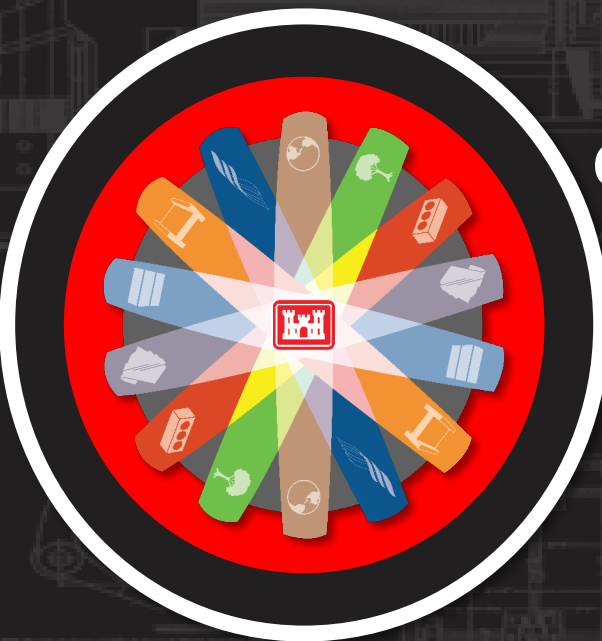
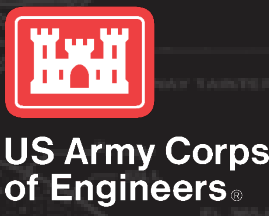




**CONNECTING
THE DOTS TO
INNOVATION**

SPACE-TIME CUBE ANALYSIS USING ESRI TOOLS

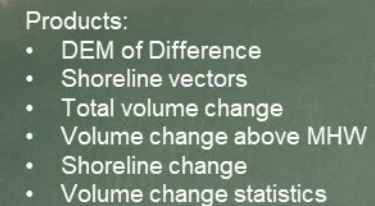
Scott Spurgeon & Brooke Walker





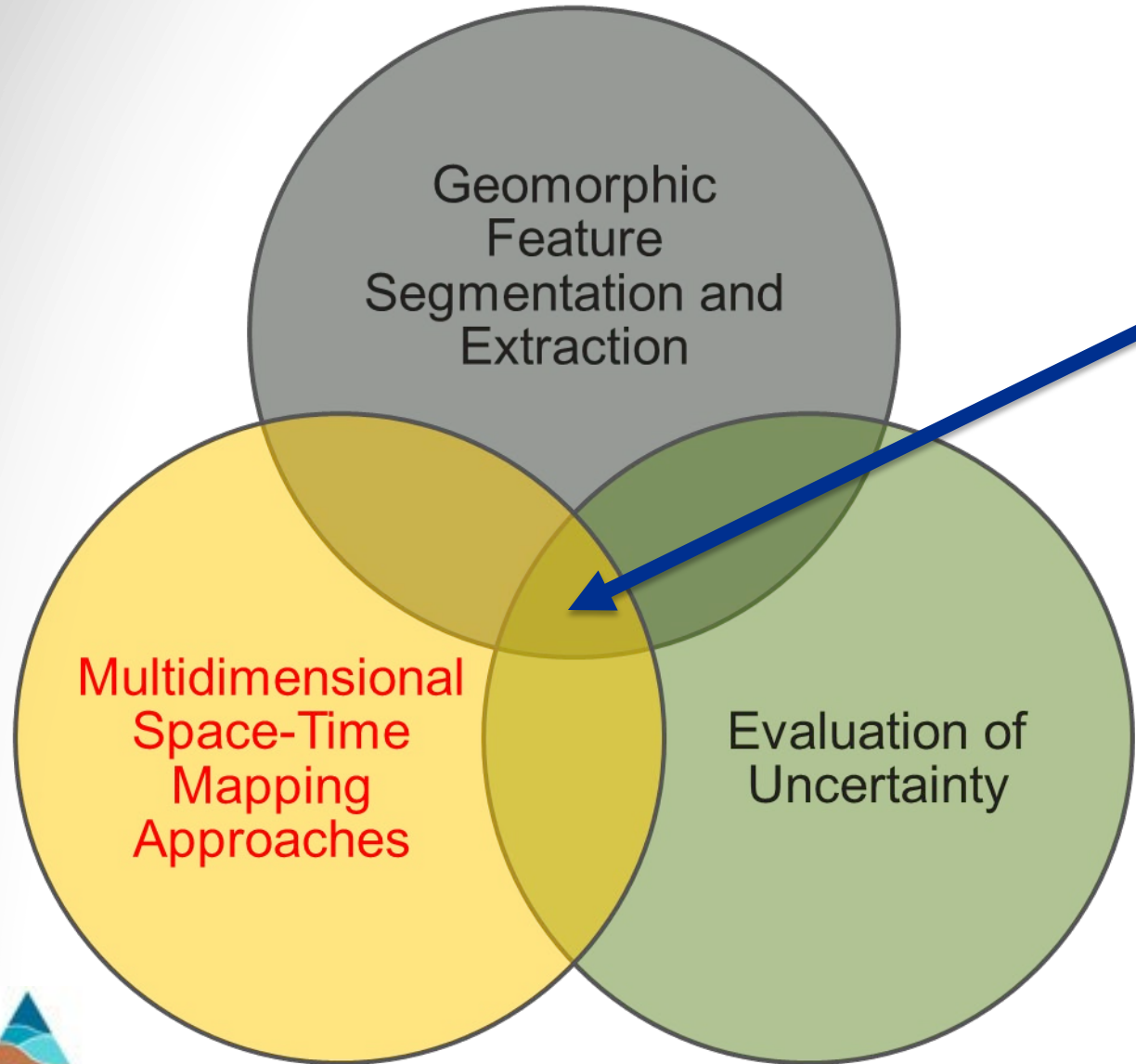
-
- The diagram shows three stacked 3D perspective views of a terrain. The top view is labeled 'Pre-Storm DEM' and shows a landscape with a river and surrounding land. The middle view is labeled 'Post-Storm DEM' and shows the same landscape after a storm, with some areas appearing eroded or changed. The bottom view is labeled 'Elevation Difference' and shows the difference in elevation between the pre-storm and post-storm states, with areas of change highlighted in purple and blue. A large black arrow points downwards from the 'Pre-Storm DEM' view to the 'Elevation Difference' view, indicating the calculation process.

DEMs of Difference & Volume Change Bins





RESEARCH AND DEVELOPMENT GOAL



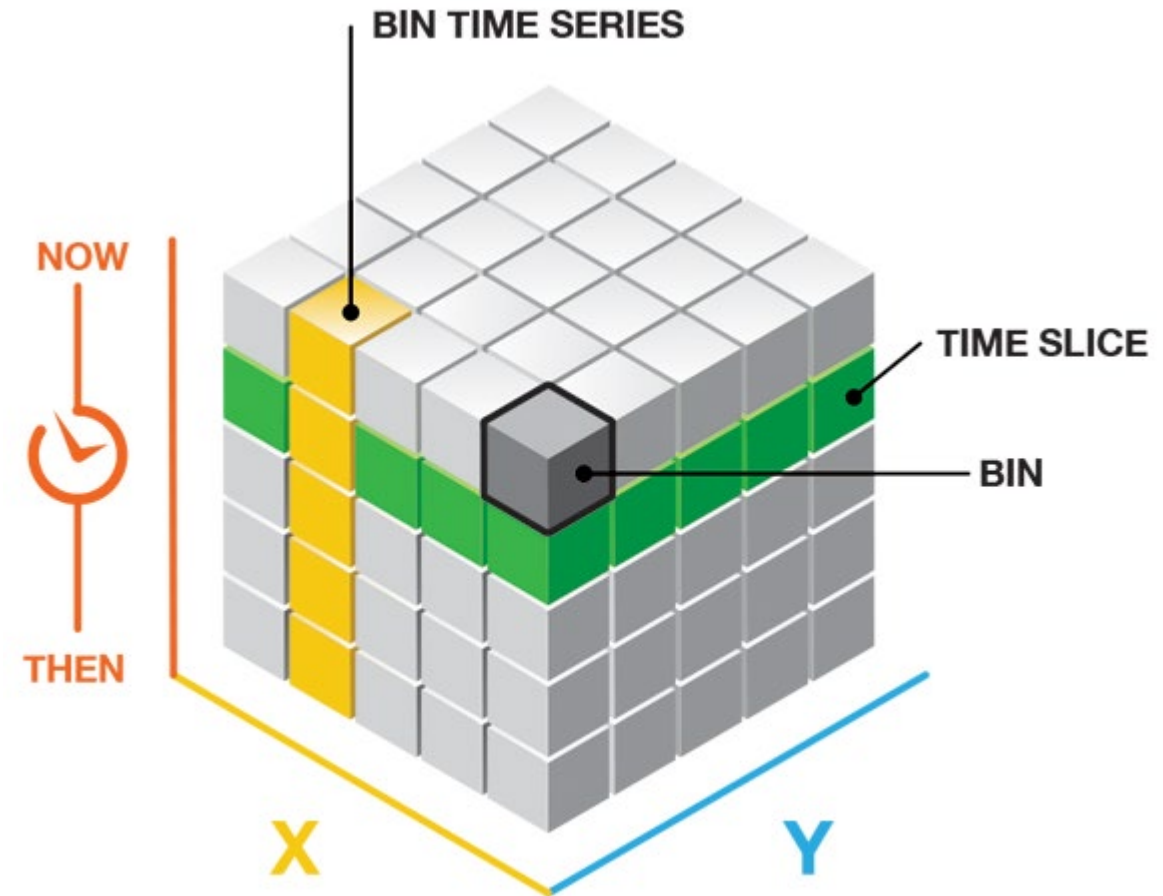
GOAL

Address requirements for a flexible volume change framework to **improve both the characterization and quantification of volumes for coastal projects** in support of sediment budget development, operations and maintenance, and project monitoring.



SPACE-TIME CUBES – WHAT ARE THEY?

- Space-Time Cubes are geostatistical tools that allow for analysis in three dimensions.
- The first two dimensions (horizontal plane) are typically x- and y-coordinates, and the third dimension (vertical axis) is typically time.
- Each x, y, and z point is defined as a “bin” within the Space-Time Cube.

