https://doi.org/10.5194/essd-2026-277
Preprint. Discussion started: 1 June 2026

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The Global TanDEM-X High-Resolution Coastline Product

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Abstract. We present a globally consistent, high-resolution (10 m) coastline product (DOI: 10.15489/entfdgi5es81, German Aerospace Center (DLR), 2026) derived from the TanDEM-X DEM product of the German SAR satellite mission TanDEM-X. This vector product was developed with the aim of refining the TanDEM-X DEM, ensuring an optimal fit with this dataset. Additionally, the TanDEM-X coastline is a key component for deriving hydrographic data in the project HydroSHEDS v2.0 and thus defines the outer boundary of watersheds and rivers. To meet hydrological requirements, the TanDEM-X coastline was first extracted automatically and subsequently manually verified and improved. Since the coastline is a mapping feature located in the coastal zone, its position depends on the source data, the method used to identify the coastline, the time of acquisition, and the purpose of mapping. Due to this complex process and the lack of true reference data, a validation of the coastline product is challenging. Therefore, the quality of the TanDEM-X coastline is evaluated through statistical and qualitative comparisons in different globally distributed coastal areas and against multiple existing coastline products.

1 Introduction

The coastline is commonly understood as the feature that divides land and ocean (Boak and Turner, 2005). It is a key element in coastal mapping activities and figuratively represents the line of separation between nautical and topographic maps. Coastlines are used in a wide variety of geographic information system (GIS) applications to mask out data from the marine or terrestrial environment (Wessel and Smith, 1996; Baum et al., 2017). Common applications include coastal, littoral, and marine spatial planning, as well as the modelling of hazards such as tsunamis and storm surges (National Geodetic Survey, 2022; Baum et al., 2017).

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The global TanDEM-X high-resolution coastline product, hereafter referred to as the TanDEM-X coastline, is a global vector dataset that outlines the boundary between terrestrial and marine environments at a resolution of 10 m. The coastline product was developed in the projects TanDEM-X and HydroSHEDS v2.0. Within the TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurement), a global digital elevation model (DEM) was created in a public-private partnership between the German Aerospace Center (DLR) and Airbus Defence and Space (Zink et al., 2014). As inherent to radar-based DEMs, open water surfaces appear rough due to decorrelation effects and therefore require editing (Huber et al., 2021; Wessel et al., 2021). For the TanDEM-X DEM editing and the TanDEM-X coastline delineation, enhancements to open inland waters and ocean areas are made following two distinct approaches. A detailed detection of rivers and lakes allows for the flattening of inland water bodies and the assignment of individual heights. In contrast, the coastline defines where geoid heights corresponding to mean sea level are introduced for the ocean. Since the TanDEM-X coastline is derived from the TanDEM-X dataset, it provides an optimal fit for improving the DEM.

HydroSHEDS v2.0 is the second version of the well-established HydroSHEDS database, which contains global digital hydrographic information (Lehner et al., 2022). This new version is currently being produced through a collaboration between McGill University, DLR, Confluvio Consulting Inc., and the World Wildlife Fund (WWF). While the first version of HydroSHEDS (Lehner et al., 2008) was derived from the DEM of the Shuttle Radar Topography Mission (SRTM), HydroSHEDS v2.0 is based on the TanDEM-X mission's elevation data. In the context of HydroSHEDS v2.0, the TanDEM-X coastline defines the outer boundary of watersheds and rivers. In this respect, the coastline determines whether rivers emptying into the same bay belong to the same watershed or are part of distinct watersheds. Thus, the coastline is created with an emphasis on a systematic and consistent representation along estuaries and river deltas.

The TanDEM-X coastline product is automatically generated on a global scale and supplemented with manual checks to ensure that hydrological requirements are met. In addition to being an important input for the TanDEM-X and HydroSHEDS v2.0 projects, the global TanDEM-X high-resolution coastline product is publicly available as a standalone product under an open license.

Validating the coastline product and comparing it to existing data products requires examining the characteristics along the coastal boundary more closely. Among existing coastline products, both "coastline" and "shoreline" are used as descriptive expressions. Both terms describe a one-dimensional feature that divides water and land, but neither has width nor a transitional or dynamic expanse (Oertel, 2018). Oertel (2018) further differentiates a coastline as an approximate borderline on a larger spatial scale from the more precise shoreline. Thus, “coastline” is the preferable term to be applied at a global scale. Alternatively, Gens (2010) associates the term “shoreline”

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with coastal sciences, whereas "coastline" is more frequently used in the remote sensing community. Here, we use coastline and shoreline as equivalent terms.

A coastline is not a static object, but rather a dynamic feature that changes over time and space (Boak and Turner, 2005; National Research Council / Committee on National Needs for Coastal Mapping and Charting, 2004). On a long-term scale, the position of the coastline varies mostly due to sediment transport either through deposition or erosion processes (National Research Council / Committee on National Needs for Coastal Mapping and Charting, 2004; Oertel, 2018) as well as sea level rise (Nicholls and Cazenave, 2010) and tectonic uplift or subsidence (Melnick et al., 2026) on even longer temporal scales. In terms of short-term variability, the most obvious effect is that the water level is a function of the tides (Boak and Turner, 2005; National Research Council / Committee on National Needs for Coastal Mapping and Charting, 2004).

Due to the temporal and spatial variability of a coastline's position, any comparison of coastlines must consider their cartographic origin. Coastlines can be classified by the feature used to determine their position which are referred to as shoreline indicators. According to Boak and Turner (2005), these features can be separated into three categories of coastal characteristics, namely: visual identification; non-visible shoreline indicators from digital images; or specific tidal datums intersected with a coastal profile. Following the approach of shoreline indicators, the coastline extraction from data is divided into two steps. First, a suitable shoreline indicator must be identified. Secondly, the shoreline indicator must be detected in the source data to obtain a coastline.

The following sections describe the characteristics of the TanDEM-X coastline product and evaluate its quality. To this end, the process of deriving the coastline is outlined. The quality of the TanDEM-X coastline product is determined by comparing it to existing coastline products. Since the nature of the coast is heterogeneous and radar remote sensing data responds differently to specific coastal characteristics, the quality analysis covers a variety of coastal types. Finally, the performance of the coastline product is evaluated based on statistical and qualitative assessments.

2 Dataset overview

The global TanDEM-X high-resolution coastline product is a global vector dataset that outlines the boundary between ocean and land at a spatial resolution of 10 m. It was developed as part of the projects TanDEM-X and HydroSHEDS v2.0 and generated by the German Remote Sensing Data Center at the DLR. The TanDEM-X coastline product is based on the first publicly released version of the global TanDEM-X DEM. The data were acquired by the TanDEM-X mission between December 10, 2010, and January 15, 2015, in raster format at a grid-cell resolution of 0.4 arc-seconds. As part of the processing, the raster data are vectorized including a pixel-based

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smoothing. The minimum spacing between two consecutive vertices of the coastline polygon is 10 m and established in the final step of the dataset production. The coastline benefits from the high overall coverage of the TanDEM-X data of more than 99.89% globally (Rizzoli et al., 2017). The coastline product is delivered in the form of polygons that outline all landmasses. It is provided in WGS 1984 World Mercator projection (EPSG:3395). The coastline dataset maps a total coastline length of 1,908,532 kilometres and includes 396,543 islands in addition to the main continental landmasses. The TanDEM-X coastline product is depicted in Figure 1.

Figure 1: Global TanDEM-X coastline (10m) visualized in Robinson projection (EPSG:54030).

