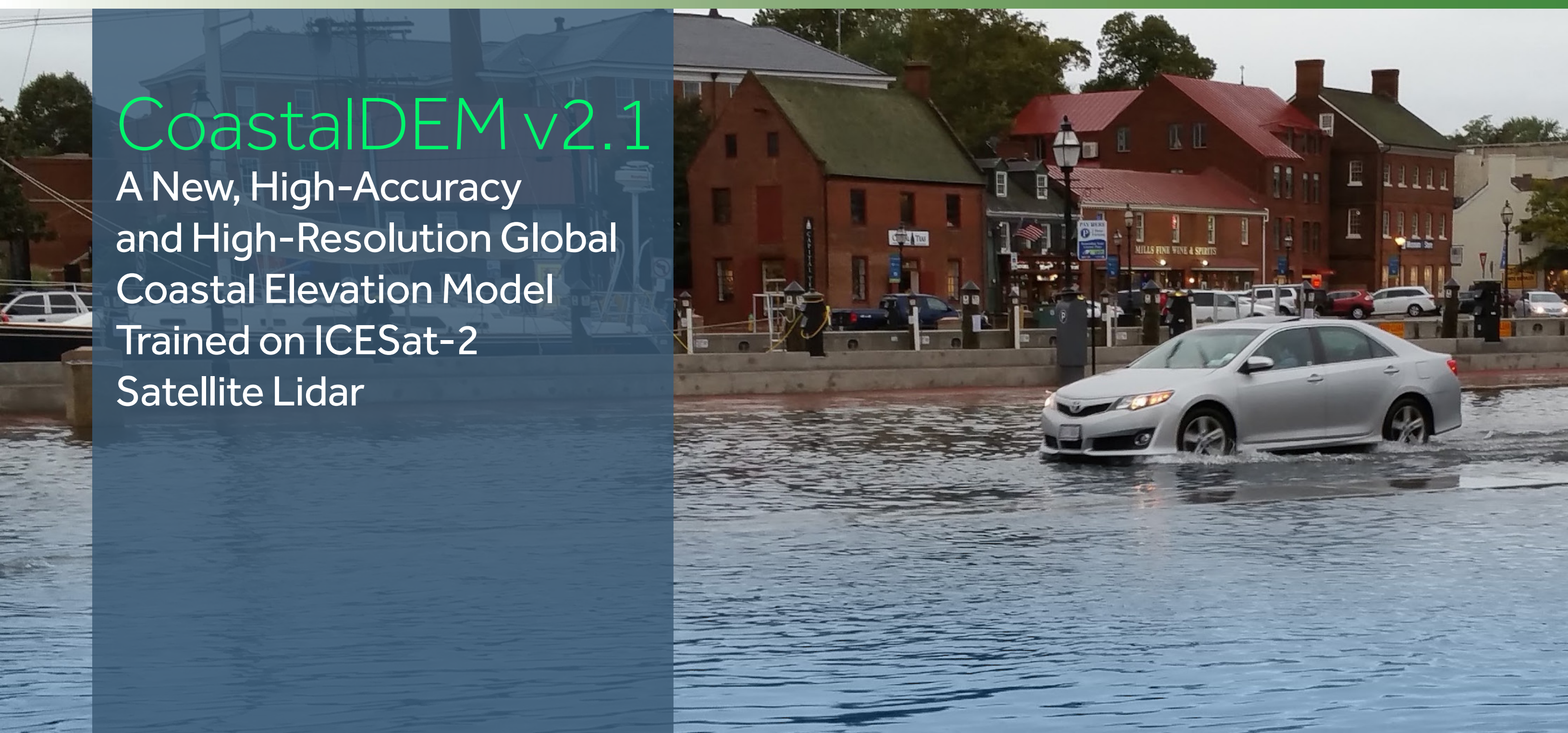

CoastalDEM v2.1

A New, High-Accuracy and High-Resolution Global Coastal Elevation Model Trained on ICESat-2 Satellite Lidar

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Research brief by Climate Central

CLIMATE CENTRAL

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A New, High-Accuracy and High-Resolution Global Coastal Elevation Model Trained on ICESat-2 Satellite Lidar

Climate Central is pleased to announce the release of CoastalDEM v2.1[1], a near-global digital elevation model for ocean coastal areas. CoastalDEM v2.1 has substantially reduced bias and error scatter than even its predecessor, CoastalDEM v1.1, making it the best-performing of all leading, publicly-available, global digital elevation models (DEMs) tested.

CoastalDEM v2.1 is the result of substantial new investment, new neural network architecture, and additional and improved input datasets. It is also informed by feedback from and interaction with many coastal flood risk practitioners and licensees of CoastalDEM from around the world.

