J., 2023. Hurricane Ian. Report AL092022. NOAA National Hurricane Center Tropical Cyclone Report, https://www.nhc.noaa.gov/data/tcr/AL092022_Ian.pdf.

Disney, M., 2019. Terrestrial LiDAR: a three-dimensional revolution in how we look at trees. *The New Phytologist*, 222(4), pp. 1736-1741.

EDR (Office of Economic & Demographic Research), 2015. Economic evaluation of Florida's investment in Beaches, http://edr.state.fl.us/content/returnoninvestment/beachreport.pdf.

Gares, P.A., Wang, Y., and White, S.A., 2006. Using LIDAR to monitor a beach nourishment project at Wrightsville Beach, North Carolina, USA. *Journal of Coastal Research*, 22(5), pp. 1206–1219.

Halls, J.N., Frishman, M.A., and Hawkes, A.D., 2018. An automated model to classify barrier island geomorphology using lidar data and change analysis (1998-2014). *Remote Sensing,* Basel, Switzerland, 10(7), pp. 1109.

Hardin, E., Kurum, M.O., Mitasova, H., and Overton, M.F., 2012. Least cost path extraction of topographic features for storm impact scale mapping. *Journal of Coastal Research*, 28(4), pp. 970-978.

Houser, C., Hapke, C., and Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology*, 100(3), pp. 223–240.

Knutson, T.R., Chung, M.V., Vecchi, G., Sun, J., Hsieh, T-L., and Smith, A.J.P., 2021. ScienceBrief Review: Climate change is probably increasing the intensity of tropical cyclones. In: *Critical Issues in Climate Change Science*, C. Le Quéré, C., Liss, P., & Forster, P. (eds.) https://doi.org/10.5281/zenodo.4570334.

Kossin, J.P., 2018. A global slowdown of tropical-cyclone translation speed. *Nature,* 558, pp. 104-108.

Mitasova, H., Hardin, E., Starek, M.J., Harmon, R.S., and Overton, M.F., 2011. Landscape dynamics from LiDAR data time series. *Proceedings of Geomorphometry 2011,* Redlands, California, pp. 1-4.

Wernette, P., Thompson, S., Eyler, R., Taylor, H., Taube, C., Medlin, A., Decuir, C., and Houser, C., 2018. Defining dunes: evaluating how dune feature definitions affect dune interpretations from remote sensing. *Journal of Coastal Research*, 34(6), pp. 1460–1470.

Woolard, J.W., Colby, J.D., 2002. Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LIDAR: Cape Hatteras, North Carolina. *Geomorphology*, 48(1), pp. 269–287.