3 Materials and methods

3.1 Data for coastline generation

The TanDEM-X coastline product is derived from data acquired within the TanDEM-X mission. The TanDEM-X DEM (Wessel, 2018) has been publicly available since 2016. The height information for this DEM was derived from single-pass SAR interferometry. The TanDEM-X data have a resolution of 0.4 arc-seconds. This resolution corresponds to a squared grid cell with a cell length of 12 m at the equator and a declining cell width in longitude. Exact grid cell sizes can be found in the TanDEM-X DEM product specifications (Wessel, 2018). The TanDEM-X DEM is accompanied by a set of quality layers. Included are a minimum amplitude layer (AM2) and a mean

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amplitude layer (AMP) both indicating the intensity of the radar backscatter, as well as a height error map (HEM), which contains information on the coherence of the radar signal from multiple acquisitions.

In addition to the TanDEM-X data, an external coastline is required as a starting point for the coastline generation. This coastline is extracted from the Copernicus DEM data (DLR e.V. and Airbus Defence and Space GmbH, 2022). The Copernicus DEM was derived from the TanDEM-X data and is available in three versions with different coverage and resolution. The Copernicus DEM is accompanied by a set of ancillary layers, including a Water Body Mask (WBM). The Copernicus WBM is a raster dataset that distinguishes between ocean, land, rivers, and lakes. From this differentiation, a coastline is deduced that serves as provisional coastline for the TanDEM-X coastline generation.

3.2 Reference datasets

Existing coastline products have been developed for different purposes and from a wide variety of data sources. In consequence, these coastlines cover different scales from local to global and exhibit varying resolutions. A well-known global coastline product is the global, self-consistent, hierarchical, high-resolution shoreline database (Wessel and Smith, 1996), which was later named GSHHG. It is derived from the two datasets World Vector Shoreline (WVS) and CIA World Data Bank II (WDB), where the higher-resolution WVS is decisive for the land-ocean boundary. More recently, the global shoreline vector (GSV) was presented (Sayre et al., 2019), with the aim of producing a more up-to-date coastline compared to the GSHHG, and for the specific purpose of globally mapping ecological coastal units. The GSV is derived from Landsat 7 satellite imagery from 2014 at 30 m resolution using a semi-automated classification. The coastline position of the vector is located between the high and low water lines on the shore. Also, the Global CoastLine Dataset GCL_FCS30 (Zuo et al., 2025) was developed at global scale with the purpose of creating a foundation for a coastline classification. The GCL_FCS30 was generated using a Modified Difference Water Index and a threshold segmentation approach on Landsat imagery from 2010 to 2020. It has a spatial resolution of 30 meters. Freely available OpenStreetMap (OSM) data include a global coastline as well. It marks the mean high water level, which is the point of the highest tide or the mean sea level for coasts without tidal influence (OSM, 2022). The original data basis for the OSM coastline is the Prototype Global Shoreline (PGS) extracted from Landsat imagery via an automatic image recognition algorithm and manually refinement (OSM, 2022). The HydroSHEDS v1.0 database (Lehner et al., 2008) contains a landmask boundary of its hydrographic data that is used as a reference coastline. The HydroSHEDS database is derived from the DEM created within the Shuttle Radar Topography Mission SRTM and acquired in 2000, and filled with HYDRO1k elevation data north of 60°N. Correspondingly, the landmask boundary has a resolution of

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135 approximately 90 meters, and 500 meters north of 60°N. As global, standardized hydrographic dataset, the coastline extracted from the HydroSHEDS v1.0 database is valuable as reference dataset during the post-processing of the TanDEM-X coastline but omitted in the quality assessment due to its relatively low resolution. As these global coastlines may not always offer adequate resolution and quality for comparison against the TanDEM-X coastline product, additional local to national datasets are considered. One of these datasets is

Table 1: Overview of reference coastline datasets used for comparison

Name of dataset	Reference	Abbreviation	Source data	Coverage
Global Self-consistent, Hierarchical, High-resolution Geography Database	(Wessel and Smith, 1996)	GSHHG	World Vector Shorelines, CIA World Data Bank II, Atlas of the Cryosphere	Global
Global Shoreline Vector	(Sayre et al., 2019)	GSV	Landsat satellite imagery	Global
Global CoastLine Dataset	(Zuo et al., 2025)	GCL_FCS30	Landsat satellite imagery	Global
OpenStreetMapCoastline	(OSM, 2022)	OSM	Prototype Global Shoreline, Landsat satellite imagery	Global
HydroSHEDS v1.0	(Lehner et al., 2008)	HydroSHEDS v1.0	SRTM DEM, HYDRO1k elevation data	Global
Continually Updated Shoreline Product	(National Geodetic Survey, 2022)	CUSP	National Shoreline vectors, lidar, imagery, and cartographic data	Continental U.S. and parts of Hawaii, Pacific Islands, Alaska, Puerto Rico and the U.S. Virgin Islands
Küstenlinie Nord- und Ostsee	(LfU, 2018)	LfU	Shapefiles from European Water and Marine Strategy Framework Directives	German Baltic and North Sea coasts
Digital Earth Australia Coastlines	(Bishop-Taylor et al., 2021)	DEA	Landsat satellite imagery	Australia

NOAA's Continually Updated Shoreline Product (National Geodetic Survey, 2022), which covers the territory of the U.S. It is compiled from multiple data sources, and its accuracy is thus variable between 1:1,000 and 1:24,000. A German coastline by the Landesamt für Umwelt Schleswig-Holstein (LfU, 2018) was established in the wake of endeavors around the European Water Framework Directive with a specified resolution of 1:5,000. It covers the German North Sea and Baltic Sea coast. Digital Earth Australia Coastlines (DEA) is a national dataset generated by using three decades of Landsat imagery, visualizing the dynamics of Australia's coastline at mean sea level (Bishop-Taylor et al., 2021).

Next to the freely available coastline data, commercial products also exist, such as the WorldDEM Ocean Shoreline. The WorldDEM Ocean Shoreline is a 12m-resolution shoreline vector derived from the WorldDEM (Airbus Defence and Space). Given that the TanDEM-X coastline product is available under a permissive license, the following evaluation considers solely freely accessible datasets. A summary of the utilized coastline datasets is provided in Table 1.

As additional hydrographic reference data, the HydroLAKES database (Messager et al., 2016) is consulted within the manual post-processing of the TanDEM-X coastline. This database presents lakes, including some lagoons, as vector shorelines at global extent. It was created from a variety of source datasets at different resolutions and scales.

3.3 Coastline extraction method from global TanDEM-X DEM data

The TanDEM-X coastline extraction is a semi-automatic process. The first stage is the automatic extraction from TanDEM-X DEM data. In the second stage, the automatically derived coastline is manually modified to suit hydrological applications at transitional water bodies between inland and ocean waters. The overall production workflow is depicted in Figure 2. The automatic extraction is described briefly in the following; further details can be found in (Huber et al. 2021). The manual correction is outlined in Sect. 3.4.

The global coastline is created batchwise in 1°x1° tiles. As such, the processing aligns with the format of the input TanDEM-X DEM data. The utilized raster datasets are the elevation (DEM), amplitude imagery (AMP), and a height error map (HEM) at a resolution of 0.4 arc-seconds, which is equivalent to 12 m at the equator and a declining cell width in longitude towards higher latitudes (Wessel, 2018). These datasets correlate with the shoreline indicators following the approach of Boak and Turner (2005) outlined in Sect. 1. Information on which area is land and which is ocean is derived from these layers. In addition to the TanDEM-X raster data, an external coastline is required as an auxiliary input dataset. The external coastline is extracted from the WBM Quality Layer of the Copernicus DEM and serves as starting point for the TanDEM-X coastline. This input coastline is

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cartographically modified via morphological dilatation or erosion using a threshold approach for the input raster layers (DEM, AMP, HEM). If the values from DEM, AMP, or HEM exceed a certain threshold for a given pixel, the pixel is assigned to the land or water mask, respectively. The threshold is a fixed value assigned to each layer; however, it can be modified for each individual tile. This allows to adapt the processing to local conditions prevailing during data acquisition, e.g. frozen water. Generally, open water areas exhibit noisy elevation values in the DEM, low amplitude signals (AMP) and high errors in the HEM due to a loss of coherence in the backscattered signal.