Background

Accurate elevation data is essential to accurately assess the vulnerability of coastal communities to threats from sea level risk and coastal flooding. While a few developed countries, such as the U.S., Australia, the U.K., and a few others in Europe, have released high-quality elevation data derived from airborne lidar, most of the rest of the world, particularly developing countries, relies on lower-accuracy global digital elevation models derived from satellite radar. These DEMs suffer from large vertical errors with a positive bias [2,3]—especially in densely populated areas, where accurate vulnerability statistics are most important, but where satellite radar sensors often mistake building tops as hills and mountains[4,5,6].

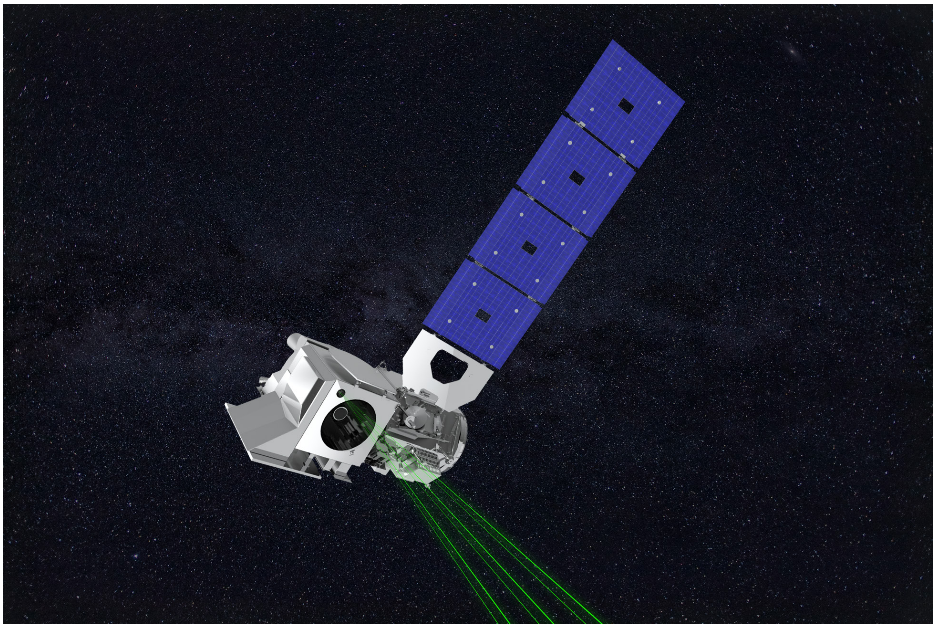
In 2018, Climate Central released CoastalDEM v1.1[3], a near-global coastal digital elevation model that used an artificial neural network to reduce errors present in a DEM derived from NASA's Shuttle Radar Topography Mission (SRTM). CoastalDEM v1.1 was tested against airborne lidar-derived elevation data in the U.S. and Australia, and showed greatly reduced vertical bias and root mean square error (RMSE) compared to SRTM in both forests and cities. Hundreds of users including corporations, government agencies, and research institutions licensed CoastalDEM v1.1 to investigate coastal flood risk due to sea level rise and storms.

Vertical bias refers to a systematic error in the modelled height of the land. In the case of NASA's SRTM, the mean vertical bias relative to elevation data from airborne lidar was positive 3.67m (12 feet) in the U.S. and 2.49m (8.2 feet) in Australia due to the tops of buildings and trees being measured in some locations rather than the land. This means the SRTM DEM overstates elevation of the land, which—as flood is the difference between water elevation and land elevation—results in understating flood risk.. Climate Central's CoastalDEM v1.1 reduced mean vertical bias to less than 0.01m (0.4 inch) in the U.S. and 0.11m (4.3 inches) in Australia[3]. The global consequences of this improvement, reduction in vertical elevation bias, was reported in the highly cited journal article in Nature Communications, New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding[7].

New Developments with CoastalDEM v2.1

Since the debut of CoastalDEM v1.1, NASA recently released an improved version of SRTM called NASADEM[11]. Climate Central used NASADEM as a better starting point for improvements using other data and machine learning techniques when creating CoastalDEM v2.1.

In late 2018, NASA launched the ICESat-2 mission[10], which measured the height of the Earth's surface using multiple laser altimeter beams, satellite lidar, across the entire globe. CoastalDEM v1.1 featured error reductions based on a neural network trained on airborne lidar in the U.S. and applied to the world dataset. Training the neural network on U.S. elevation data ran the risk that elevation corrections generated by the neural network might not be appropriate adjustments in areas in the world where buildings (building rooftops being the predominant source of error) are substantially different from the U.S. Climate Central used global ICESat-2 satellite lidar data, rather than U.S. airborne lidar data, as ground truth for CoastalDEM v2.1. This gives the neural network a more robust global representation of the built environment.