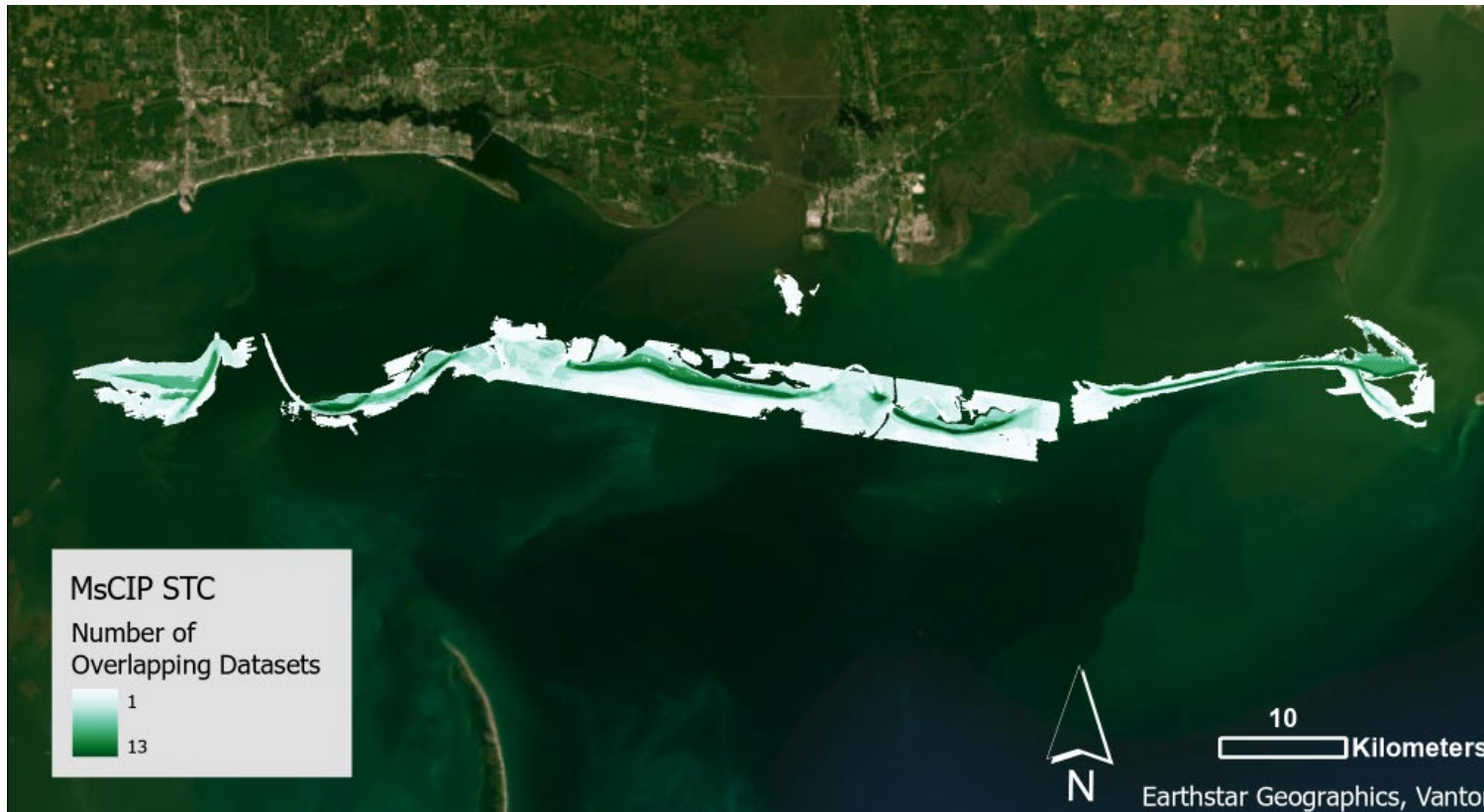




SPACE-TIME CUBE WORK SO FAR



- ✓ STCs built for the AOI (Mississippi Barrier Islands)
- ✓ STC analysis completed for AOI
- ✓ ERDC TN Published
 - ArcGIS Pro workflow overview
 - Best practices when utilizing elevation data



ERDC/CHL CHETN-II-62
May 2026



US Army Corps
of Engineers®

Workflow to Build Space-Time Cubes in ArcGIS Pro with High- Resolution Elevation Data

by Scott L. Spurgeon and Brooke M. Walker

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) presents a workflow to build space-time cubes (STCs) using high-resolution digital elevation models (DEMs). The workflow leverages ArcGIS Pro's mosaic dataset architecture and multidimensional tools to analyze temporal changes across elevation datasets. This workflow is intended to (1) guide users who may not be familiar with STCs through a step-by-step workflow, (2) share a set of best practices, and (3) highlight considerations when using remotely sensed elevation datasets. This CHETN is a part of a larger effort to develop the next generation of volume change tools for application in the coastal environment.

INTRODUCTION: Volumetric change analysis in the coastal environment is well-documented in literature (Mitasova 2003; Farris and List 2007)¹ including the use of proxies for volume change (e.g., shoreline change and profile change). However, these proxies rely upon the assumptions of an equilibrium profile and consistent alongshore geomorphology, resulting in uncertainties in the volume estimates. Instead, more direct approaches, such as a DEM of difference (DoD), can complete volume change analysis by calculating the sum of difference raster cell values for elevation change (Gorman et al. 1998; Zhang et al. 2005). However, the DoD approach is also limited; fixed-in-space bins may not be directly comparable across time because of storm and anthropogenic changes, and the net volume quantities may not be directly comparable from one dataset to another where bathymetric data coverage varies. Additionally, the DoD approach does not provide sediment transport directionality information (Andrews et al. 2002). Other 3D analyses are typically focused on static spatial relationships. STC geographic information system (GIS)-based toolboxes that use elevation rasters are in early stages and require additional research to identify workflows, document best practices, and ensure proper application with remotely sensed raster data (Deng et al. 2023). This CHETN addresses this need by documenting best practices and special considerations when creating STCs with rasterized elevation datasets. The goal of this work is to benefit coastal practitioners as they complete volume change analysis to capture sediment transport patterns during planning, construction, and monitoring phases of projects. After establishing this workflow, future work should include STC analysis recommendations, best practices, considerations for errors and uncertainties, and potential toolbox development.

BACKGROUND: An STC is a geostatistical data representation, composed of voxels or bins which represent discrete elements in a three-dimensional space (Figure 1). These bins are arranged in the x, y, and z directions with x and y elements typically representing their respective x- and y-coordinates, while the z direction is represented by time. For raster data, each raster cell has a value

¹ S. L. Spurgeon, C. S. Sylvester, and S. S. Jackson, draft special report, "Multi-Temporal Change Detection in the Coastal Zone: Literature Review," US Army Engineer Research and Development Center.

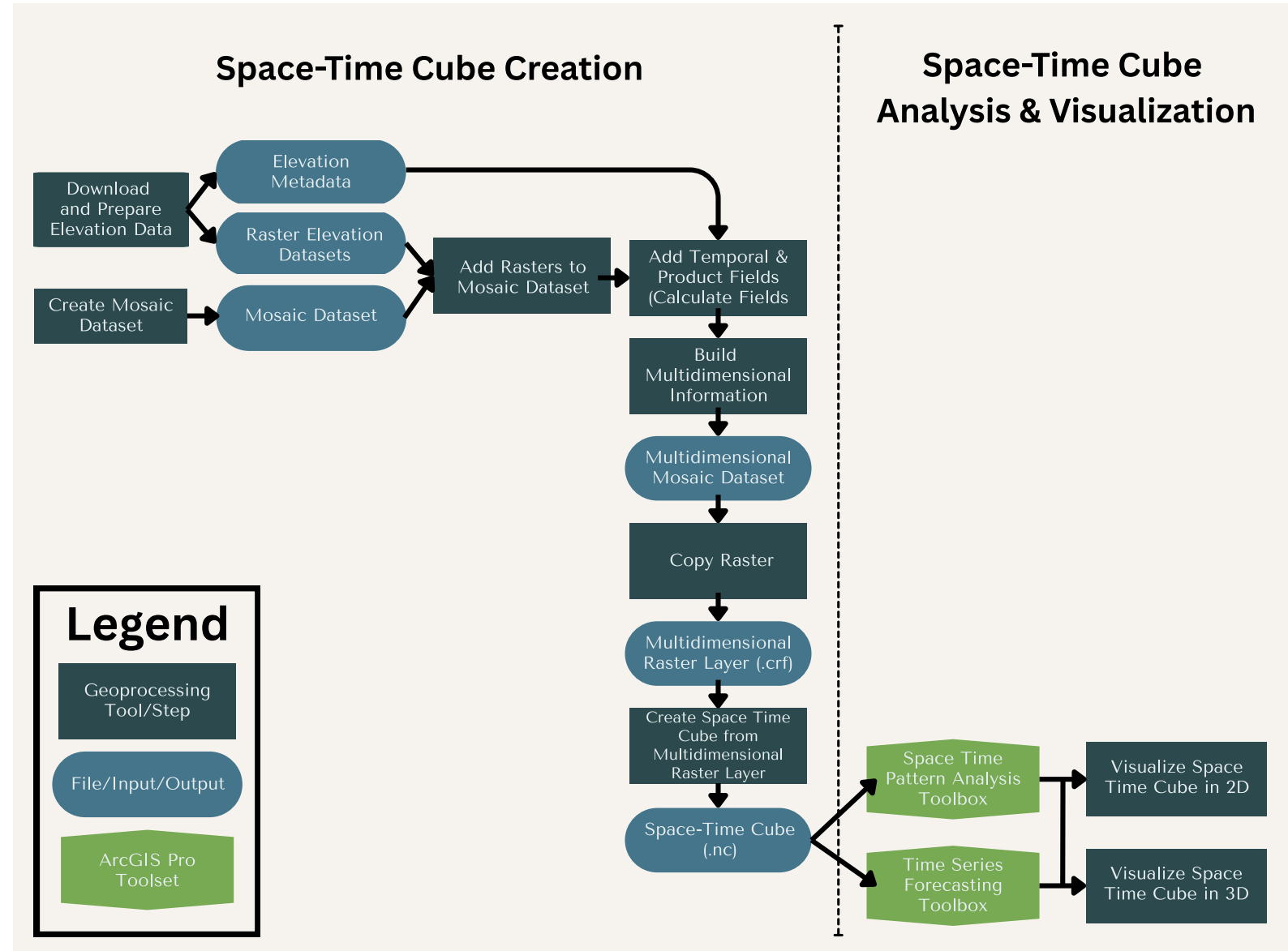
Distribution Statement A. Approved for public release: distribution is unlimited.