An elevation value above mean sea level in the DEM is, however, not a reliable indicator for land, because it can occur in occur in noisy open water areas according to the AMP layer. Therefore, all input layers must be analyzed in combination.

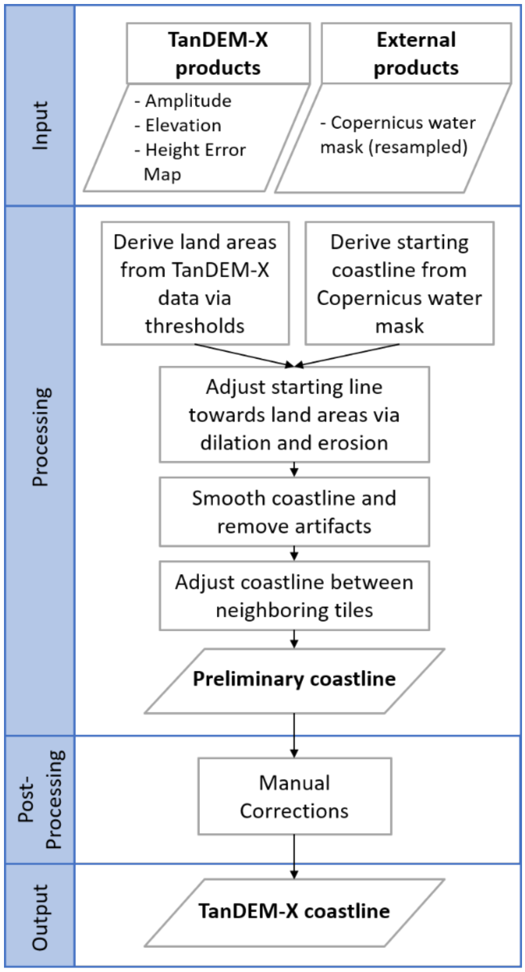

Figure 2: Workflow for the semi-automatic TanDEM-X coastline delineation

Since inland water areas and ocean cannot be differentiated from the radar data, the automatically derived coastline remains within a defined boundary around the externally defined starting point. This distance threshold is a fixed value but can be modified for each tile depending on the characteristics of coastal area. In the next step, artifacts are removed, e.g. falsely identified ocean pixels fully enclosed by land area are eliminated (i.e., flipped to be land), and a pixel-based smoothing is applied at the land-ocean boundary. Nonetheless, after vectorization the polygon dataset (where all land is represented as a polygon) maintains its edgy shape originating from the raster-based approach. Lastly, the coastline polygons of neighbouring tiles are adjusted to achieve a smoothed transition. The result is a preliminary global coastline polygon.

The preliminary coastline consists of closed polygons, which do not contain any holes. The overall quality of the coastline corresponds to that of the TanDEM-X dataset. The spatial resolution of 0.4 arcseconds is transferred to the coastline product.

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3.4 Criteria for manual coastline correction

Because specific elements of the automatically derived coastline, including its efficacy for hydrologic applications, are considered insufficient, the coastline is post-processed. Due to the natural variability of transitional water bodies and how they shape the coastal zone, manual input is required to attempt a consistent coastline at global scale. As a general mapping rule, the depiction of coastal characteristics is determined by the underpinning TanDEM-X DEM data. These key characteristics of the coastline product are outlined for various coastal forms in Sect. 4.2 and 4.3.

The manual corrections are directed particularly toward water bodies in the coastal zone that cannot be conclusively classified as either ocean or inland water. Due to the gradual transition, these water bodies often feature mixed characteristics or cannot be distinguished by radar data. Local conditions include, for example, the salinity of water, the presence of flora and fauna, the extent of tidal influences, and sediment transport. Aiming to obtain a globally consistent coastline product, the coastline is therefore manually modified. In this process, the margin within which the coastline can deviate from the starting line is adapted to suit local conditions. This applies to river deltas and estuaries, where consistent positioning is challenging due to the inherent variability and individual shaping. The position of the coastline cannot be tied to specific parameters, such as the width of a river. For example, even a relatively small distributary channel within the vast expanse of the Amazon River Delta can exceed the width of another river's main channel at its widest point. This challenge is addressed by an expert-driven heuristic approach within the post-processing. To determine the coastline position, reference coastlines (see section 3.2) are taken into consideration. As a rule, the presence of a river mouth is indicated by locally introducing an artificial shape to the coastline. This indicates not a true land-ocean but an inland water-ocean boundary. It allows the presence of rivers to be inferred when viewing the TanDEM-X coastline without background information, such as satellite imagery.

Similarly, lagoons, inlets, and other coastal features have been reviewed in the manual post-processing. For the TanDEM-X coastline, such water bodies are considered to be part of the ocean when an open connection to the ocean is visible in either (1) the TanDEM-X DEM, i.e. the width of the opening exceeds the resolution of the underpinning data or elevation has been smoothed out during previous processing of the DEM, or (2) in the amplitude data, in particular considering that wet sand appears similar to water. Lagoons and coastal inlets are further evaluated by comparison with their representations in other coastlines that serve as reference datasets, in particular including the GSHHG coastline (Wessel and Smith, 1996) as well as the products of HydroSHEDS v1.0 (Lehner et al., 2008) and HydroLAKES (Messager et al., 2016).

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Alongside revision of the water-water boundary, minor technical corrections of the coastline vector dataset are also implemented in this step. Two examples of manually modified areas are islands and humanmade coastal infrastructure. The origin of these misalignments can be ascribed to the resolution of the input data and the resulting coastline. Islands, which are part of the TanDEM-X coastline, must be of a size that is detectable in the source data, i.e., islands cover at least one pixel. Furthermore, islands must have a certain minimum distance to neighboring islands or mainland in order to be detectable as separate features. In the case of islands, features that are not considered permanent are removed, i.e., tidal flats that appear as islands in the preliminary coastline polygon. Islands are considered permanent when vegetation is present or the appearance of the ground is rocky in satellite imagery. Sporadically, islands entirely missing in the TanDEM-X DEM can be filled with external height information, e.g., from the Copernicus or SRTM DEMs. Narrow elongated humanmade structures (e.g., piers or protective walls) that, due to size and orientation, appear as multiple pixel-sized islets are fused to one single feature. Structures that are identified as floating non-permanent structures, such as boats in harbors, are removed. Layover and shadow effects in the SAR data may locally occur where the terrain is very steep, e.g., at fjords. This effect cannot be compensated for during the processing and might cause a local displacement of the coastline.

3.5 Validation strategy

The validation of the TanDEM-X high-resolution coastline is performed by comparison with reference coastline products. The areas chosen for validation are intended to capture a range of coastal characteristics. A quantitative statistical evaluation is conducted based on local higher resolution products outlined in Sect. 4.2. As statistical measures, the mean distance, maximum distance, and standard deviation of distances between the TanDEM-X coastline and corresponding local reference coastlines are computed. Where local references are absent, the OSM coastline is used for comparison. Distances between two coastlines are calculated by extracting equidistant points from the TanDEM-X coastline and searching for the closest point on the reference line using default GIS tools. The statistical evaluation is complemented with a visual comparison in Sect. 4.3. For this qualitative analysis, global coastline products are considered in addition to the regional references.