DEMs are gridded representations of the surface of the earth and each granular grid element is referred to as a pixel. CoastalDEM v2.1 predicts corrections for all NASADEM pixels on land between -10 m and 120 m elevation range, whereas CoastalDEM v1.1 only considered SRTM pixels whose elevation fell between 1 and 20 m. While computationally more expensive, this choice was aimed at improving results both in low, flat regions with areas of negative vertical error and locations with tall skyscrapers that cause errors when satellite lidar mistakes rooftops for ground.

Advances in artificial intelligence architecture allowed Climate Central to develop CoastalDEM v2.1 using a larger, more sophisticated convolutional neural network architecture. Neural networks use computational elements referred to as 'hidden units' to generate results. CoastalDEM v2.1 uses many thousands of hidden units to learn the highly nonlinear relationships between each of the input variables and the ground truth elevation. In addition to the benefits of massively greater numbers of computational units, the v2.1 convolutional neural network architecture is better suited to the problem than the v1.1 perceptron neural network architecture.

New and updated input variables contribute to better elevation corrections. CoastalDEM v1.1 used a total of 23 input variables, including SRTM elevation, population density, and vegetation density. For CoastalDEM v2.1, Climate Central acquired more accurate versions of many of these datasets and added new inputs. In addition, the convolutional neural network architecture allows over a thousand input variables for each pixel. These give the neural network much more context for each location to better improve predictions and reduce errors.

Improved Coastal Elevations

In order to assess worldwide accuracy of global DEMs, Climate Central compared land elevation measurements from NASA's ICESat-2 as ground truth to CoastalDEM v2.1, and 5 other recently released, widely-available global DEMs: CoastalDEM v1.1[3], NASADEM[11], TanDEM-X[12], MERIT[8], and AW3D30[13]. All DEMs were evaluated at their native horizontal resolutions, including both versions of CoastalDEM at 1 arc-second (≈ 30 m or 98 feet).

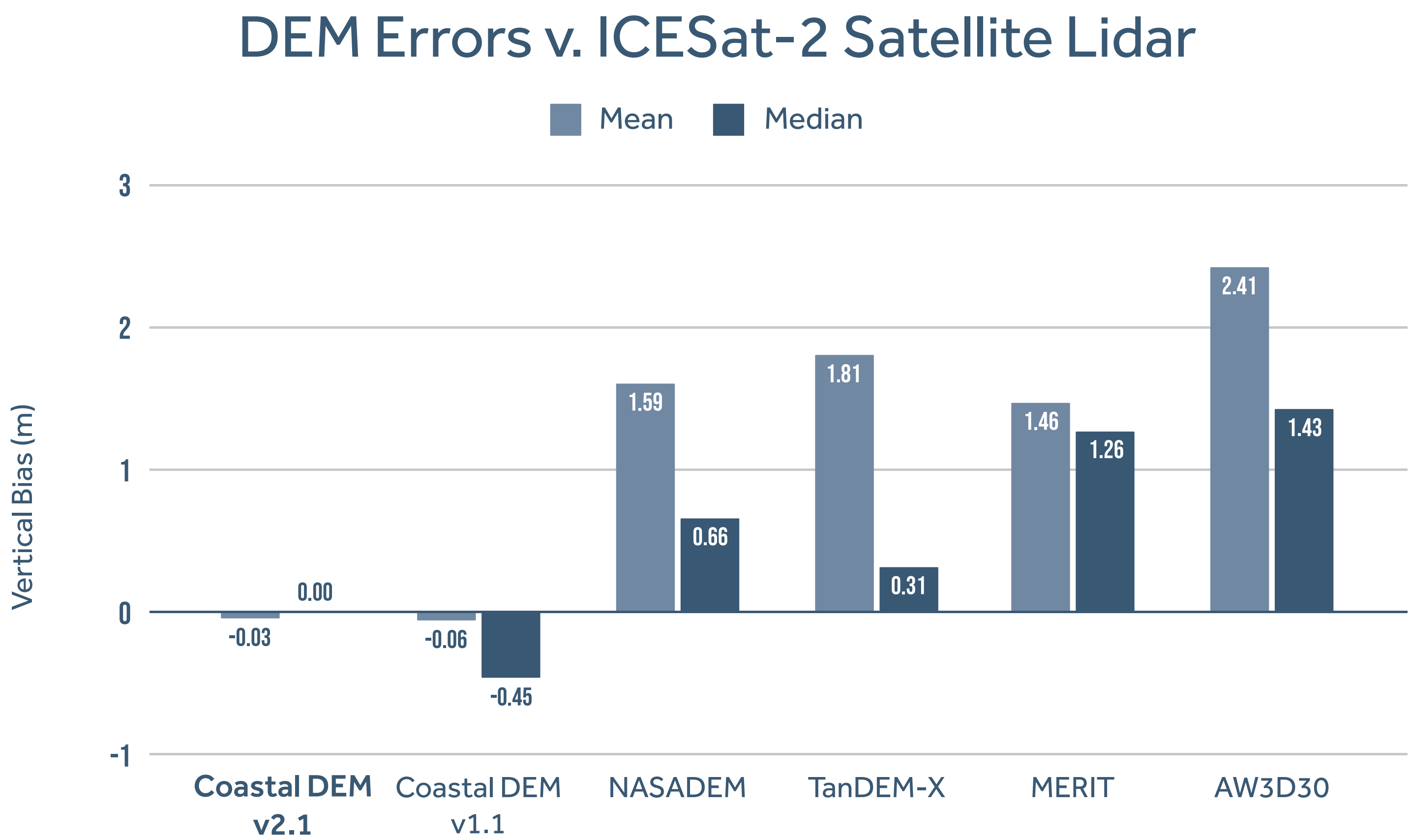
Climate Central empirically found that DEM performance—the ability to accurately correct elevations to ground truth—varies by elevation. Since CoastalDEM was created for the primary purpose of modeling coastal floods on land presently just above sea level with special interest in populated areas, land between 0 and 5 m and where population density exceeds 1,000 people per square kilometer is of greatest interest.