<https://dx.doi.org/10.21079/11681/50251>



SPACE-TIME CUBE CREATION

- Space-Time cubes provide statistical analyses methods across the entire domain
 - Hotspot Trend Analysis over time
 - Spatial Pattern Identification
 - Time Series Forecasting
- ArcGIS Pro has various geoprocessing tools to create, visualize, and analyze space-time cubes.
- For many tools, “statistically significant” is derived from global statistics (e.g. p-value of 0.05)

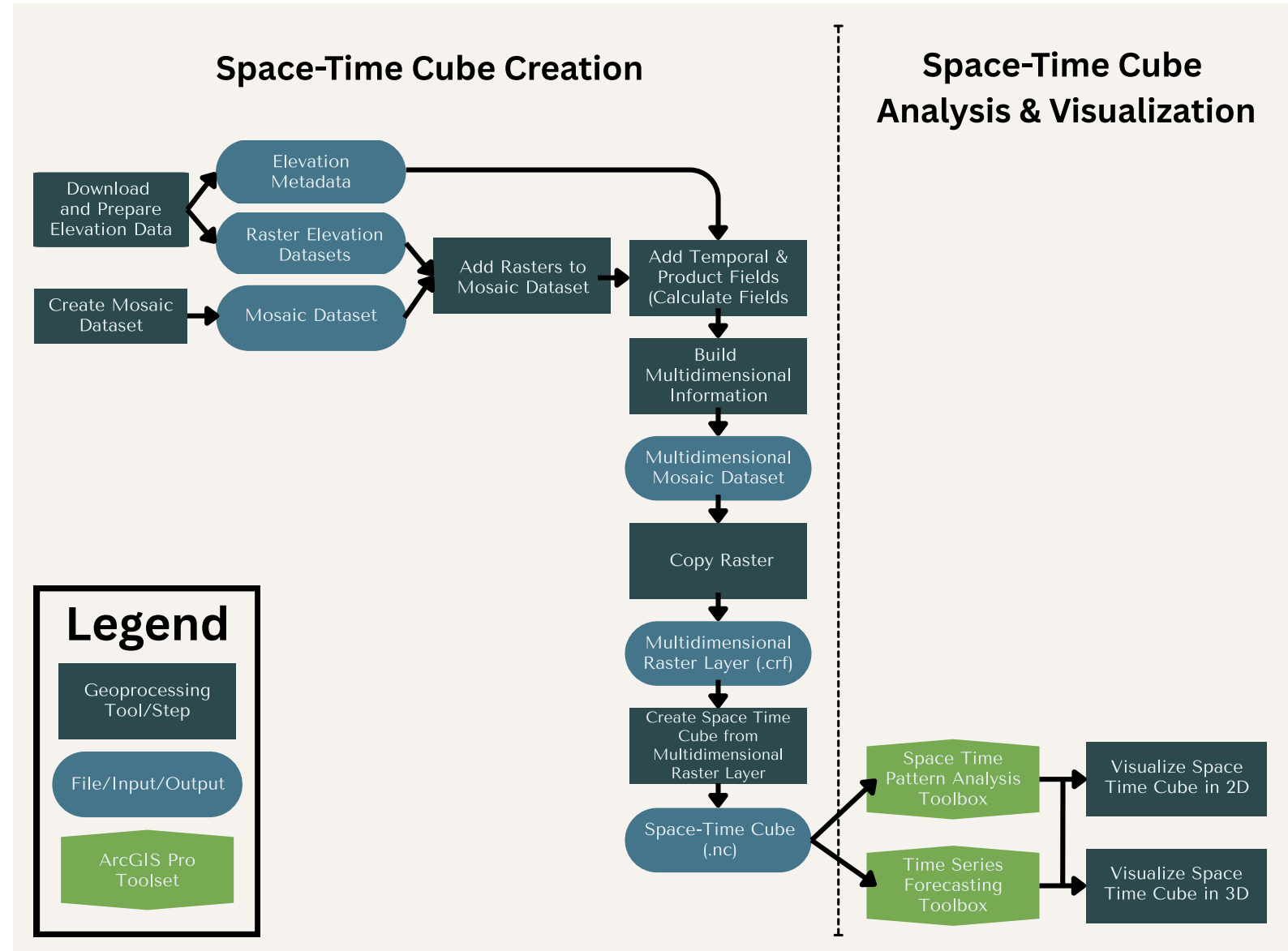




ARCGIS PRO SPACE-TIME CUBE TOOLBOXES



- Two ESRI ArcGIS Pro toolboxes are available for analysis of STCs:
- Space-Time Pattern Mining
 - Change Point Detection
 - Emerging Hotspot Analysis
 - Local Outlier Analysis
 - Time Series Clustering
 - Time Series Cross Correlation
- Time Series Forecasting
 - Curve Fit Forecast
 - Evaluate Forecasts by Location
 - Exponential Smoothing Forecast
 - Forest-based Forecast



SPACE-TIME PATTERN MINING



U.S. ARMY



US Army Corps
of Engineers®



ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER



CHANGE POINT DETECTION



Tool Overview

Identifies when and where **statistically significant** changes occur in time series data.

Analyzes time series and identifies point locations where there are a) abrupt shifts, b) trend changes, or c) changes in stability/variability.

Potential Applications with Elevation Data

Coastal Management

- Storm impacts, nourishment effectiveness, dune system monitoring, climate change planning.

River/Estuarine Management

- Changes in deposition rates in river deltas, wetlands, and reservoirs, verification of restoration/nourishment progress.

Key Input Parameters

- Space Time Cube in .nc format
- Change Type
 - Mean shift, Standard Deviation, Slope, or Count
- Method
 - Auto-detect (number of change points determined by the tool, defined by the detection sensitivity value)
 - Defined – user selected number of change points.
- Detection Sensitivity
 - Between 0 and 1 – larger value will result in more change points per location.
- Minimum Segment Length
 - Minimum number of time steps within each segment (change type impacts the default length).

Best Practices & Lessons Learned

Change Points

- Too many change points per location, overfitting
- Too few change points, misses clear breaks/shifts

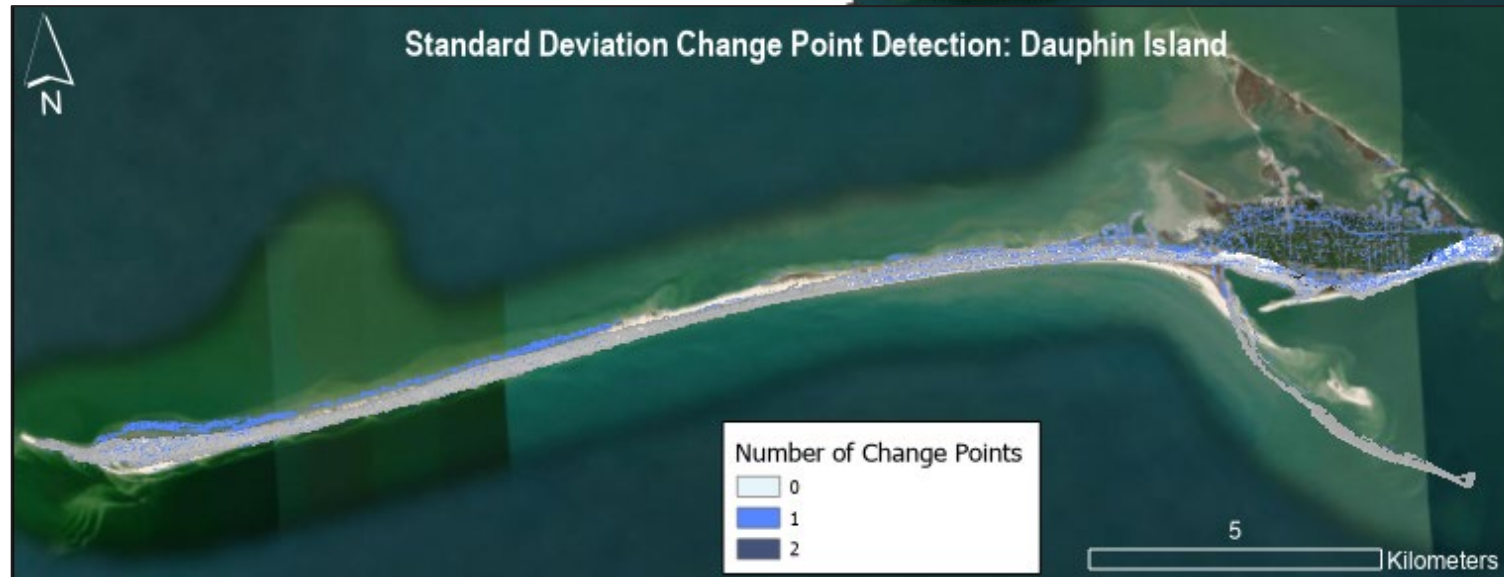
Sensitivity

- Increase Sensitivity if every location has 5+ change points.
- Decrease if you know you're missing large events

Temporal Resolution: 10-15 time points



CHANGE POINT DETECTION RESULTS

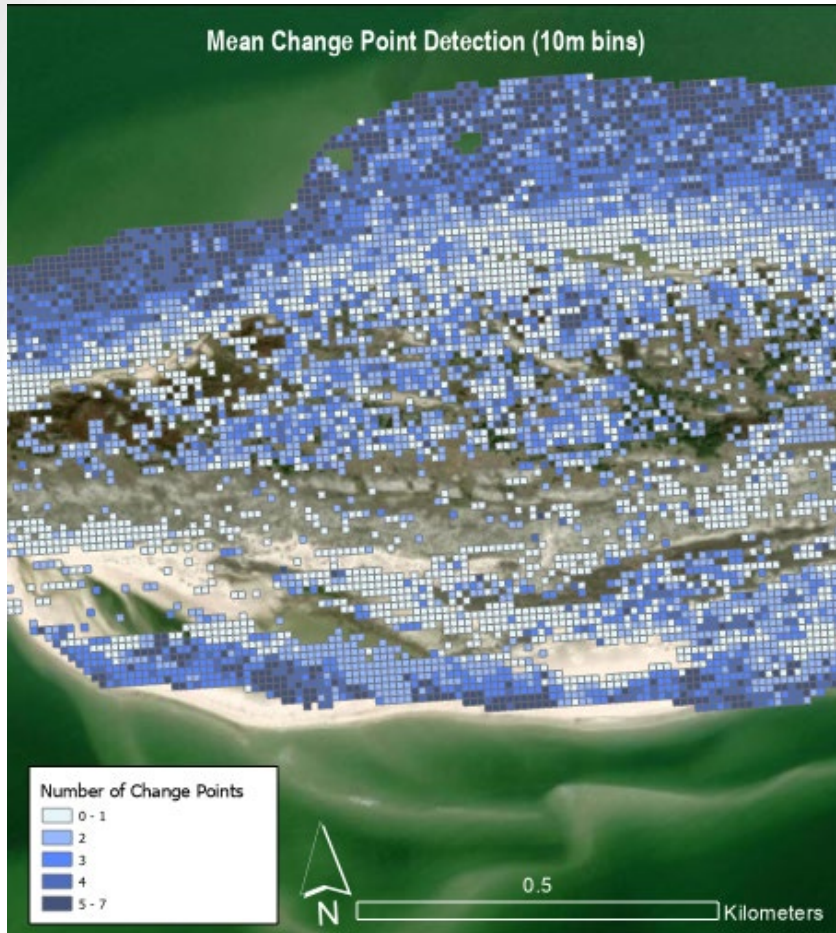




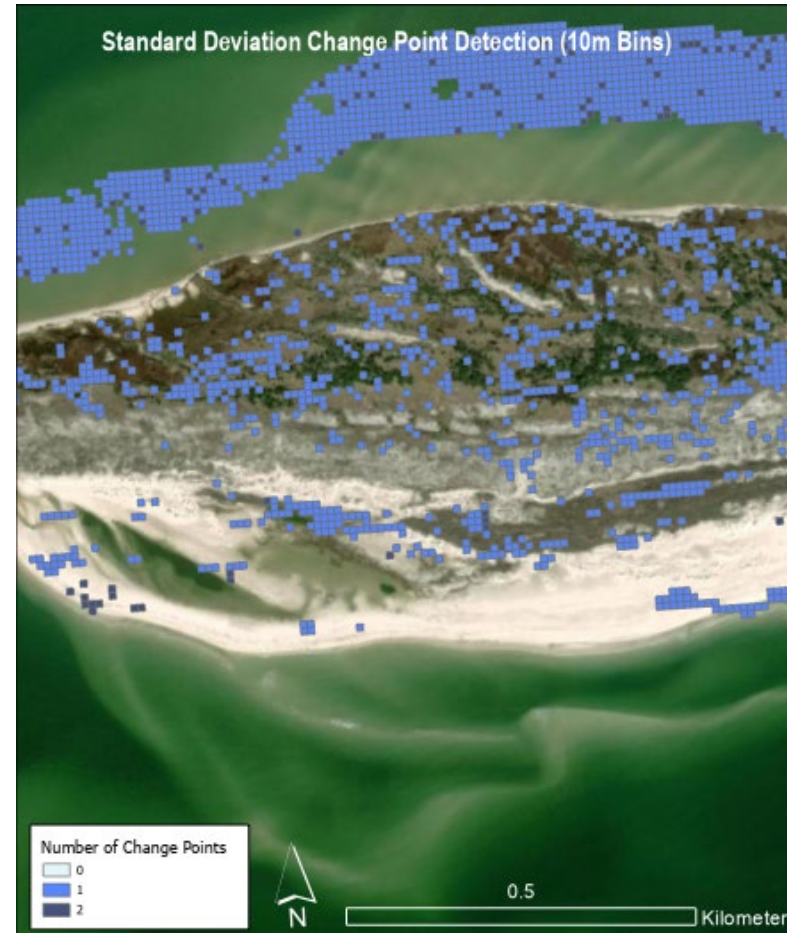
CHANGE POINT DETECTION RESULTS, CONT.