4 Discussion and validation

The accuracy of the coastline is evaluated through comparison with reference coastline datasets. Since the coastline vector dataset reflects how coastal properties are captured by radar acquisition, the analysis features study areas exhibiting diverse radiometric characteristics. The study areas are deduced from the coastal classification outlined in the following Sect. 4.1. The location of study areas is shown in Figure 3. Where available, a suitable reference

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dataset at fine resolution is considered for each study area. Global and local coastline products used in the comparison are described in Sect. 3.2. The comparison is divided into a statistical analysis in Sect. 4.2 and a qualitative description in Sect. 4.3. For the statistical comparison, the distance between the coastline and the corresponding reference dataset is assessed. Since the quantitative evaluation is only suitable when both coastlines cover the same coastal stretch, a visual comparison complements the validation.

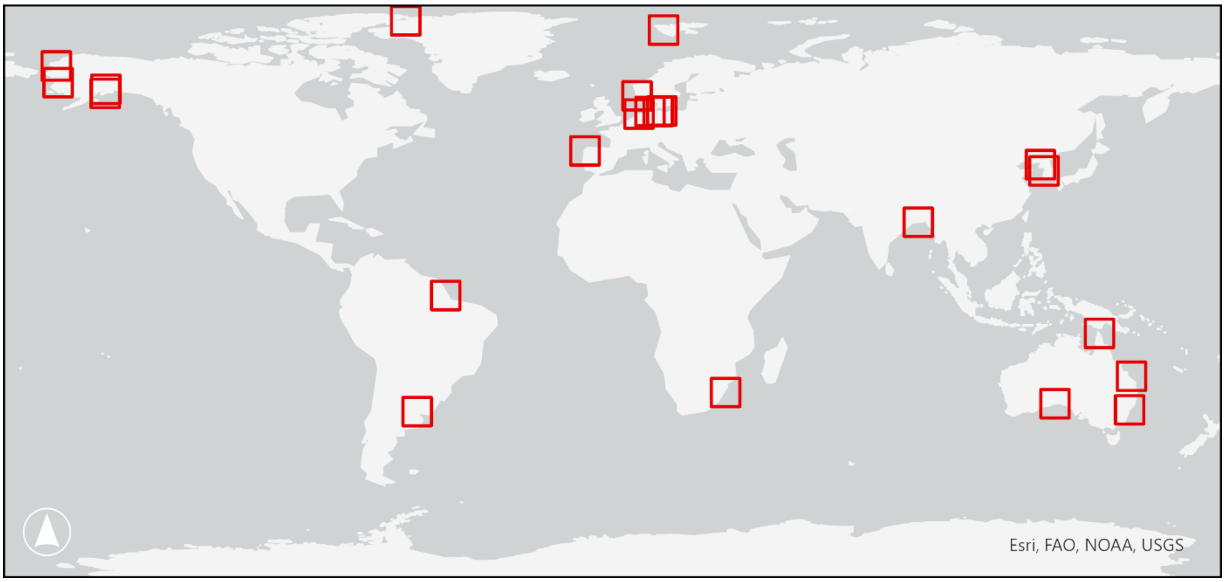

Figure 3: Locations of study areas for quality assessment. The base map was developed and designed by Esri, FAO, NOAA, and USGS | Powered by Esri.

4.1 Coastal types

The classification listed in Table 2 offers a broad but non-comprehensive overview of coastal types. Different coastal areas are subject to constant change and allow for a variety of mixed forms. The used classification scheme focuses solely on representative coastal types in order to select study areas for validation. The coastal types differ greatly from one another in terms of their extent and appearance in the radar image. Form and shape of the coast directly influence the data from which the automatic algorithm extracts the TanDEM-X coastline. Sandbanks and wide sandy beaches, for example, are under the influence of tides and only temporarily above the water surface. Among other influencing factors, the time of data acquisition is therefore decisive for the extent of the coast in the resulting data product. Furthermore, certain limitations of the radar system itself affect the appearance of coastal areas.

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A variety of coastal study areas was chosen to determine the accuracy of the TanDEM-X coastline product. The selection was guided by the aim of covering a wide variety of coastal appearances and the different challenges they pose for coastline extraction. Steep coasts such as rias, fjords, and firths are very similar in their radar depiction. Despite featuring different formations, their main characteristics, such as cliffs, usually simplify accurate image acquisition and allow for an accurate coastline delineation. Flat coasts present more challenges, as reflected in the variety of coastal types and their characteristics. In tidal areas, the position of the coastline changes horizontally with the water level. This effect is typical for mudflats and sandy beaches.

Table 2: Simplified coastal classification.

Form	Coastal type	Dominant processes
Steep coast	Ria Fjord Firth	Erosion, abrasion, cliffs, tides
Flat coast	Skerry Bodden Delta	Erosion. deposition
	Coral reef Mangroves	Phytogenic, zoogenic, biogenic deposition
	Mudflats Lagoon-barrier Sandy coast	Tides, deposition, marine erosion
	Estuary	Tides

Figure 3 provides an overview of the globally distributed study areas. Steep coasts and cliffs are examined on Rügen in Germany and Nullarbor National Park in Australia. A ria coast used for comparison is located in Spain. The study areas covering fjords are in Norway and Alaska, USA. Along the Baltic Sea coast in Germany, firths and bodden features are studied. Mudflats are found along the German North Sea coast and in Alaska, USA. Flat coasts, sandy beaches, and lagoons are examined in the USA and in South Africa. Coral reefs are typically located offshore and form a coastline where the reef structures emerge above sea level, for example in a study area featuring reef structures in the East of Australia. Study areas with mangrove forests are in Australia and in the

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Sundarbans between India and Bangladesh. River deltas and estuaries featured in the qualitative analysis include the Yukon Delta in the USA, the Amazon Delta in Brazil, and the Rio de la Plata in South America.

4.2 Statistical evaluation

In order to analyze the quality of the TanDEM-X coastline product, the coastline is compared to existing coastlines in a quantitative way. To obtain descriptive results, a close-to-ground-truth coastline dataset is required. Because none of the existing global coastline products is deemed superior to others, local reference datasets are consulted where available. An overview of reference coastlines is outlined in Sect. 3.2.

Table 3: Comparison of the TanDEM-X coastline with local reference coastlines.

Study area type	Region	Sample points [-]	Maximum distance [m]	Mean distance [m]	Standard deviation [m]
Bodde	Western Pomerania, Germany	58,782	351.65	18.04	25.08
Firth	Kiel, Germany	11,687	137.31	13.43	14.24
Fjord 1	Kenai Fjords NP, Alaska	4,777	233.01	14.86	25.57
Fjord 2	Lysefjord, Norway	44,049	250.42	14.11	16.21
Ria	Ria Baixas, Spain	10,636	297.46	14.68	31.16
Steep Coast 1	Rügen, Germany	1,901	54.33	13.89	11.14
Steep Coast 2	Nullarbor NP, Australia	6,328	69.33	16.16	12.97
Sandy Coast	KwaZulu-Natal province, South African	849	98.08	34.46	22.09

Table 3 displays statistical measures comparing the TanDEM-X coastline with local reference datasets. For the study area in Germany, the LfU coastline is considered, while the CUSP coastline is used in Alaska, and the DEA for reference in Australia. The OSM coastline is utilized where no local reference is available, i.e., for study areas in Norway, Spain, and South Africa. According to Table 3, the TanDEM-X coastline has the lowest distance to the reference for the firth and steep coast study areas in Germany, followed by the two fjord study areas and the

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ria coast. The common feature of all five study areas is the clear identification of the coastline in the underpinning SAR data. Fjord 1 and the Ria study area exhibit elevated standard deviations, likely attributed to variations in the cut-off of their respective fjord and ria structures, leading to greater maximum distances. Similarly, the bodden coast has a comparatively large standard deviation and maximum distance due to varying interpretations of bays along the coast. For the sandy coast study area in KwaZulu-Natal province, north of Durban, South Africa, the mean distance between TanDEM-X and OSM is relatively high compared to other test sites, whereas the maximum distance remains comparatively short. A detailed assessment shows that, although both coastlines are approximately parallel, they are spatially offset, with OSM positioned close to the waterline in the satellite imagery and TanDEM-X located further inland on the beach.