CoastalDEM v2.1 virtually eliminates global median bias to less than 0.01 m (0.5 inch) (Table 1) (Figure 1A). CoastalDEM v2.1 outperforms the other global DEMs by a significant margin in the whole of the most important 0 to 5 m elevation band, including all areas regardless of population density. For example, CoastalDEM v2.1 shows a mean vertical bias of -0.03 m (1.2 inches), CoastalDEM v1.1 has a mean bias of -0.06 m (2.4 inches), while the other DEMs show mean biases that range from 1.46 m (4.8 feet) to 2.41 m (7.9 feet) (Figure 1). A little more than an inch compared to almost 8 feet is huge when attempting to evaluate coastal flood risk due to sea level rise.

Table 1: Global bias error statistics across each DEM in the less than 5 m elevation band, and three population density bands (any density (Any), more than 1,000 people per square km (>1,000), and more than 10,000 people per square km (>10,000)). ICESat-2 is used as ground truth. For each row, only pixels whose elevation falls below the elevation threshold (according to ICESat-2 or the DEM), and whose population density falls within the given band, are considered. Rows presenting CoastalDEM v2.1 performance statistics are in blue.

DEM	Population Density	Mean Bias	Median Bias
CoastalDEM v2.1	Any	-0.03 m	0.00 m
CoastalDEM v1.1	Any	-0.06 m	-0.45 m
NASADEM	Any	1.59 m	0.66 m
TanDEM-X	Any	1.81 m	0.31 m
MERIT	Any	1.46 m	1.26 m
AW3D30	Any	2.41 m	1.43 m
CoastalDEM v2.1	>1,000	-0.11 m	0.08 m
CoastalDEM v1.1	>1,000	-0.47 m	-0.29 m
NASADEM	>1,000	1.21 m	1.01 m
TanDEM-X	>1,000	1.81 m	1.35 m
MERIT	>1,000	1.95 m	1.79 m
AW3D30	>1,000	2.60 m	2.19 m
CoastalDEM v2.1	>10,000	-0.20 m	0.42 m
CoastalDEM v1.1	>10,000	-1.15 m	-0.52 m
NASADEM	>10,000	2.05 m	2.01 m
TanDEM-X	>10,000	2.85 m	2.59 m
MERIT	>10,000	2.85 m	2.88 m
AW3D30	>10,000	4.25 m	3.70 m

Figure 1: **Global mean and median bias error statistics across each DEM in the less than 5 m elevation band, and all population density bands. ICESat-2 is used as ground truth.**



Using this new global ground truth data from ICESat-2, CoastalDEM v1.1 is found to contain small errors with a slight negative bias, meaning the land is slightly higher than represented in the DEM. This is consistent with field observations from CoastalDEM v1.1 users in locations where broad expanses of coastal land are only a few centimeters or inches above the high tide line. CoastalDEM v2.1 corrects that observed bias and shows the highest global accuracy when evaluated using these criteria.