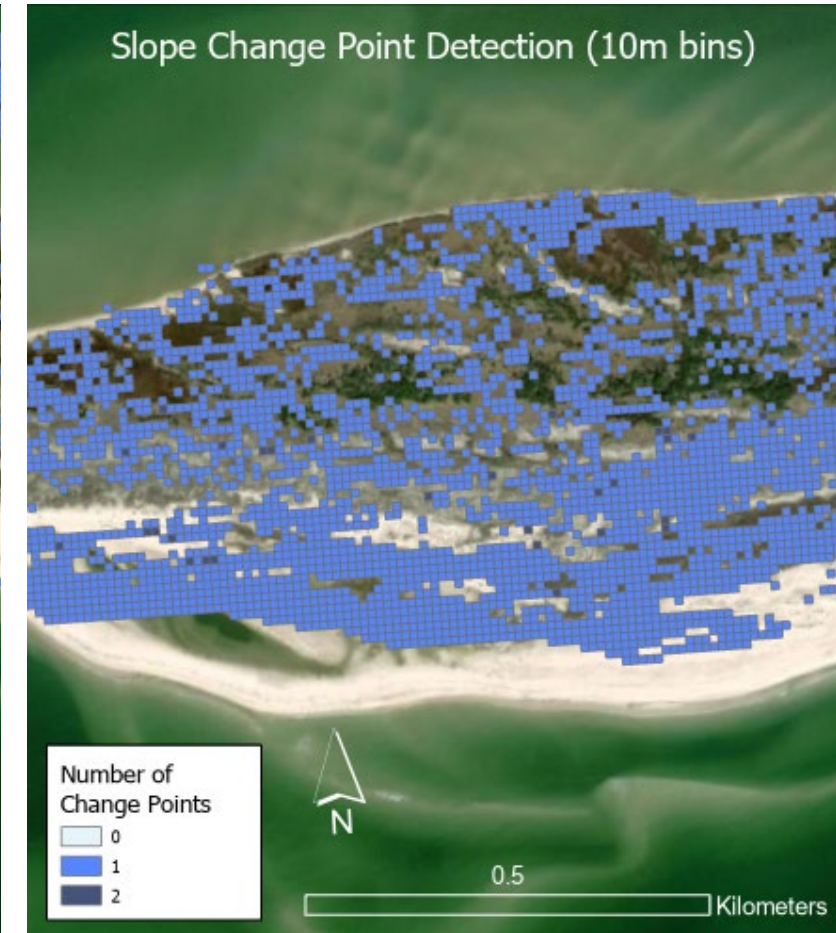
Mean Change Point Detection (10m bins)



Standard Deviation Change Point Detection (10m Bins)



Slope Change Point Detection (10m bins)





EMERGING HOTSPOT ANALYSIS



Tool Overview

Identifies locations within a space-time cube that exhibit statistically significant trends in value over time and classifies the locations by the pattern that is displayed.

Potential Applications with Elevation Data

Detection of areas of statistically significant accretion and erosion (hot and cold spots) when utilizing difference rasters within the STC.

Key Input Parameters

1. Fill Empty Bins: Space Time Neighbors (during STC creation)
2. Conceptualization of Spatial Relationships: Contiguity Edges & Corners
3. No minimum number of neighbors (e.g., left blank)
4. Neighborhood Time Step: 1
5. Global Window: Entire Cube (e.g., entire island, all time slices)

Best Practices & Lessons Learned

1. Utilizing a STC with difference rasters provides the most meaningful results.
2. 10 dataset minimum means the “least common area” of any 10 datasets is considered valid – when using difference rasters, this area can be limited.
3. Interpolation between rasters can artificially get around the 10-dataset minimum, but care should be taken when interpreting results.

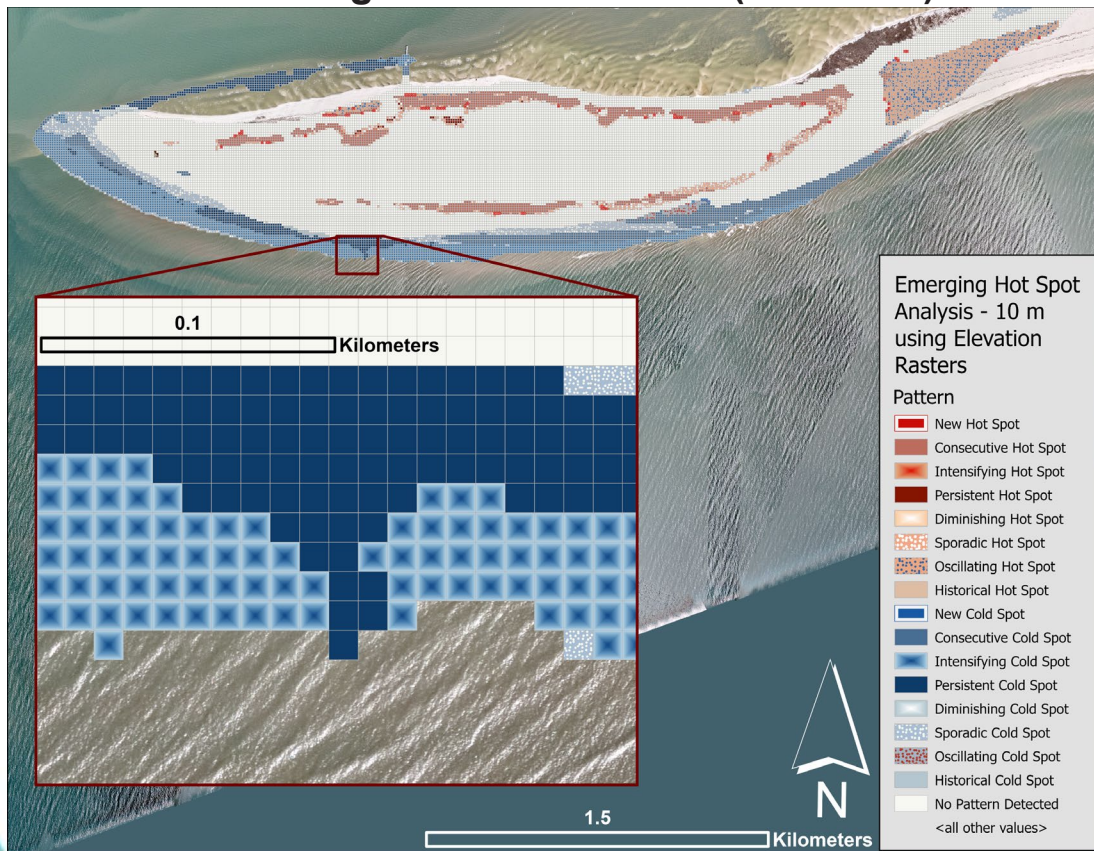


ELEVATION VS. DIFFERENCE RASTERS – SPATIAL DATA COVERAGE SHIFT

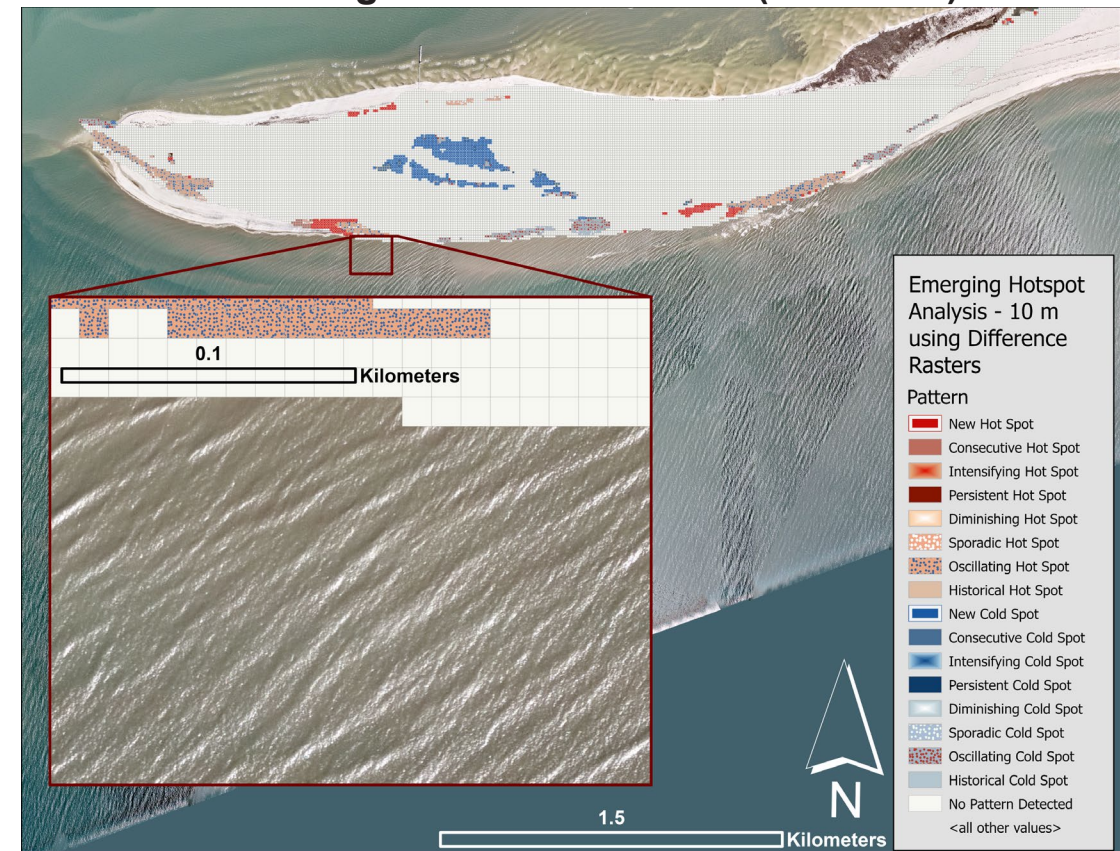


- Since STCs using elevation rasters only display statistical areas of high or low elevations, detection of accretion or erosional trends may be difficult. If difference rasters are used to build the STC instead, hot and cold spots become areas of accretion and erosion, making results much more meaningful.
- However, since 10 datasets are required to generate a trend and difference rasters only consist of the common area between rasters, the STC using difference rasters is a least common area of least common areas.