Alongside the statistical analysis between the TanDEM-X coastline product and reference coastlines, the total length of various coastline products is assessed. However, it must be considered that characteristics of the compared products, which influence the coastline length, vary, and a higher precision cannot be concluded from a greater length. This includes, for example, the intended purpose of their development, the resolution of the source data, and the time of creation. Therefore, the statistical analysis is complemented with a qualitative comparison in the Sect. 4.3. Table 4 illustrates the total length of coastline products at global extent. In this comparison, the GSV has the greatest total length. This coastline generally includes detailed information in branched coastal systems such as deltas and mangroves. Both the TanDEM-X and OSM coastlines fall within a comparable range. GSHHG has approximately 85% of the length of the TanDEM-X and OSM coastlines. This difference may, in part, relate to the date of creation and the resolution of the GSHHG product. The GCL_FCS30 coastline product is not included in this comparison, because the available GCL_FCS30 vector is not globally complete, as it excludes areas such as Greenland, the Canadian Arctic, and Antarctica. Following the same approach, Table 5 in the appendix breaks down the lengths of all coastlines for the individual study areas.

Table 4: Comparison of total coastline lengths

Dataset	Total length [km]
TanDEM-X coastline	1,908,532.70
OSM	1,918,360.03
GSHHG	1,614,980.29
GSV	3,826,892.73

4.3 Qualitative assessment of the TanDEM-X coastline product

A statistical comparison between coastline products is most indicative where both datasets cover a similar stretch of coast. Therefore, the quantitative analysis is complemented by exemplarily looking at test sites that exhibit

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larger differences in coastline positions. The study areas presented in the following section focus on different coastline positions arising due to coastal characteristics.

The quality of the TanDEM-X coastline compares to the quality of the underpinning DEM in terms of resolution, coverage, and depicted features. The global DEM is generated by mosaicking TanDEM-X acquisitions acquired over a period of five years. The lowest level of noise when retrieving the elevation is achieved when several acquisitions cover the same area. However, reliable height information can be maintained even when only one acquisition provided a processable signal. This effect causes a patchy coverage of tidal flats whenever a mix of low and high tide conditions were present during acquisition. Consequently, the automated detection process may interpret some areas within tidal influence as land in the coastline product, and some islands in mudflats may then be potentially eliminated during manual editing, but uncertainties remain. At sandy shores, the TanDEM-X coastline is often placed on the beach, commonly closer to the vegetation than to the average waterline, because the backscattered radar signal of sand is comparable to that of water. Overall, the shape of the TanDEM-X coastline appears jagged and has not been smoothed. The reason for this is that the coastline is derived from a raster dataset. For straight stretches of coast like beaches this can be regarded as a limitation. At the same time, the jagged shape fits better to irregular coast types like skerries and cliffs.

Panels (a) and (b) in Figure 4 show two study areas **influenced by tides**. Example (a) depicts two islands in the Lower Saxon Wadden Sea National Park in Germany. The depicted coastlines vary in shape. GCL_FCS30 only covers the island of Juist but has no information on Memmert in the bottom left-hand corner of the image. All other coastlines include both islands; they differ however in shape and size. GSV produces the largest land area, while the TanDEM-X coastline product exhibits the smallest area. Along the western edge of Juist, the largest deviations occur. The different coastline positions may arise from how sandy areas are derived from the source data of each coastline product. Also, the eastern coast of Juist shows different solutions. As the different shapes may correlate with the landward migration of Juist (Eitner, 1996), which features sediment deposition at the eastern spit, the differences may thus correlate with the time of acquisition of the underpinning data. Example (b) in Figure 4 shows a coastal stretch along the waterway Turnagain Arm in Alaska, USA. Here, OSM deviates the most from the other coastline products. While the tidal influence cannot clearly be defined from the satellite imagery, OSM seems to be the only examined coastline that aligns with the vegetation scarp.

The coastline at **mangrove coasts** is influenced by vegetation. Mangrove forests are vegetated wetlands in tropical and subtropical regions. Located in intertidal flats, mangroves are submerged at high tide and fall dry at low tide. In SAR data, the water level below the canopy cannot be retrieved due to the density of the canopy cover.

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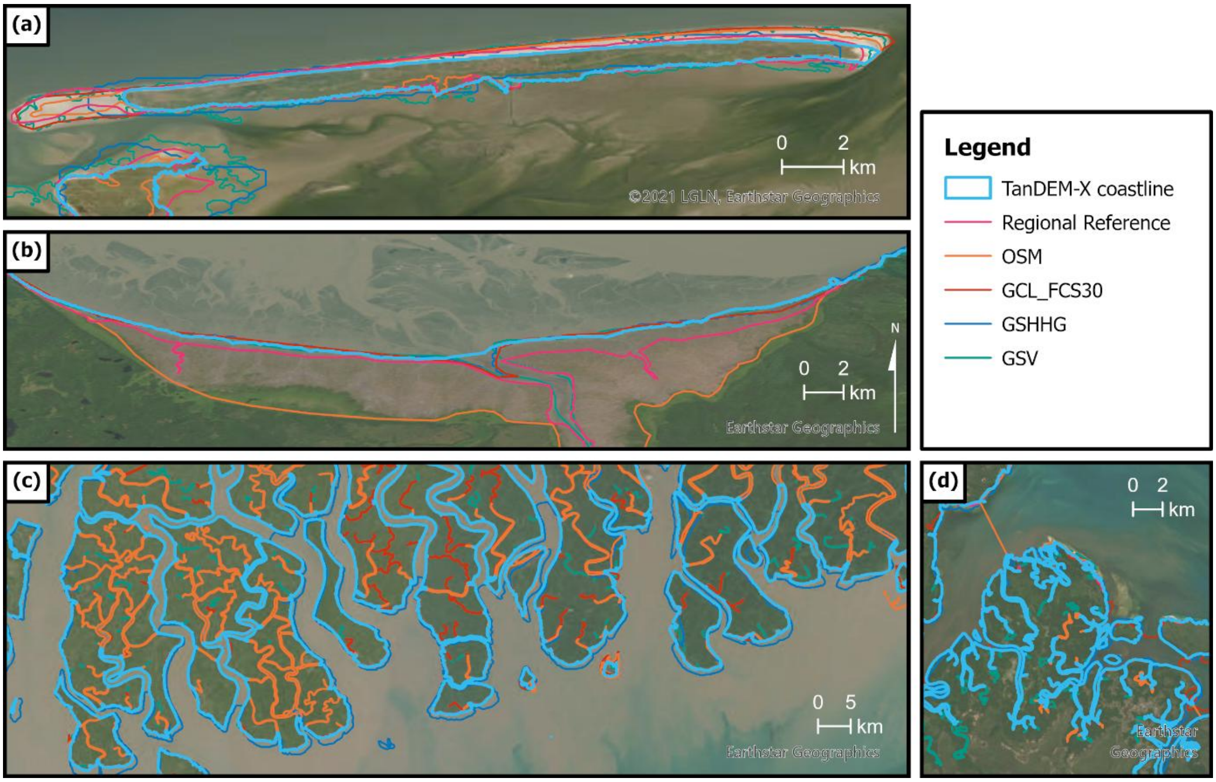

Figure 4: Visual comparison of the TanDEM-X coastline and reference coastlines for mudflats in Germany (a) and Alaska (b), and mangrove coasts in the Sundarbans (c) and Australia (d). Imagery: (a) © 2021 LGLN, Earthstar Geographics, (b) –(d) © Earthstar Geographics.