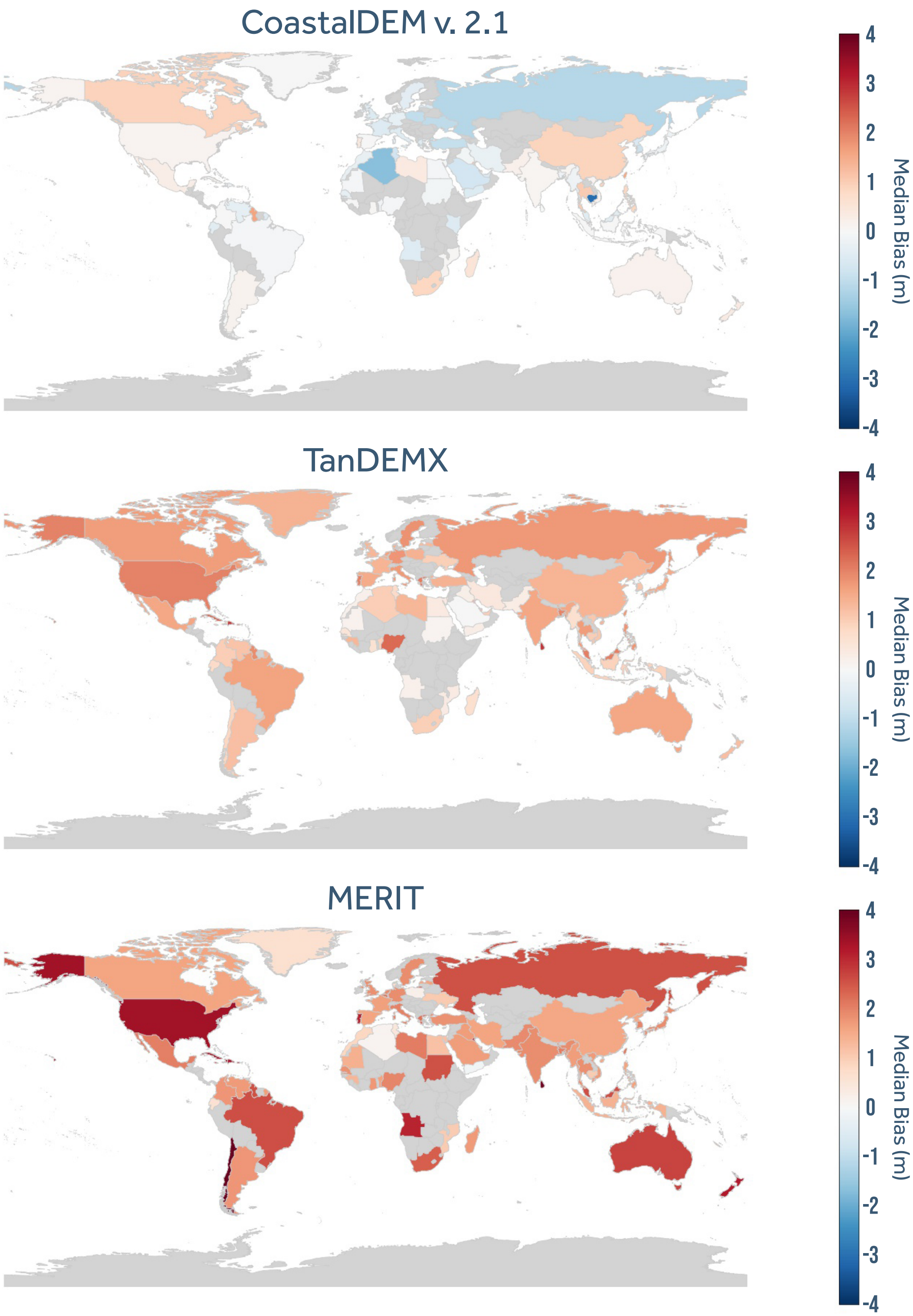
In coastal areas with moderate urban development, defined as greater than 1,000 people residing per square kilometer, and in the less than 5 m elevation range at greatest risk from tides, storms, and sea level rise, median vertical bias improves from -0.28 m (-11 inches) with CoastalDEM v1.1 to 0.09 m (+3.5 inches) with CoastalDEM v2.1. These CoastalDEM v2.1 bias results are 3X less than the bias of CoastalDEM v1.1 and 10X less than biases exhibited by the other comparable DEMs.