STC using Elevation Rasters (10m Bins)



STC using Difference Rasters (10m Bins)

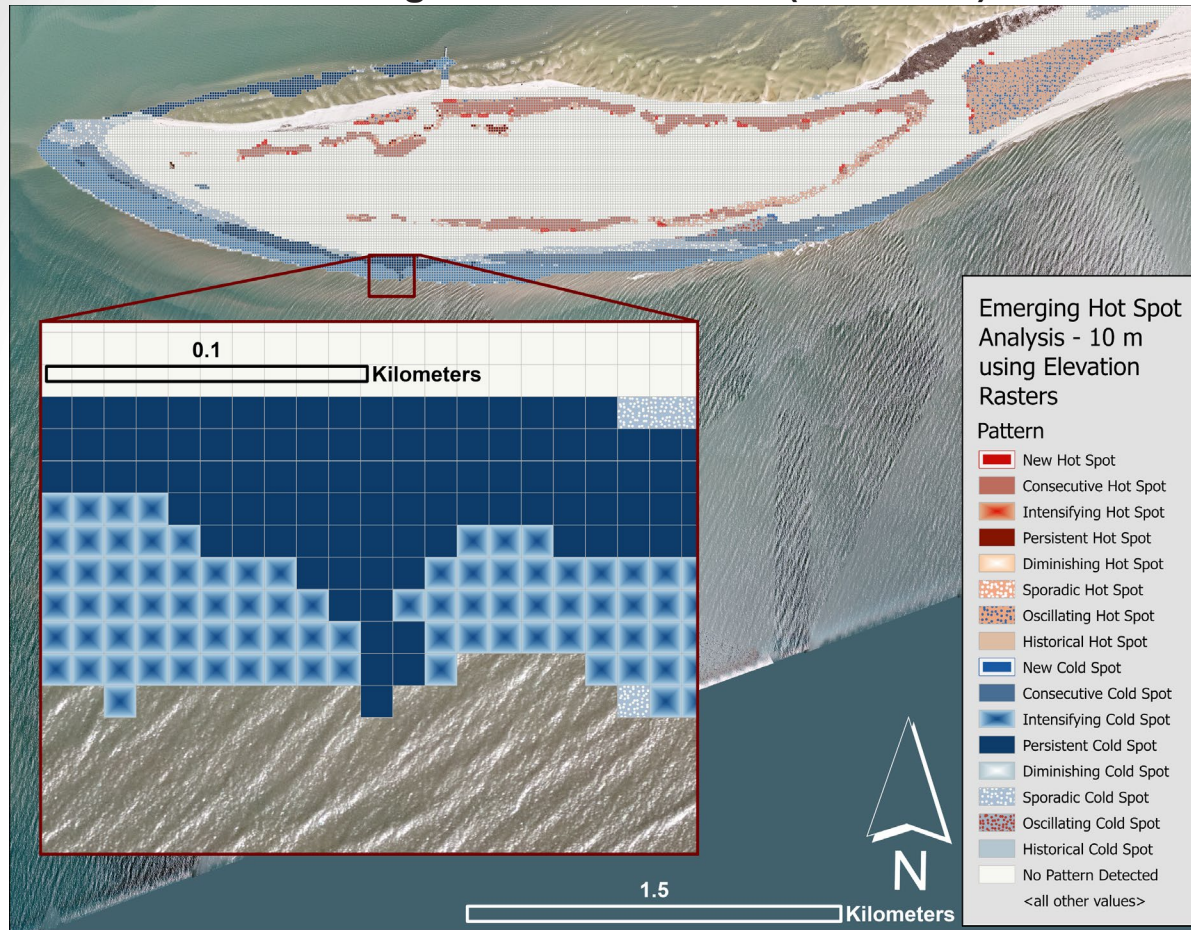




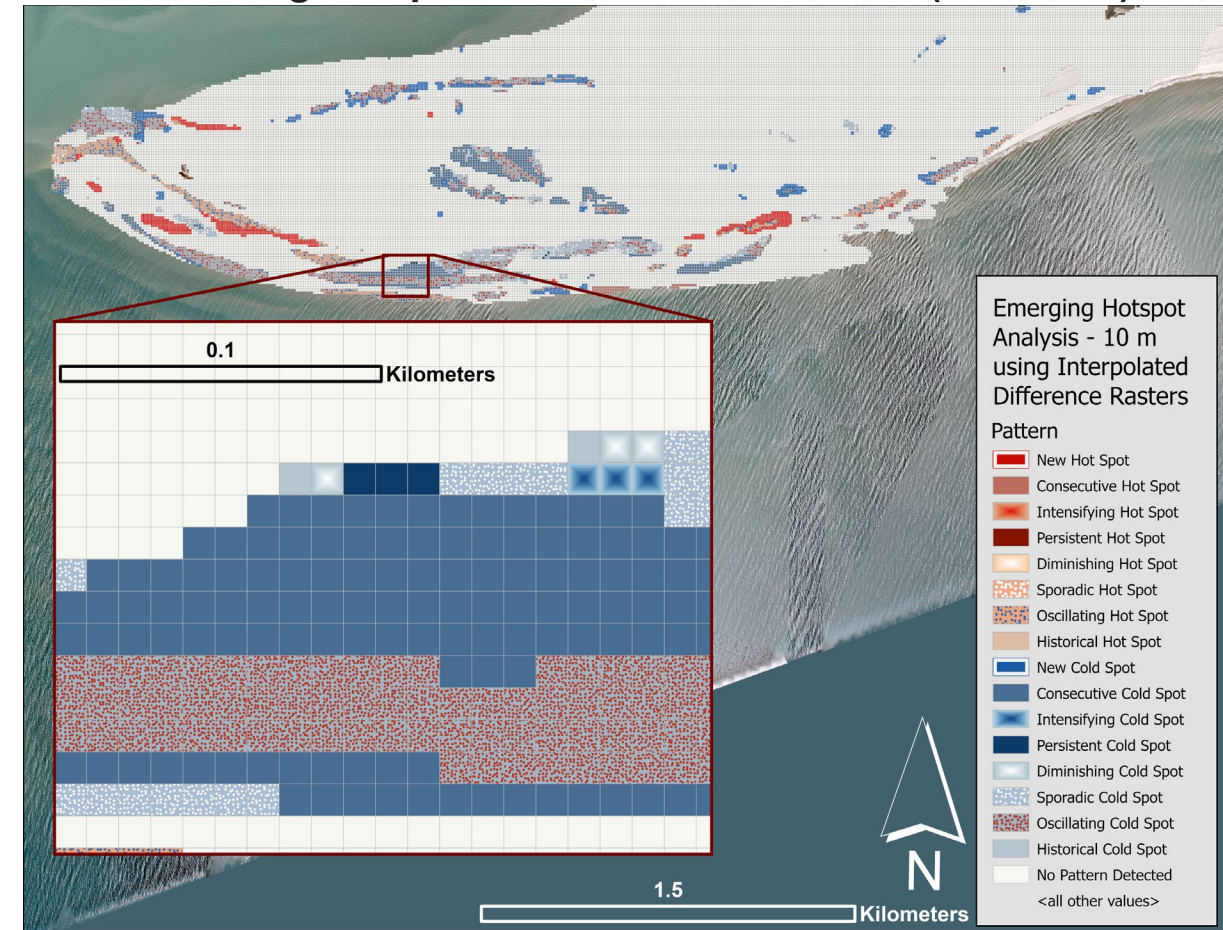
ELEVATION VS. INTERPOLATED DIFFERENCE RASTERS – TREND SHIFT



STC using Elevation Rasters (10m Bins)



STC using Interpolated Difference Rasters (10m Bins)



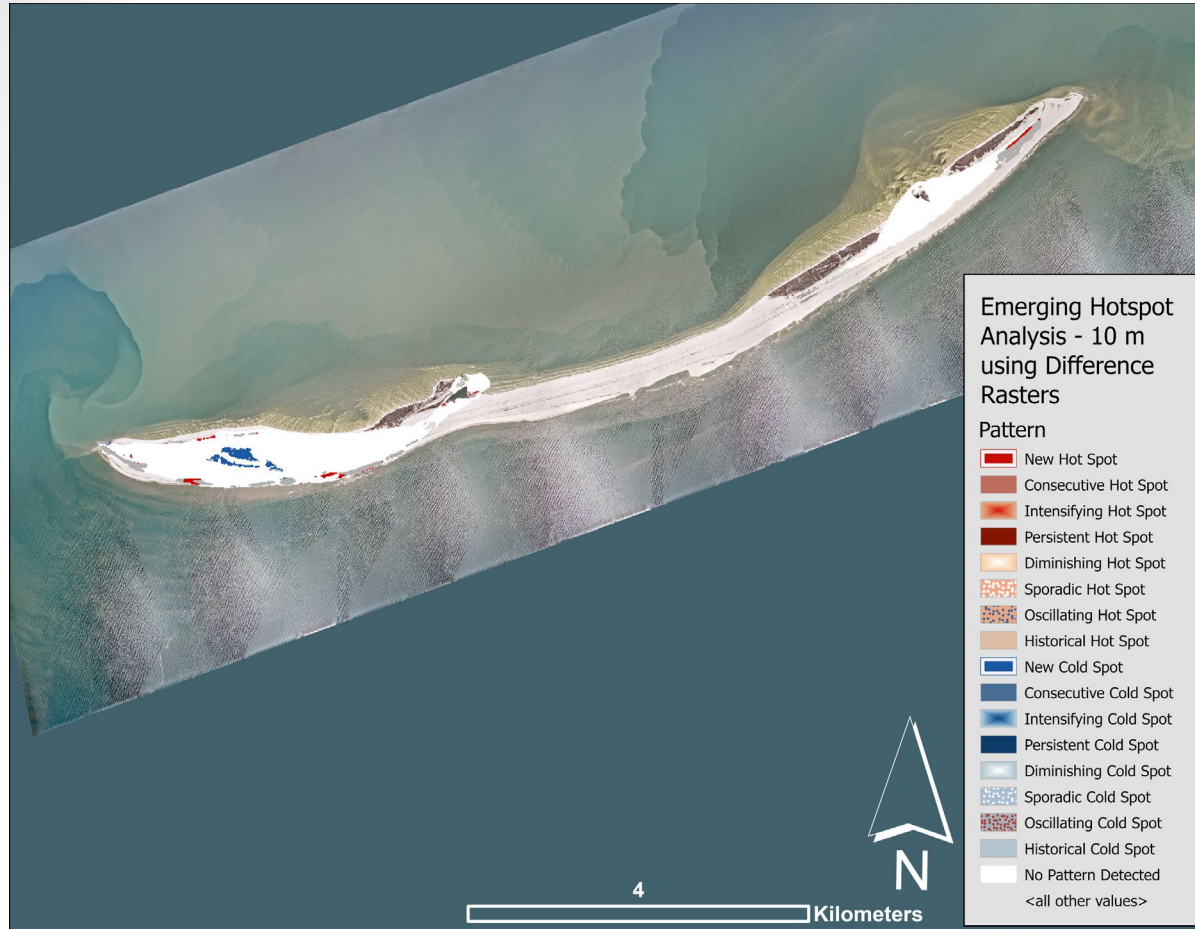
- To attempt to resolve spatial gaps and further explore potential results, interpolated rasters were created and then difference rasters were created from the original and interpolated rasters, effectively doubling the number of input datasets.
- This artificial densification of data allows for closer comparison between elevation raster STC and difference raster STC results.