Therefore, the TanDEM-X coastline corresponds to the dividing line between forest and open water. As shown in examples (c) and (d) in Figure 4, mangroves typically feature a structure that looks like river mouths, often with multiple increasingly narrow branches. The TanDEM-X coastline includes the wider branches but omits the smaller ones. A comparison of the different reference coastlines demonstrates a varying level of detail. Panel (c) in Figure 4 shows a detail of the Sundarbans mangrove forest. GCL_FCS30 includes multiple branches and goes far inland. Also, GSV shows a high level of detail with regard to the branched waterways. GSHHG only includes larger inlets, however containing multiple islands along the coast. For the second example from Australia in panel (d) of Figure 4, a high level of detail can again be observed for GSV. Different from other coastlines, OSM cuts

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off the wider inlet to the left in the image while containing multiple branches east of it. Also, GCL_FCS30 is less detailed for the Australian study area.

Similar to vegetation at mangrove coasts, **ice sheets** obscure the exact position where land ends. Therefore, the coastline is affected by floating glacier tongues and ice shelves in northern latitudes and Antarctica. Most coastline products define the coastline based on the ice cover extent. This phenomenon is illustrated using the Petermann glacier in Greenland and a tongue of the Esmarkbreen glacier in Svalbard, displayed in Figure 5. In both cases, the glacier tongues' bay is surrounded by mountains and is characterized by a rocky shore. Accordingly, all products correspond well except for the area of the glacier tongue itself. Here, the coastline follows the edge of the ice at the time of its generation. As the glacier tongue of the Esmarkbreen glacier (Figure 5 b) only shows small variations, the corresponding coastline lengths of all products are similar (see Table 5, Ice Shelf 2). The glacier tongue of the Petermann glacier (Figure 5 a) is about 70 to 80 km long, 20 km wide and up to several hundred meters thick (Rignot, 2008). The grounding line is not visible in satellite imagery, and its identification requires complex measurements. Therefore, all coastline products follow the front line of the glacier tongue. In 2010, a giant iceberg of 260 square kilometers broke off and significantly shortened the floating part of the Petermann glacier (Falkner et al., 2011). The GSHHG was produced before this event, and its length is accordingly shorter. The OSM and the TanDEM-X coastlines were derived from different sources acquired at different times, which results in different representations of the glacier tongue's tip. The GCL_FCS30 is not available for Greenland and northern Canada.

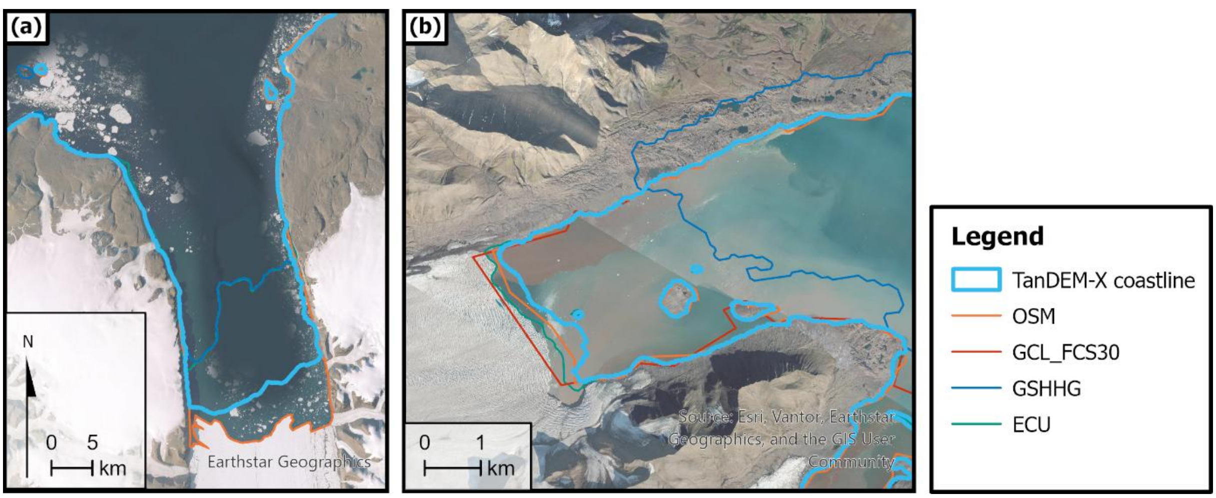

Figure 5: Coastal areas with floating ice at the Petermann Glacier in Greenland (a) and the Esmarkbreen in Svalbard, Norway (b). Imagery: (a) © Earthstar Geographics, (b) © Esri, Vantor, Earthstar Geographics, and the GIS User Community.

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Coral reefs present a challenging coastal type. The area above water is small and difficult to differentiate from areas where the water is very shallow. When remotely located from larger land, the data availability above coral reefs is limited. The TanDEM-X coastline includes coral reefs only if the area is covered by the TanDEM-X dataset. The coastline attempts to capture the areas of a reef that are located above water. This is challenging to distinguish from the underpinning SAR data. The breaking of waves causes an intense signal in the amplitude data. Therefore, the surf area can resemble land. Overall, reference coastlines are less complete across reef areas. A detail of Capricornia Cays National Park on the East coast of Australia illustrates reef structures in panel (a) of