In segments of coastline with very high population density where more than 10,000 people per square km reside and where errors in satellite lidar measurements caused by tall buildings are most severe, and the same 0 to 5 m elevation range, CoastalDEM v2.1 shows a positive median bias of 0.42 m (1.4 feet) as compared to CoastalDEM v1.1's median bias of -0.38 m (-1.2 feet). The median biases of the other DEMs range from 2.04 to 2.84 m (6.7 to 9.3 feet). In heavily urbanized areas with the most people, this difference in elevation bias, CoastalDEM v2.1's 0.42 m versus more than 2 m, profoundly understates risk due to sea level rise. For comparison, most of the newest IPCC AR6[14] sea level projections estimate 0.5 to 1.0 m of sea level rise by 2100. In other words, the difference between CoastalDEM and the other DEMs is about 3X greater than the latest range of sea level rise amounts from the IPCC.

Performance Across Nations

Having a global satellite lidar elevation dataset from ICESat-2 affords the opportunity to evaluate CoastalDEM v2.1's performance across nations. Using colors and shading, Figure 2 uses Choropleth maps to show CoastalDEM v2.1's low vertical bias as compared to the other DEMs. These views give DEM users an indication of the relative confidence, in terms of bias when compared to satellite lidar ground truth from ICESat-2, they may have in CoastalDEM 2.1 versus the comparable global DEM's accuracy by region and country.

Figure 2: Choropleth maps presenting median bias under CoastalDEM v2.1, TanDEM-X, and MERIT in low-elevation regions across coastal nations, using ICESat-2 as ground truth. Only pixels with elevation < 5 m and population density >1000 people per square km are considered, and only nations with n ≥ 1000 of these pixels are evaluated.



Global ICESat-2 v. U.S. Airborne Lidar as Ground Truth

In addition to evaluating CoastalDEM v2.1's performance against ICESat-2, we evaluated its performance against airborne lidar-derived elevation data available in the U.S. and Australia.

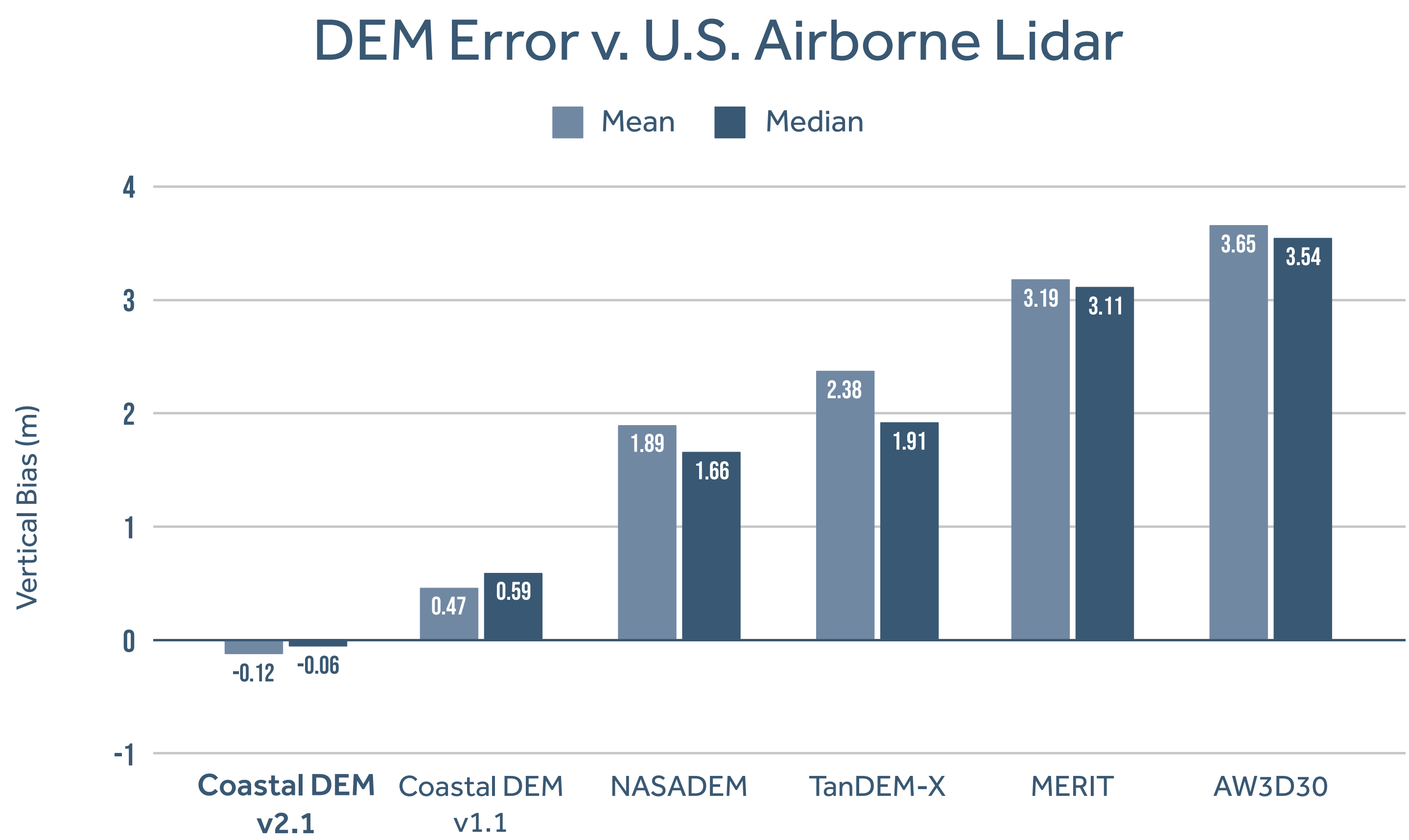
CoastalDEM v2.1's neural network is trained using global ICESat-2's elevation data as ground truth; CoastalDEM v1.1's neural network was trained using NOAA's U.S. coastal airborne lidar elevation data.