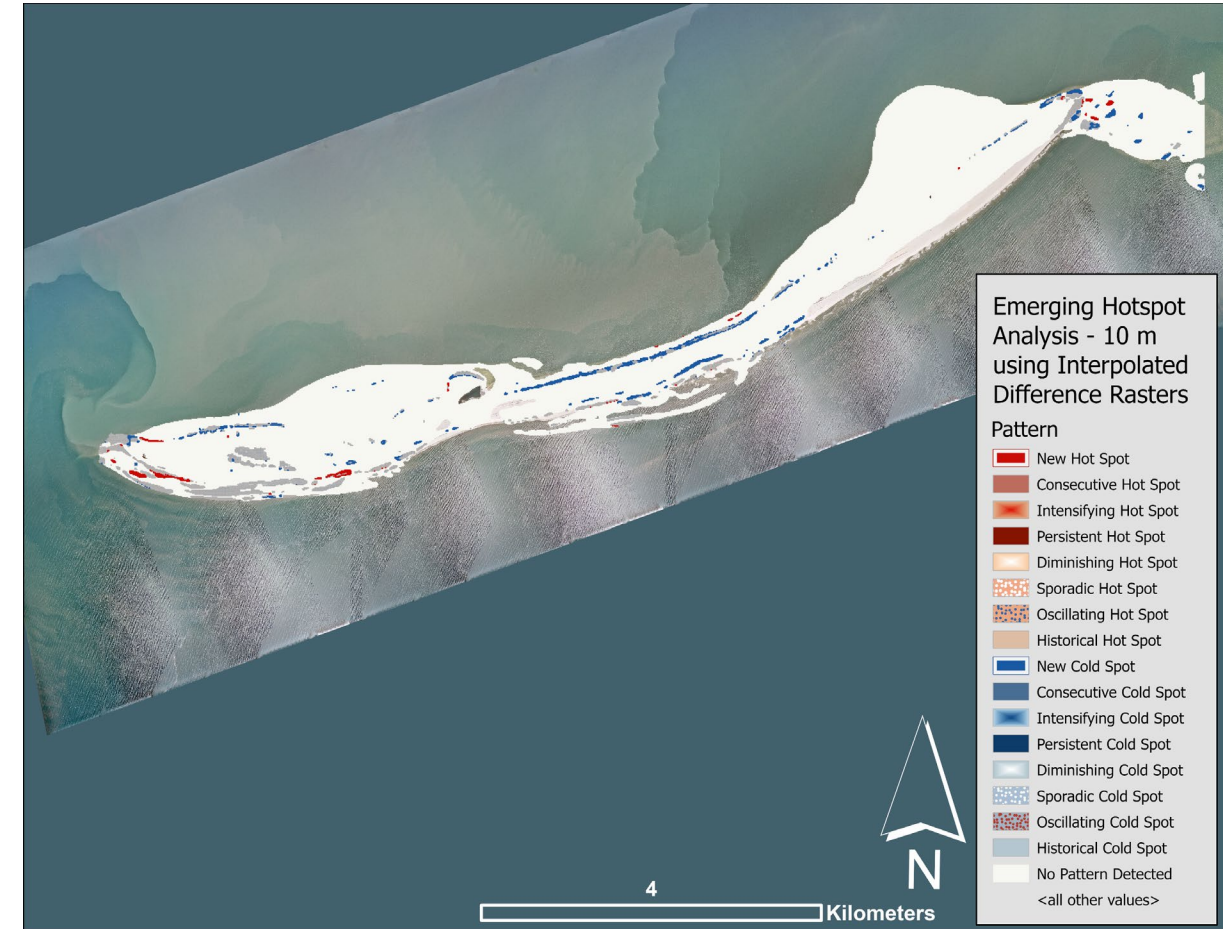
DIFFERENCE VS. INTERPOLATED DIFFERENCE RASTERS – SPATIAL DATA COVERAGE SHIFT



STC using Difference Rasters (10m Bins)



STC using Interpolated Difference Rasters (10m Bins)



- While the densification of data is artificial, the STC is able to generate significantly more coverage area as the 10-dataset minimum is being met for a greater number of bin time series.
- Caution must be taken here, however, as the trend analysis may be overfit to the data as the interpolation will show a constant trend between two real datasets.



LOCAL OUTLIER ANALYSIS



Tool Overview

Identifies locations where the values are statistically anomalous relative to their neighbors in both space and time.

- Uses the Local Outlier Factor – each location has a neighborhood defined in space and time.
- Compares the density of values in the neighborhood to the values in the neighbors' neighborhoods.
- Lower densities relative to their neighbors are flagged as outliers.

Potential Applications with Elevation Data

- Detecting Geomorphic anomalies
 - Locations that erode or accrete out of step with their surroundings or contradicts the prevailing trend
- Post Storm analysis
 - High or low storm impacts; slow or fast recovery
- Characterization of hotspot instability
- Data quality control
 - Flags survey artifacts, interpolation errors before running more intense analysis

Key Input Parameters

- Space Time Cube
- Analysis variable
- Conceptualization of Spatial Relationships
 - Fixed Distance, K Nearest Neighbors, Contiguity Edges, Contiguity Corners)
- Number of Spatial Neighbors/Neighborhood Distance
 - minimum or exact # to include in the calculations
- Neighborhood Time Step
 - # of time steps included in the analysis neighborhood
- Number of Permutations
 - controls the Monte Carlo simulations
- Global Window – controls bins for comparison

Best Practices & Lessons Learned

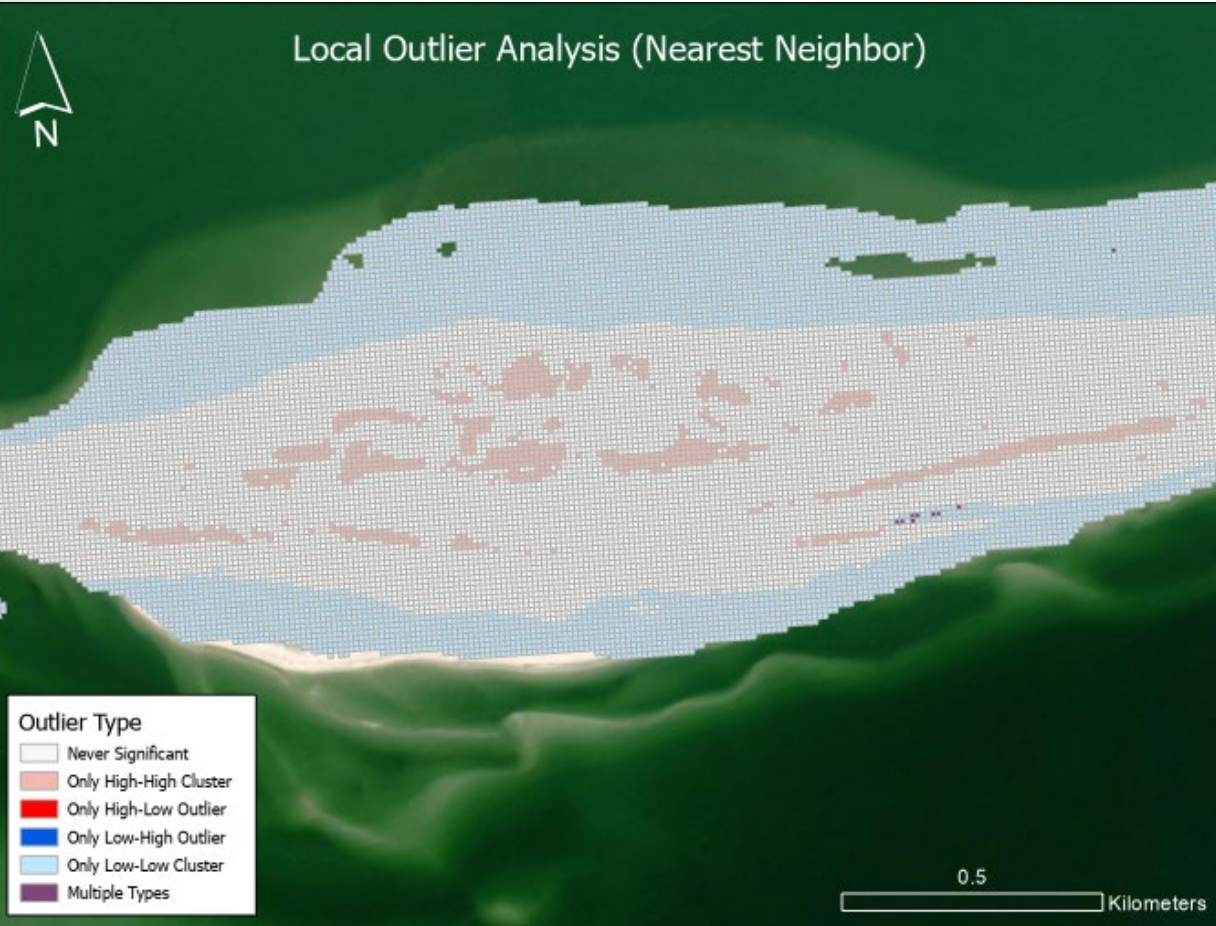
- Irregular temporal bins, inconsistent spatial aggregation will produce outlier classifications that are really data problems.
- Run the tool with different spatial neighborhood sizes to compare the results for sensitivity to the methodology.
- Match the spatial neighborhood scale to the scale of the process that is most vital to the analysis.



LOCAL OUTLIER ANALYSIS RESULTS



Local Outlier Analysis (Nearest Neighbor)



Local Outlier Analysis (Nearest Neighbor)





TIME SERIES CLUSTERING



Tool Overview

Identifies locations within a space-time cube that exhibit similar patterns over time and distributes the locations into distinct groups accordingly.

- Highlights locations that share similar temporal behaviors.