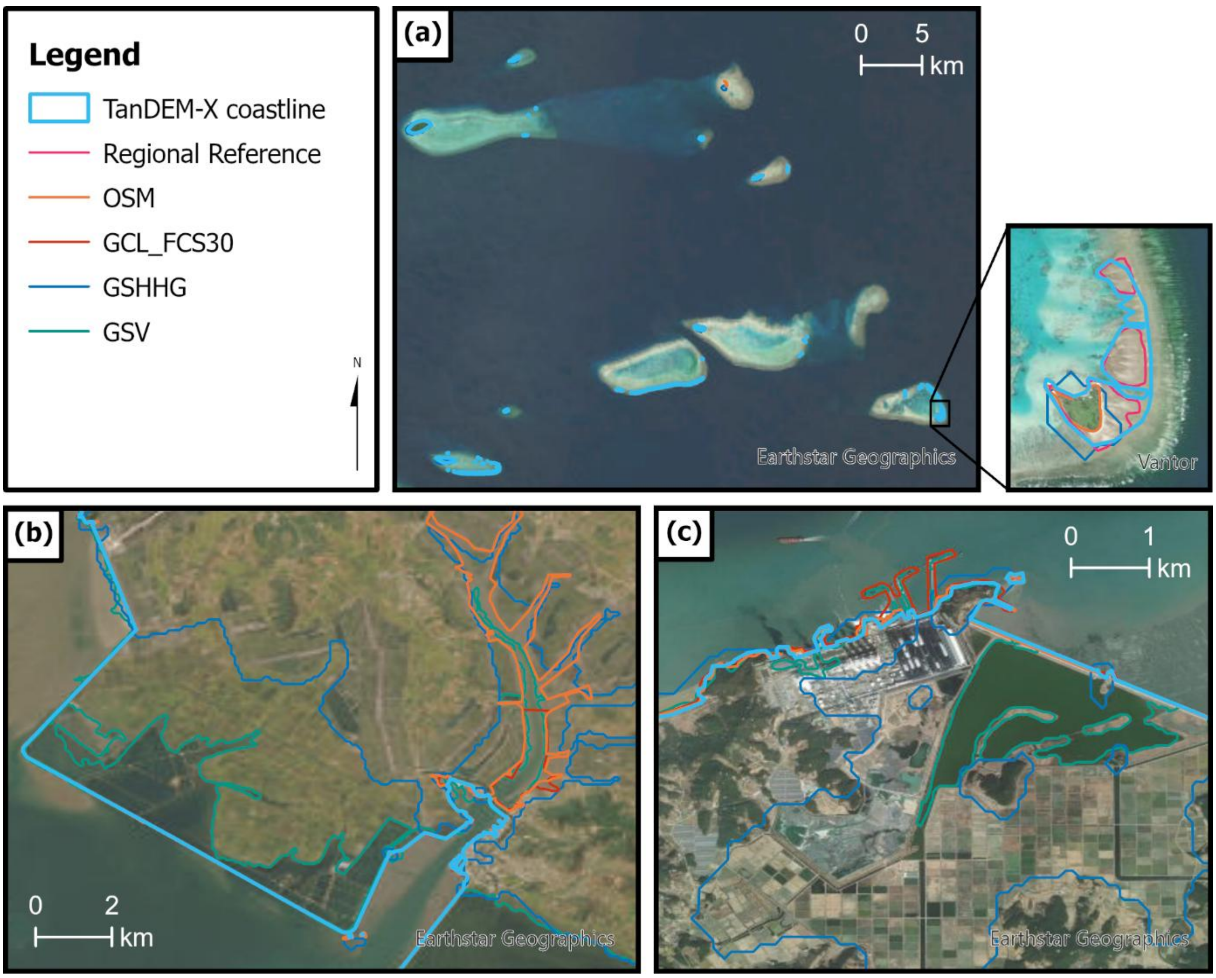

Figure 6: Detail of reef formations of the Australian coast (a), and areas subject to land reclamation practices in the Democratic People's Republic of Korea (b) and the Republic of Korea (c). Imagery: (a) © Earthstar Geographics and Vantor, (b) and (c) © Earthstar Geographics.

Figure 6. At this location, the GSHHG, OSM, and DEA coastlines are available as local references. While DEA and TanDEM-X provide similar information, the extent of land is smaller in GSHHG and OSM and limited to the greened area of cays.

Alongside natural settings, **human activities in the coastal zone** create challenges, due to both perceived changes caused by visual structures (e.g., piers) and actual changes in the location of the coastline through landscape alterations. Such practices include land reclamation and are, for example, observed in Southeast Asia. Figure 6 visualizes differences of global coastline products for one study area in the Democratic People's Republic of Korea (b) and one study area in the Republic of Korea (c). Differences between the coastline products originate from their date of generation, the tide level during data acquisition, and the definition of the border between land and ocean. As shown in Figure 6 (b) and (c), the GSHHG reaches much further inland in comparison to other coastline products. This is likely attributable to the fact that it is the oldest product, originally published in 1996. Also, the GSV product is placed landwards in the comparison, while others show a higher correlation among each other and are placed along structures parallel to the coast, just like dikes. However, the different products vary in details like piers and moles. Locks and culverts can lead to different shapes in detail whenever the coastline is drawn further inland. This is highlighted in Figure 6 (b), where the TanDEM-X coastline product cuts a land reclamation-affected bay at its mouth while all other products follow the bay further inland. Evaluating the coastline lengths (see Appendix Table 5, Land Reclamation 1 and 2), the highest correspondence is observed between the TanDEM-X and the GCL_FCS30 coastlines, both of which were released recently. GSHHG and GSV tend to be longer as they were either produced before the land reclamation activity (GSHHG) or do not consider artificial structures (GSV). The length of the OSM fits very well with the GCL_FCS30 and the TanDEM-X coastlines in case of panel (c), but differs for panel (b).

Where inland water flows into the ocean, the positioning of the coastline may be subject to larger differences between the coastlines depending on the approach that is applied. This is because a clear border does not exist and cannot be retrieved from the data. Next to **deltas and estuaries**, this also affects other water bodies in the coastal zone such as lagoons. Examples of deltas and lagoons are thus highlighted in the following.

Figure 7 shows the deltas of the Yukon River (a) and the Amazon River (b). While the level of detail is similar between OSM and TanDEM-X coastlines, the definition of the border between river and ocean differs significantly. While the TanDEM-X coastline attempts to treat very different deltas in a consistent way by locating where a river mouth widens significantly, the OSM coastline exhibits a greater variance. At the Amazon Delta, the OSM coastline is placed at the large inlets, while it features detailed river branches of the Yukon River Delta. The high level of detail of the CUSP coastline in panel (a) and GSV in panel (b) can be attributed to the respective

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purpose of creation, requiring to capture branched delta systems. GCL_FCS30 is only available for the Amazon Delta (b) and includes the main distributaries, while leaving smaller ones out.

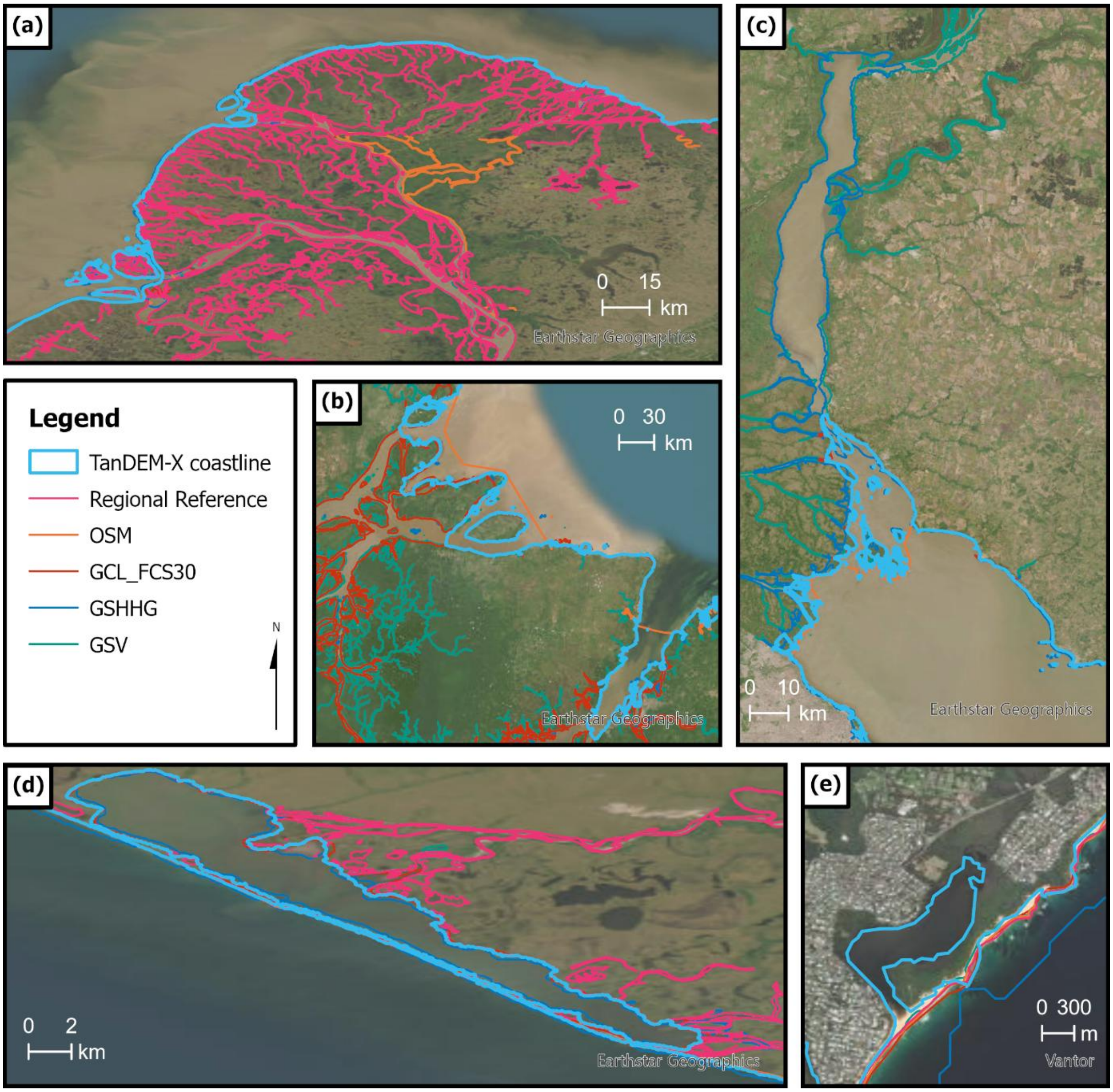

Figure 7: Comparison of coastline products at river deltas, estuaries, and lagoons: (a) Yukon Delta, (b) Amazon Delta, (c) Rio de la Plata, (d) Kivalina in Alaska, and (e) Wamberal Lagoon in Australia. Imagery: (a) - (d) © Earthstar Geographics, (e) © Vantor.