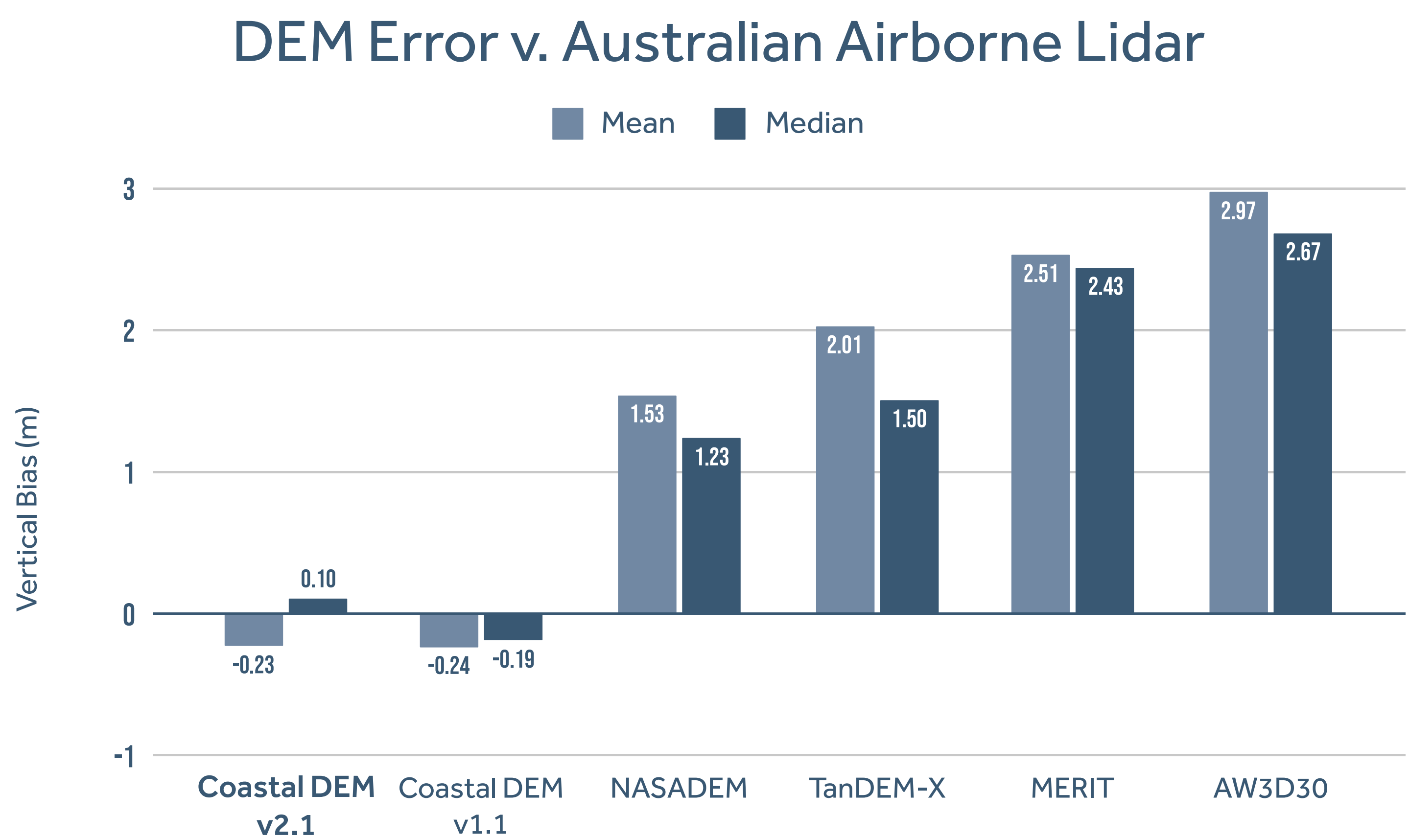
National results for both the United States and Australia, where grid cell population densities exceed 1,000 people per square kilometer, are presented in Table 2. The results show that CoastalDEM v2.1 exhibits median bias substantially closer to zero than each competing global DEM, and even outperforms CoastalDEM v1.1 in the US, which is particularly notable as the latter was specifically trained using NOAA's lidar-based US coastal DEMs as ground truth.

Table 2: Error statistics in the USA and Australia across each DEM in the less than 5 m elevation band. Airborne lidar-derived elevation data are used as ground truth. For each row, only pixels are included whose population density exceeds 1,000 per square kilometer.

DEM	Nation	Mean Bias	Median Bias
CoastalDEM v2.1	**US**	**-0.12 m**	**0.00 m**
CoastalDEM v1.1	US	0.47 m	-0.45 m
NASADEM	US	1.89 m	0.66 m
TanDEM-X	US	2.38 m	0.31 m
MERIT	US	3.19 m	1.26 m
AW3D30	US	3.65 m	1.43 m
CoastalDEM v2.1	**Australia**	**-0.23 m**	**0.08 m**
CoastalDEM v1.1	Australia	-0.24 m	-0.29 m
NASADEM	Australia	1.53 m	1.01 m
TanDEM-X	Australia	2.01 m	1.35 m
MERIT	Australia	2.51 m	1.79 m
AW3D30	Australia	2.97 m	2.19 m

Figure 3: Global mean and median bias error statistics in relation to U.S. (A) and Australian (B) airborne lidar elevation data across each DEM in the less than 5 m elevation band, and where population density is greater than 1,000 people per square kilometer.





These error statistics derived from DEMs based on airborne lidar are overall similar to the global results using data based on ICESat-2 satellite lidar. The airborne lidar ground-truth values were not used in computing CoastalDEM v2.1. The consistency in error assessment across testing approaches suggests the construction of the neural network model is valid and robust.

What's Next for CoastalDEM

Climate Central has invested and will continue to invest significant resources and energy into improving CoastalDEM. As more and improved additional data sets become available, Climate Central intends to add them in improving the neural network.

Climate Central is proud of CoastalDEM's performance. Yet the company acknowledges that it is not better than quality, expensive airborne lidar elevation data. In fact, Climate Central encourages coastal countries to develop and release quality airborne lidar data at no cost for use in evaluating coastal flood risk and in so doing, retire the need for CoastalDEM.

The original SRTM data from which NASADEM and CoastalDEM were derived was collected in the year 2000. The surface of the earth, especially in river deltas where groundwater and fossil fuel extraction are high, is changing with time. In addition, artificial earth works have the potential to alter the coastal risk profiles represented by SRTM, NASADEM, and CoastalDEM. This temporal quality calls for more up-to-date and regular refreshes of coastal DEMs with airborne lidar and new remote sensing capabilities that may become available.

Summary

CoastalDEM was developed to provide an improved, widely available, near-global digital elevation model for the primary purpose of evaluating coastal flood risk considering storms and sea level rise. With this use case in mind, elevations below 5 m are of particular interest as they span the range of most tides, storms, and projected sea-level-rise scenarios through the year 2100.

AVAILABILITY

CoastalDEM v2.1 is available at 30 m and 90 m horizontal resolution by license from Climate Central at:

https://go.climatecentral.org/coastaldem

No-cost, non-commercial licenses at 90 m horizontal resolution are available to qualified academic and research organizations.

Coastal areas with high population density are both areas where accurate vulnerability assessments are especially important and areas where the urbanized, built environment has challenged remote sensing technologies intended to measure ground elevations, resulting in material vertical bias that negatively impacts coastal flood risk assessments. Reducing vertical bias was the primary objective of creating CoastalDEM v1.1 and the objective of further investing in the improvements with CoastalDEM v2.1.

Performance data indicate vertical bias is consistently and substantially reduced with CoastalDEM v2.1. With version 2.1, CoastalDEM further improves its reduced-bias performance lead over comparable global DEMs. Near-zero bias means smaller elevation errors propagating into coastal flood analysis so critical to understanding the threats posed by sea level rise.

With no-cost licenses available and vertical bias demonstrably near zero, CoastalDEM v2.1 is a superior global DEM for sea level rise and coastal flood risk assessments.

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