Potential Applications with Elevation Data

- Coastal subsidence patterns (rate of erosion)
- Erosion behaviors (stable, seasonal, accelerating)
- Seasonal elevation changes
- Sediment deposition (finding patterns of accumulation in river deltas)

Key Input Parameters

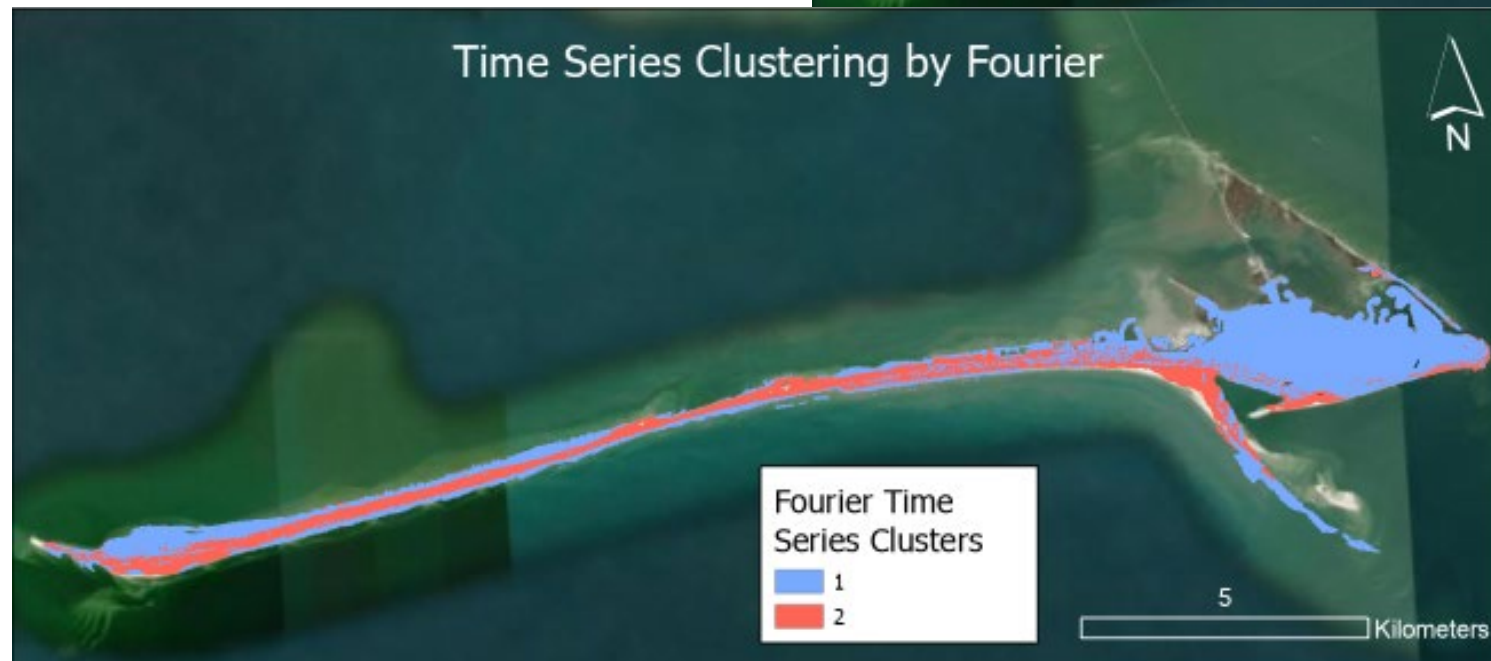
- Space Time Cube in .nc format
- Analysis Variable – comes from the STC
 - elevation, mean, or count
- Characteristic of Interest
 - Value – locations of similar values over time
 - Correlation Profile – locations that increase or decrease proportionally at the same time
 - Fourier Profile – locations that have similar seasonal patterns over time

Best Practices & Lessons Learned

- Requires a STC with bare earth data only.
- Value analysis is very basic, but the correlation profile analysis may provide a quick way to look at sediment transport around an island.



TIME SERIES CLUSTERING RESULTS



TIME SERIES FORECASTING



U.S. ARMY



US Army Corps
of Engineers®



ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER



TIME SERIES FORECASTING TOOLBOX OVERVIEW



The Time Series Forecasting Toolbox contains various tools:

- Forest Based Forecast
- Curve Fit Forecast
- Exponential Smoothing Forecast
- Evaluate Forecasts by Location

However, the forecasting toolsets have various significant limitations:

- Requirement to hold back at least 20% of datasets for validation and verification of the forecast.
- Without a very large stack of datasets, there is no ability to forecast forward
- Many forecast types don't accurately predict elevation values

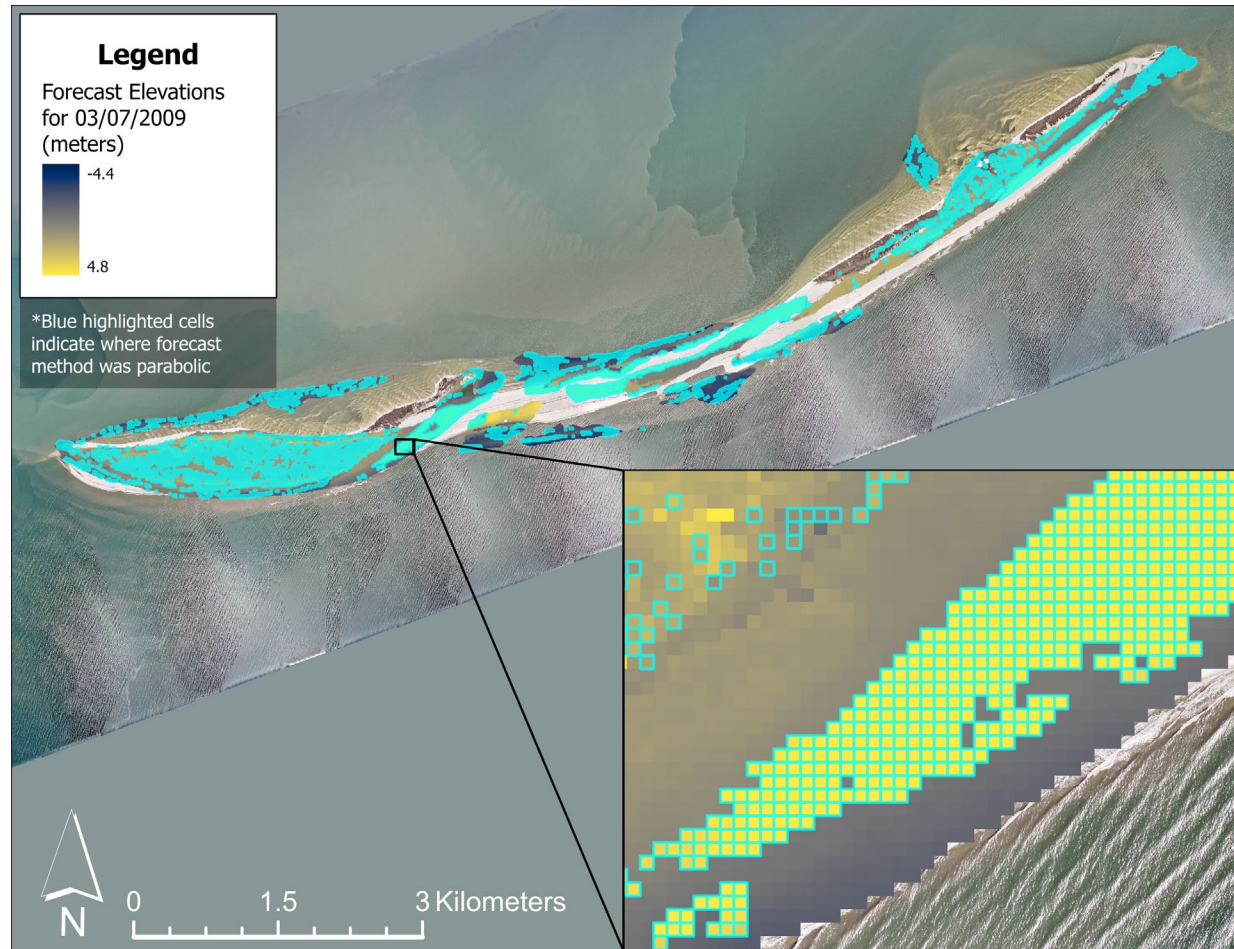


Figure 1. Curve Fit Forecast example results (10m Bins)



FOREST-BASED FORECASTING



Tool Overview

Utilizes forest-based regression to predict future time slices within the STC. The forest-based model creates many independent decision trees that all generate their own prediction, and those predictions are then aggregated to make the final prediction.

Potential Applications with Elevation Data

Utilizing the forest-based and boosted classification and regression tool as the underlying algorithm, this tool forecasts future values based on a regression. This tool is expected to be much stronger than the Curve Fit or other forecasting methods whenever complex trends, seasonality, or other non-mathematical function shapes occur.

Key Input Parameters

Number of Time Steps to Forecast: As many steps as you would like to forecast, with the validation limitation in mind. Additionally, cannot be more than 50% of time steps in the STC.

Time Step Window: The number of time steps that will be used when training the model. Ensure that this window is large enough to capture an entire season, if applicable.

Number of Time Steps for Validation: As many as possible while maintaining proper time steps for forecasting. Recommended to be at least as many steps as planned number of steps to forecast. Cannot be more than 25% of time steps in STC.

Model Scale: Specifies the scale that will be used to estimate the forecast and validation models; individual cells, time series cluster, or the entire cube.

Forest-Specific Parameters: Leaf size, tree depth, and number of trees are all optional inputs that allow for fine-tune adjustments to the model creation.

Best Practices & Lessons Learned

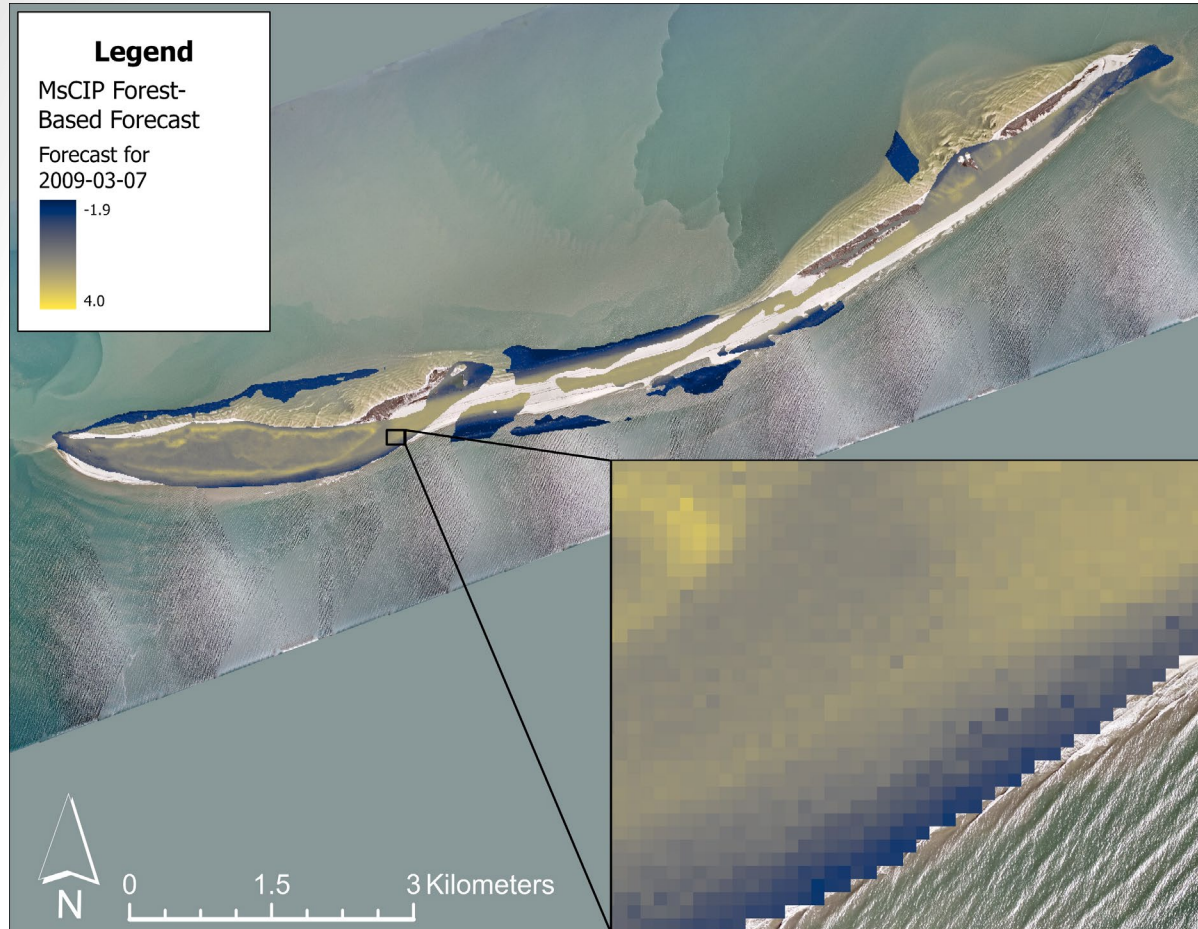
1. Similar to the curve fit forecast tool, this tool utilizes a forecast and a validation model from the given data. As such, a number of time steps to exclude for validation is selected by the user and the number of time steps that can be forecast is limited to 50 percent of the time steps in the STC.
2. This is the only forecast tool within the ESRI suite that allows for multiple scales to be selected when forecasting.
3. This forecast method seems to work well with elevation data: the training of the model helps ensure that data from a long time ago isn't being used to actively forecast the current value, meaning that the effects of storms, nourishment, or other events don't cause unreasonable values in the future.