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Panel (c) in Figure 7 features the Río de la Plata in South America and compares four different coastlines. The rivers Río Uruguay and Río Parana empty into the Río de la Plata from the north and west, respectively. The mouth of the Río Parana is located in a flat area and forms a delta, while the mouth of the Rio Uruguay is not as branched and forms an estuary. From the east, the Río Negro empties into the same water as the Río Uruguay. Depending on the coastline definition, the Río Negro flows into the Río Uruguay or directly into the ocean. This situation is represented differently by the coastline products of TanDEM-X, OSM, GSHHG, and GSV. The TanDEM-X and the OSM coastlines define the line between inland water and ocean closer to the ocean. Accordingly, all three rivers join before emptying into the Río de la Plata in the case of the OSM coastline and thus form one catchment. In the case of the TanDEM-X coastline, the coastline position creates a separate catchment for the Río Uruguay and the Río Parana. Here, the Río Negro is a subbasin of the Río Uruguay. The coastlines of GSHHG and GSV reach much further inland. In both cases, the Río Negro forms a separate main river basin as it drains directly into the ocean instead of another river.

Lagoons are a common coastal feature. They are typically found where the tidal range is limited and the topography is rather flat. Partly divided from the open ocean, lagoons are challenging to handle in any coastline product due their different appearances. For the TanDEM-X coastline, the lagoon is considered ocean when an opening in the separating stretch of land, i.e., the barrier, is identified in the source data. This is particularly uncertain, however, when the barrier is mainly sandy, as the signal of sand resembles that of open water. In such a case, the lagoon seems to be connected to the ocean through open water even if in reality it may be fully enclosed. An example of this is shown in panels (d) and (e) of Figure 7. In the case of the Wamberal Lagoon in Australia (Figure 7 e), the TanDEM-X coastline differs from other reference coastlines in how the lagoon is treated. In panel (d) of Figure 7, multiple coastline products include the depicted lagoon in Alaska.

5 Data availability

The TanDEM-X high-resolution coastline product is freely available under a CC BY 4.0 license. It can be accessed via the EOC Geoservice of the German Aerospace Center DLR at https://geoservice.dlr.de/web/datasets/tdm_coastline (DOI: 10.15489/entfdgi5es81, German Aerospace Center (DLR), 2026). If the dataset is presented or used to support results of any kind, we ask to include a reference to the dataset in publications.

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6 Conclusions

The TanDEM-X coastline product is a global vector dataset that outlines the boundary line between land and ocean. Derived from the TanDEM-X DEM dataset, the coastline product has a spatial resolution of 10 m. This resolution determines the level of detail with which features are represented in the coastline. The TanDEM-X coastline product has global coverage following the extent of the underpinning source data which were acquired between 2010 and 2015. Manual corrections are applied to augment the coastline initially derived from an automatic workflow and provide a globally consistent vector product. To achieve this, global reference lines are consulted and guidelines are followed as outlined above. A quantitative and qualitative comparison with other coastline products reveals the overall high quality of the TanDEM-X coastline. Regarding transitional water bodies in the coastal zone, such as river deltas, estuaries, and lagoons, the TanDEM-X coastline attempts consistent positioning of the land-water transition line, which is informed by and benefits from the hydrological requirements established within the project HydroSHEDS v2.0 for which the TanDEM-X coastline provides the land boundary. Recognizing the complex and dynamic nature of coastlines, all static coastline products are a result of the data from which they are created, the time of acquisition, and the purpose of development. This challenge is addressed by using a clear processing approach combined with an expert-based post-processing. The TanDEM-X coastline as a product cannot be validated against an absolute ground truth, but its strengths and limitations are visualized in a comparison. Overall, the TanDEM-X coastline reflects the characteristics and backscatter properties of the underpinning radar data, including a very high resolution, a clear distinction between water and land at steep and rocky coasts, and a challenging interpretation of wet sand.

Appendix

The following table presents a detailed breakdown of statistics for all examined coastal areas. It features the coastline lengths of the TanDEM-X coastline, as well as the length of global coastlines and local reference coastlines, where available.

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Table 5: Overview of coastline lengths for all study areas

Coast type	Region	TanDEM-X [km]	Regional reference [km]	OSM [km]	GSHHG [km]	GSV [km]	GCL_FCS30 [km]
Bodde	Western Pomerania, Germany	342.84	392.49	361.36	283.78	277.60	152.13
Firth	Kiel, Germany	68.21	66.34	65.68	47.98	58.86	63.29
Fjord 1	Kenai Fjords NP, Alaska	24.15	25.86	22.63	18.05	20.13	18.99
Fjord 2	Lysefjord, Norway	227.47	-	243.40	201.56	239.00	203.64
Ria	Ria Baixas, Spain	78.15	-	84.09	81.29	81.61	69.12
Steep Coast 1	Rügen, Germany	11.04	9.87	9.79	10.07	10.31	9.67
Steep Coast 2	Nullarbor NP, Australia	53.91	49.82	50.65	50.13	49.48	48.39
Sandy Coast	KwaZulu-Natal, South African	7.46	-	6.50	7.01	6.52	6.52
Delta 1	Yukon, Alaska	335.53	7,481.04	2,131.60	613.26	2,059.26	553.16
Delta 2	Amazon, Brazil	3,723.12	-	2,438.75	10,746.44	25,174.31	9,661.37
Delta 3	Rio de la Plata, Argentina/Uruguay	993.33	-	406.58	1,255.03	2,882.81	544.68
Mudflat 1	Wadden Sea, Germany	51.55	48.90	53.98	45.92	82.18	36.57
Mudflat 2	Cook Inlet, Alaska	40.71	63.75	52.69	41.32	50.08	38.25
Reef	Capricornia Cays NP, Australia	66.20	32.58	26.33	28.63	22.57	-
Lagoon 1	Kivalina, Alaska	66.88	198.13	17.61	66.41	81.86	58.80
Lagoon 2	Wamberal Lagoon, Australia	6.61	2.10	2.06	1.47	2.06	2.00
Mangroves 1	Sundarbans NP, Bangladesh/India	2,155.89	-	4,479.51	1,541.36	5,950.42	4,371.56
Mangroves 2	Newcastle bay, Australia	330.95	135.71	135.72	132.26	382.11	65.91
Land Reclamation 1	Namp'o, DPR Korea	36.17	-	74.05	81.37	82.58	40.47
Land Reclamation 2	Taean, Republic of Korea	10.77	-	11.47	30.54	24.82	12.86
Ice Shelf 1	Kennedy Channel, Greenland	173.14	-	181.73	149.54	140.60	-
Ice Shelf 2	Isfjord, Spitsbergen	22.16	-	18.89	10.89	20.55	16.51

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Author Contributions

LW led the production workflow and dataset presented, with input from CK, LG, MH, BL, UM, and AR. Validation datasets were collected and curated by LW, CK, and LG. BL advised on hydrologic aspects of the product development. Management of the project and work presented was overseen by AR. All authors contributed to the manuscript text.

Competing Interests

The authors declare that they have no conflict of interest.

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