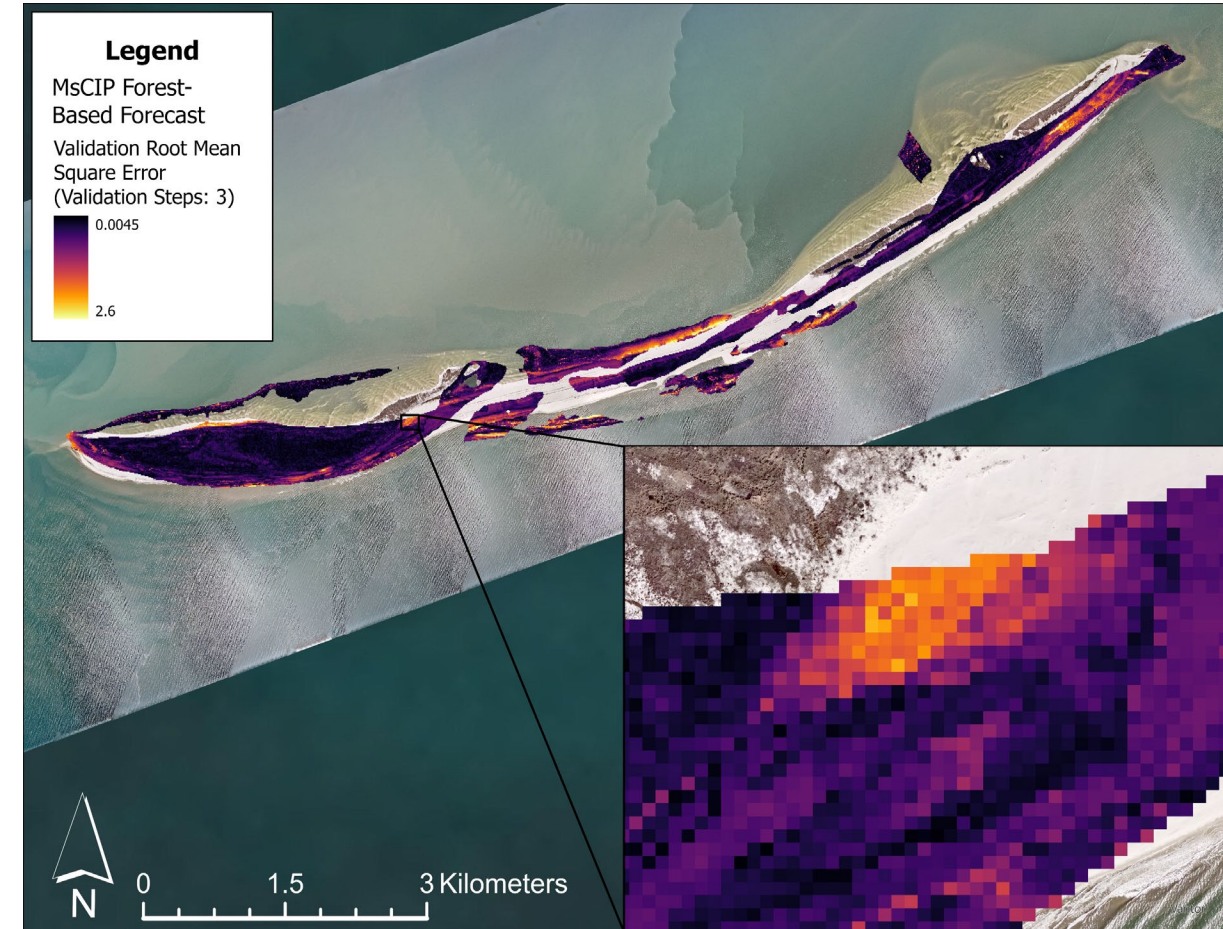
FOREST-BASED FORECASTING EXAMPLE



Forest Based Forecast for 2009 (10m Bins)



Forest Based Forecast Validation RMSE (10m Bins)



- The forest-based forecast generated the most realistic values across all forecast types
- Validation RMSE spiked in edge locations and where major changes have taken place (e.g. large storm impacts or placements), while the stable portion of the island showed lower RMSE error.



SUMMARY – LIMITATIONS & CONSIDERATIONS



Input Data Quality Matters

Data input into space-time cubes can greatly affect output statistics. Post-storm, post-nourishment, digital surface models vs. digital elevation models, and spatial resolution and uncertainty all have downstream effects.

Temporal Data Density Effects

Data that is temporally dense is ideal. Utilizing irregularly spaced, sparse data can limit many STC tools as there is a minimum of ten datasets and statistics become more robust with additional high-quality data.

Forecasting Tools

While some forecasting tools are able to generate realistic forecast values, none of the models are informed by coastal engineering understanding. Furthermore, all forecasting methods require very temporally dense data to be actionable.



SUMMARY – WHICH TOOLS SHOULD I USE?



Change Point Detection

Ideal for finding statistically significant changes from the norm – storm, nourishment, or other events. Raw value and trend changes are detected.

Emerging Hotspot Analysis

Ideal for detection of areas of statistically significant accretion and erosion (hot and cold spots) when utilizing difference rasters within the STC.

Local Outlier Analysis

Ideal for detection of outliers from the geospatial local norm. One of the few tools that utilizes spatial neighborhood information to derive products. Ideal to pair with emerging hotspot analysis.

Time Series Clustering

Ideal for grouping areas that exhibit similar patterns over time. Use cases with both elevation and difference rasters.

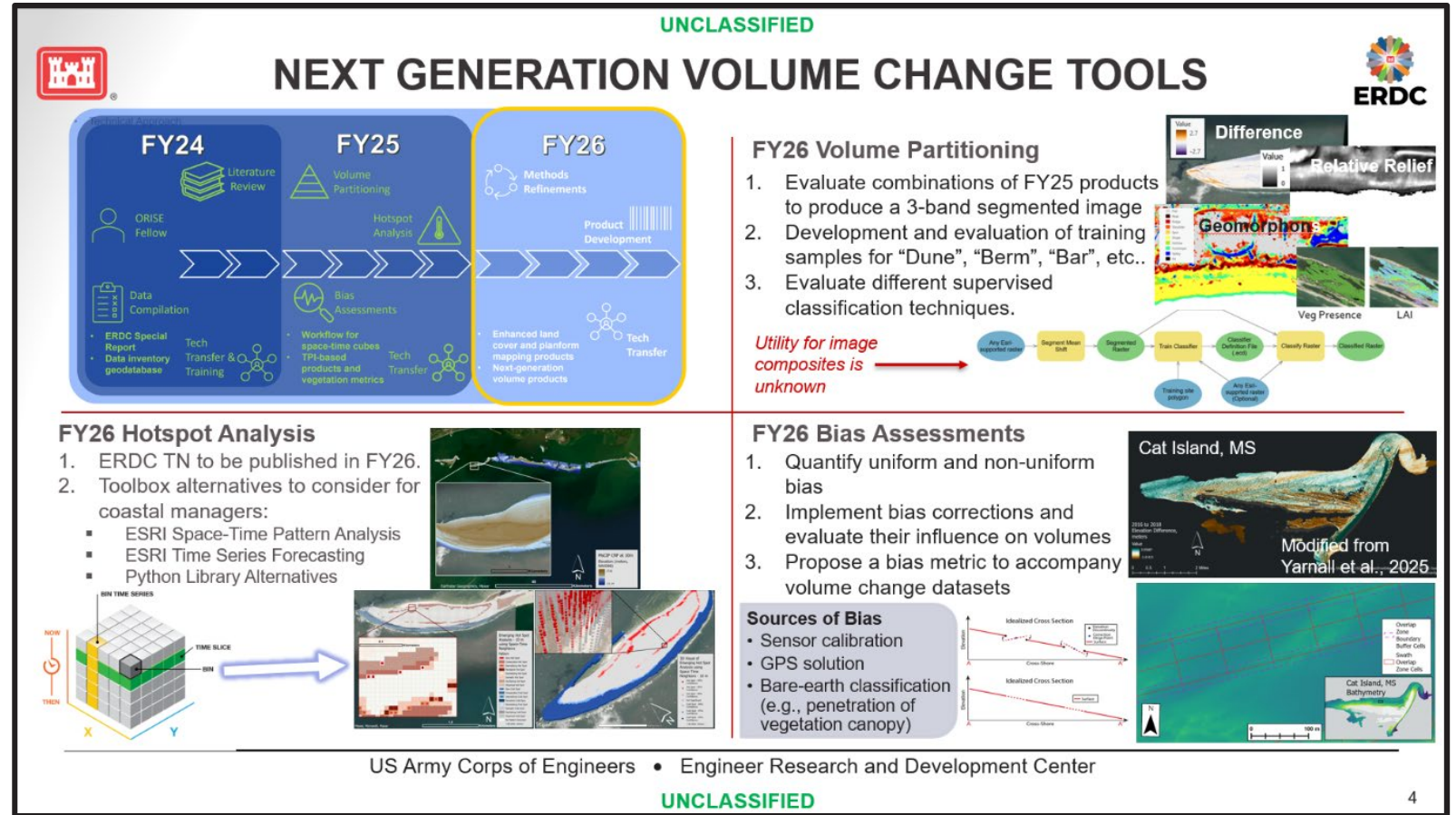


CONNECTING BACK TO NEXT-GEN VOLUME CHANGE



Goals of Next-Gen Volume Change Analysis

- ✓ Modernized geospatial volume change framework that leverages high-resolution elevation datasets and advanced spatio-temporal analysis methods to expand understanding of elevation change patterns and improve volume estimates.
- ✓ Advancement of available products that inform a broader understanding of coastal change.



QUESTIONS?

Scott Spurgeon & Brooke Walker
CIRP Next Gen Volumes Team



U.S. ARMY



US Army Corps
of Engineers®



ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER