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Small Islands DEMs and Topographic Attributes Analysis: A Comparative Study among SRTM-V4.1, ASTER-V2.1, High Topographic Contours Map and DGPS

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Abstract: Rising sea levels due to global warming and climate change impact may prove a disaster for small islands. Accurate DEM can help to understand SLR (sea level rise) impact, coastal zones flooding risks assessment and hydrological attributes modeling and extraction. Currently, DEMs are available from several different sources using active and passive remote sensing systems. This research compares absolute surface heights accuracies retrieved from three independent DEMs datasets. The Shuttle Radar Topographic Mission (SRTM-V4.1) and the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER-V2.1) with 30-m pixel size, and a DEM-5 of 5-m spatial resolution generated from high topographic contour lines map at scale of 1:5,000 using simple Kriging interpolation method. Moreover, topographic attributes (slope and aspect) have been retrieved and compared. For the elevations validation purposes, a dataset of 400 GCPs uniformly distributed over the study site were used. These were measured using a DGPS assuring ± 1 and ± 2 cm accuracies, respectively, for planimetry and altimetry. The obtained results show that globally the landscape scale plays an important role in the selection of the DEM pixel size, which must reflect the real topographic attributes. Indeed, the derived DEM-5 from high topographic contours map (1:5,000) using simple Kriging exhibit the best accuracy of ± 0.65 m which is less than the tolerance or the total error (± 0.78 m) calculated based on errors sources propagation. Then, the results show an accuracy of ± 3.00 m for SRTM-V4.1 with which is less than the absolute vertical height accuracy (± 5.6 m) advocated by NASA for African continent and Middle-East regions. As well, the achieved ASTER accuracy was ± 8.40 m compared to the estimated error (± 17.01 m) by USGS and JAXA. Obviously, high spatial resolution and accurate DEM-5 is a crucial requirement to simulate and evaluate costal zones inundation under different SLR and storm flow scenarios for small islands. Decidedly, the elevation of small islands with topographic features not higher than 134 m can be estimated using SRTM-V4.1 with relatively acceptable accuracy. Whereas, this DEM is not significantly consistent for accurate SLR scenarios simulations. Without doubt, ASTER-V2.1 DEM was an excellent alternative compared to SRTM with 90-m pixel size, but actually with SRTM-V4.1 full resolution (30-m) ASTER-V2.1 will likely see its limited uses in geosciences applications. Indeed, ASTER is not providing accurate information to simulate the impact of SLR scenarios on small islands.

Key words: DEM, SRTM-V4.1, ASTER-V2.1, topographic contours, Kriging, DGPS, topographic attributes, seal level rise.

1. Introduction

According to United Nation [1], small islands developing countries (or states) by definition are small low-lying coastal zones, limited in size, and most vulnerable to the global warming and climate change impacts. Moreover, they have vulnerable economies and depend both on narrow resource bases and on international trade, with limited means to influence the terms of that trade. Around the world, there are approximately 52 small islands developing countries among them 37 are identified as independent nations including Kingdom of Bahrain [2]. The most environmental catastrophes experienced by these small islands are SLR (sea level rise), cyclones,

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volcanic eruptions, earthquakes, landslides, coastal inundation and erosion, and infrastructure destruction [1, 3]. Obviously, these negative natural disasters constitute severe and significant long-term menaces to small islands [1, 4-8]. Consequently, several international organizations have pointed to the need to produce comprehensive impact assessments of SLR, especially on small islands, in order to establish proper adaptation and mitigation policies [9].

During the last half century, the measurement of sea levels has become more accurate [8]. This is due to advances in both mathematical modeling, information technology, and computer sciences, which together have allowed for the collection of increasingly more accurate and extensive data especially towards the last three decades [7, 10]. The risk and danger are becoming imminent since the predicted SLR of over 1 m in this century [11]. Other climate models have predicted a global SLR between 0.18 m and 0.60 m. Similarly, by reference to the past two decades between 1980 and 2000, Solomon et al. [12] expected the global mean SLR may range from 0.18 to 0.80 m. However, other scientists included the contribution of rapid dynamic effects to ice sheets on SLR by 2100, concluding that 0.8 m SLR is "*likely*", but 2.0 m is "*plausible*" if the highest reasonable rates of acceleration are included in the model [13]. Of course, to be 1 or 2 metres SLR, the potential impacts increase significantly when populations and their related economic activities are highly concentrated along the coastal zones [14, 15]. For instance, an SLR of one metre would render Tuvalu and the Maldives uninhabitable [16]. Other small islands as Kingdom of Bahrain have a very limited capacity to adapt to climate change. It is exposed to risk of SLR due to the inability to accommodate significant landward migration of coastal habitats [17].

Furthermore, accurate DEM (digital elevation model) can help to understand the SLR impact, coastal zones and flooding risks assessment, flood inundation modelling, erosion and landslide [18], disaster and environmental process management, topographic attributes extraction, hydrologic indices modeling, etc. [19-21]. Moreover, DEM represent the topography that drives surface flow and is arguably one of the more important data sources for deriving variables used by numerous hydrologic models [22] and scenarios simulating SLR impact. Based on the requested accuracy and/or the nature of the project which is often determined by economical aspects (investment vs. accuracy), as well the condition of surveying environment (e.g. terrain accessibility, topography and geometry, vegetation cover, etc.) DEM can be created by several methods. These include surveying engineering, stereo-photogrammetry, altimetric GPS in situ measurements, Lidar altimetry, radar interferometry (InSAR), topographic map contours, and stereoscopic pairs of optical satellite imageries. However, although several DEMs such as SRTM (Shuttle Radar Topography Mission), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and GDEM (Global Digital Elevation Model) are freely available today on the web, choosing the appropriate data for a specific project remains a difficult decision [23].

Considering the high sensitivity and vulnerability of small islands to SLR, DEM accuracy analysis must be considered for different hydrologic connectivity modeling to project future change and probably to simulate the impact of several SLR scenarios. Otherwise, the question of an optimal DEM pixel size for small islands remains to be answered and probably depends on the variable as well as the properties of the landscape of interest. Consequently, this research compares absolute surface heights accuracies retrieved from three independent DEMs datasets. The SRTM-V4.1 and the ASTER-V2.1 with 30-m pixel size, and a DEM-5 (5 m) generated from high topographic contour lines map at scale 1:5,000 using simple Kriging interpolation method. As well, topographic attributes (slope and aspect) have been retrieved and compared. For elevations validation purposes, a dataset of 400 GCPs (ground control points) uniformly distributed over the study site were used. These were measured using a DGPS (Differential Global Positioning System) assuring ± 1 and ± 2 cm accuracies, respectively, for planimetry and altimetry. All the used DEMs were referenced to the same geographic coordinates system using UTM map projection (zone 39), WGS-84 geodetic reference, and EGM-96 (Earth Gravitational Model 1996) vertical datum. Kingdom of Bahrain was chosen as a study area for its smallest size with diver topographic features, not higher than 134 m, including narrow ravines and steep ridges, but also exhibits coastal plain topography along its coast.

2. ASTER and SRTM DEMs Accuracies Assessment: Literature Review

A large group of international scientists and investigators has conducted studies to validate the accuracy of the ASTER and the SRTM DEMs products considering several terrain morphology, different environment and target, etc. Testing the ASTER DEM over Vancouver (west Canadian territory), Toutin [24] demonstrated that the derived DEM is almost linearly correlated with the terrain slopes. Over the central Siberia (Russia) which is relatively flat area, SRTM (30-m) and space borne Lidar such as Shuttle Laser Altimeter-02 (SLA-02) were cross-validated by reference to field observation [25]. The obtained results showed that SRTM total error was ± 11.38 m for bare surfaces, but it reached ± 24.79 m for forest canopy. In southeastern Michigan (US), Brown et al. [26] combined national elevation data (NED) and GPS survey to evaluate the SRTM accuracy. They reported that the SRTM (30-m) mission specifications for absolute and relative height errors for the GCPs targets using DGPS were exceeded (≤ ± 3.3 m). A more extensive analysis of the SRTM and DGPS data indicates that it meets the absolute and relative accuracy requirements. Over Poland areas, the SRTM (30-m) data were validated using GPS in situ measurements and considering flat and hilly terrain, the obtained absolute accuracies were about ± 2.9 and ± 5.4 m, respectively, for flat and hilly regions [50]. Considering only SRTM (30-m) DEM, Gorokhovich and Voustianiouk [27] used GPS in situ measurements and two independent sites: the Catskill Mountains site in New York region (U.S.) and Phuket site in Thailand. Both sites are covered with bush and forest type vegetation up to 10 m high, but with some differences in geomorphometric characteristics. In Thailand site, elevations, slopes, and aspects were more variable than in Catskill Mountains. The results of this study showed that absolute average vertical errors could range from ± 4.07 m in Catskills to ± 7.58 m in Phuket.

Tighe and Chamberlain [28] used land elevation measurements and National Geodetic Survey verification check points to evaluate and to compare the accuracies between SRTM (30-m) and ASTER-V2 over several sites across the US representing various terrain slops (0º to 30º), different environment (arid, semi-arid and temperate) and mixed vegetation canopies (barren, shrub, deciduous, evergreen, mixed and wetland). They reported that overall the DEM accuracies were achieved with ± 15.27 m for SRTM and ± 18.52 for ASTER. However, they demonstrated that these accuracies vary with land cover classes; for example for bare soil with slopes less and greater than 10º, errors are ± 18.64 and ± 19.35 m for ASTER and SRTM, respectively. Based on a set of geodetic GCPs over Western Australia, Hirt et al. [29] have shown that the vertical accuracy of ASTER is approximately ± 15 m. They also reported that this accuracy varies as a function of the terrain type and shape, and it is relatively low in areas with low topographic variability. Using over 228,000 accurate point heights from Australian National Gravity Database, Rexer and Hirt [30] compared the SRTM-V4.1 and ASTER-V2.1 over the Australian continent. They showed that SRTM-V4.1 data are mostly superior to the stereoscopic ASTER-V2.1 with elevation error approximately ± 6.2 and ± 8.5 m for SRTM-V4.1 and ASTER-V2.1, respectively.

In Nigeria, Menegbo and Doosu [31] demonstrated that SRTM-V4.1 and ASTER-V2.1 DEM absolute vertical accuracies with reference to GPS ground control station are, respectively, ± 6.30 m and ± 8.86 m. Using a large scale topographic map for validation purposes in north-east of Tunisia, Ouerghi et al. [32] showed a satisfactory vertical accuracies ± 7.62 m for SRTM and ± 10.53 m for ASTER. They also discussed the significant accuracy of watershed delineation and drainage system extraction using SRTM-V4.1 data than ASTER-V2.1 DEM. In Amazonas state, northern Brazil, Grohmann [33] showed that ASTER-V2.1 presents a high level of noise and artefacts with low correlation to the terrain morphology. While, SRTM-V4.1 have a good correlation with Topographic data. Recently, Zhang et al. [34] evaluated the SRTM-V4.1 errors distribution across China territory and their associations with different topographic and land cover factors. They showed that globally the topographic attributes derived from SRTM-V4.1 represent adequately the topography of China. They demonstrated that slope was the dominant factor affecting elevation error compared with other landscape and topographic features (aspect, vegetation, etc.). Unlike other studies that have found in general a positive bias on SRTM-V4.1, mainly caused by vegetation and/or bare soil, this study across the China territory shows overall negative mean errors. The mean errors on glaciers, deserts and wetlands are, respectively, - 1.05 m, - 2.03 m and - 2.43 m. The greatest concentration of positive errors was the urban built-up type, with a mean error of + 1.05 m [34].

For moderate size volcano features quantification in Hawaii (US) and Tanzania (Africa), Kervyn et al. [35] reported a relative good accuracy for SRTM-V4.1 (± 8 m) compared to ASTER-V2.1 (± 13 m) by reference to a medium scale topographic maps, 1:24,000. To estimate mountain glacier volume variations in the French Alps using SRTM elevations, Berthier et al. [36] observed clear biases with altitude both on ice-free and glacier-covered areas; underestimation by up to 10 m. However, in southeast Alaska and adjoining Canada, the glacier volume changes determination using SRTM was assessed at ± 5 m accuracy through comparison between airborne laser altimetry and GCPs locations measured with GPS [37]. For hydraulic information retrieval in the area of "Alzette River" north of Luxembourg, Schumann et al. [23] compared remotely sensed water stages (waterline estimation) from LiDAR, topographic contours and SRTM (30-m). As was expected, the Lidar derived the water stages exhibit the lowest root mean square error (RMSE = ± 0.35 m), followed by the contours DEM (± 0.7 m). A surprisingly good performance of SRTM 30-m (RMSE = ± 1.07 m) suggests that this is a potentially valuable source for initial flood information extraction in large, topographically homogeneous floodplains, which exhibit a gently sloping river gradient. Considering a large River basins (Elbe) in Germany, Haase and Frotscher [38] reported that SRTM (30-m) data could be informative and applied in mesoscale and macroscale river network basin and terrain analyses for flood risk and wetlands ecology assessments with a cost effective economical factor. For water surface elevation estimation in Amazon River channel using SRTM (30-m), LeFavour and Alsdorf [20] obtained ± 5.51 m absolute error.

According to Chrysoulakis et al. [39], the planimetric and altemitric accuracies of the produced ASTER DEM over Greek islands are ± 15 and ± 12.41 m, respectively. They considered these precisions satisfactory for watershed management, hydrological applications, and the ortho-rectification of satellites images acquired over the same area with the same spatial resolution. Over the Grenada island in the southeastern Caribbean where the highest point is about 840 m, Chirico [40] quantified DEMs RMSE through the comparison among SRTM with 90-m, ASTER with 30-m and contours map (1:25,000) derived DEM with 10-m pixels size and he validated the results by reference to topographic benchmark measurements. He obtained ± 8.48 m for DEM-10, ± 22.46 m for ASTER 30-m and ± 25.53 for SRTM 90-m. The author explains these accuracies by the fact that in the study area the highest relief is dominated by forest cover, while areas with moderate slopes are generally under cultivation or are mixed use regions.

In the literature, no study focalized on the DEM accuracy analysis for SLR impact modelling, topographic attributes extraction and hydrological variables derivation over small islands, which have specific characteristics. Nevertheless, few studies have dedicated on large-scale impacts of SLR on small islands [3, 6, 41]. Fish et al. [42] exploited a GIS (geographic information system) to predict the effects of SLR on sea turtle nesting habitats on Bonaire, Netherlands Antilles. Sim [8] did a quantitative SLR scenarios investigation on transportation infrastructure, lowland, tourism, urban areas, economic activities, population, and erosion scenarios over the Caribbean islands using the same DEMs (SRTM-90 and ASTER-30) analyzed by Chirico [40] as discussed above. The analysis was designed to be compatible with the methods used in the World Bank study of the vulnerability of selected developing countries to rising sea levels [6]. However, if Chirico [40] obtained elevations accuracies of ± 22.46 m for ASTER 30-m and ± 25.53 for SRTM90-m over the Carrabin islands, based on this coarse accuracies many questions remain about the validity of Sim [8] SLR risk scenarios results and analysis. In fact, if the extreme SLR was predicted to be 1 or 2 m [13], how it is possible to trust the Sim [8] simulated scenarios results based on such elevation accuracies? Analyzing the influence of the both space-borne ASTER and SRTM DEMs (with 30-m pixel size) by reference to Lidar high resolution (1-m) on the accuracy of SLR prediction over the Moss Landing in the California coastline (U.S.), Tulger and Gunduz [43] demonstrated that ASTER was completely inaccurate for such study. As well, SRTM (30-m) overestimated largely the inundated areas, 3 to 6 times higher. Additionally, in the Australian low-lying coastal zones, CRC [44] showed that SRTM with medium resolution (30-m) might not meet the acceptable requirements to support SLR risk scenarios analysis. Paradoxically, other scientists [45] have been satisfied with SRTM 90-m pixel size for SLR risk simulations between 0.5 and 1.0 m inundation in the low-lying area of Vellar-Coleroon estuarine region of the Tamil Nadu coast in India.

Despite all these positive and favorable analyses to SRTM compared to ASTER, other scientists have raised the opposite. Indeed, for the coastal zones study in Eastern-Province of China, using a medium scale topographic map for validation, Luana et al. [46] analysed the quality of SRTM-V4.1 and ASTER-V2.1 and their accuracies as a function of slopes and elevation. They showed that ASTER-V2.1 DEM is relatively accurate than SRTM-V4.1 DEM, respectively, ± 12.12 m and ± 13.74 m. However, this error is much higher compared to that advanced by Zhang et al. [34] over the same Chinas territory as discussed above. Moreover, Tighe and Chamberlain [28] obtained different results depending on the land cover type and the slope variability. For overall accuracies, they achieved ± 15.27 m for SRTM (30-m) and ± 18.82 m for ASTER. But for vegetation canopies only (grass, shrub, deciduous and evergreen) they obtained ± 10.03 m for ASTER and ± 18.81 m for SRTM (30-m). The literature review about this topic shows a wide range variation of SRTM-V4.1 accuracies, it seems to indicate that the vertical precision of this active system depends considerably on location, terrain characteristics and surface feature properties. Based on this literature analysis, Tables 1 and 2 summarize the reported height accuracies for SRTM and ASTER around the world.

Table 1 Reported height accuracies for SRTM DEM.

SRTM DEM			
Accuracy (± m)	Geographic location	Target	Reference
15.27	Several sites in US	Mixed	[28]
16	World	Global	[47]
8	Hawaii (USA)	Volcano	[35]
6.30	Nigeria	Mixed	[31]
13.74	China	Coastal zone	[46]
12.41	Greek islands	Mixed	[39]
11.38	Russia	Bare soil	[25]
10	Germany	Lake Ammer region	[48]
7.6	Thailand	Hills and Coastal Plain	[27]
7.62	Tunisia	Mixed	[32]
2.9	Germany	Mixed	[38]
6.2	Australia	Mixed	[30]
5.51	Amazon	Water surface	[20]
4.07	New-York (US)	Mountains	[27]
5.0	Alaska and Canada	Glacier	[37]
10	French Alps	Glacier	[36]
3.6	Global	Various	[49]
3.3	Michigan (US)	Bare soil	[26]
2.9 and 5.4	Poland	Flat terrain and Hills	[50]
1.07	Luxembourg	Water surface	[23]
2.4	China	Mixed	[34]

Table 2 Reported height accuracies for ASTER DEM.

ASTER GDEM			
Accuracy (± m)	Geographic location	Target	Reference
22.46	Caribbean island	Mixed	[40]
18.52	Several sites in US	Mixed	[28]
15	Australia	Mixed	[29]
13	Hawaii, US	Volcano	[35]
8.86	Nigeria	Mixed	[31]
12.12	China	Coastal zone	[46]
12.41	Greek islands	watershed	[39]
10.53	Tunisia	Mixed	[32]
8.5	Australia	Mixed	[30]

3. Material and Methods

3.1 Study Site

The Kingdom of Bahrain (26° 00’ N, 50° 33’ E) is a group of islands located in the Arabian Gulf, east of Saudi Arabia and west of Qatar (Fig. 1). The archipelago comprises 33 islands, with a total land area of about 765.30 km^2 and high population densities, 1755/km^2 [51]. According to the aridity criteria and to great variations in climatic conditions, Bahrain has an arid to extremely arid environment [52]. The main island is characterized by high summer temperatures around 45 °C in summer (June-September) and an average of 17 °C approximately in winter (December-March). The rainy season runs from November to April, with an annual average of 72 mm, sufficient only to support the most drought resistant desert vegetation. Mean annual relative humidity is over 70% due to the surrounding

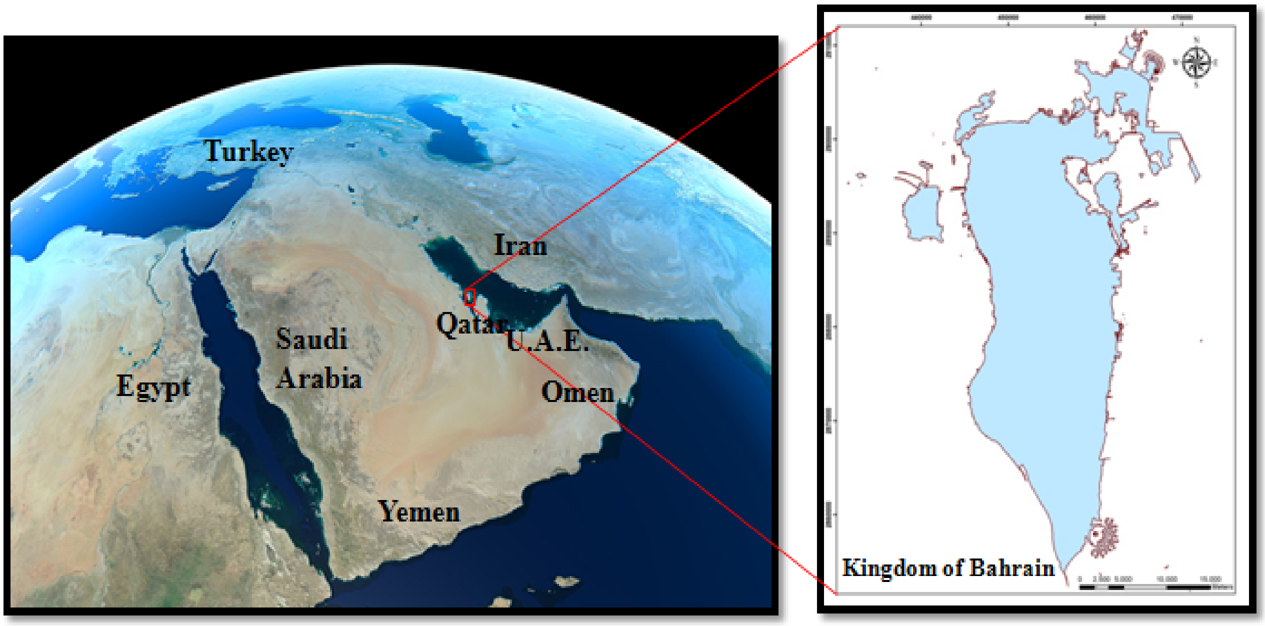


Fig. 1 Study site (Kingdom of Bahrain).

Arabian Gulf waters, and the annual average potential evapotranspiration rate is 2099 mm [53]. Jabal-Dukhan forms the highest point (134 m) in the center of the island; this small mountain is surrounded by an interior basin beyond, which lies the inward facing multiple escarpments. Most of the coastal areas do not exceed 5 m above the sea level and most of the intensive development is located on the narrow coastal plains [54]. To protect the infrastructure along the coastline from SLR, government of Bahrain adopted a regulation for sea fill levels varying from 1.75 to 4.75 m, depending on the geographic location. Even modest rises in sea level are expected to result significant environmental impact and storm surges in the coastal zone where much biological diversity and most of the population, agricultural land and capital assets are located [55-57].

3.2 ASTER-V2.1 Data

The ASTER GDEM is a joint product developed and made available to the public by the METI (Ministry of Economy, Trade, and Industry) of Japan and the United States (U.S.) NASA (National Aeronautics and Space Administration). It is generated from data collected by the optical instrument ASTER onboard the TERRA spacecraft [58]. This instrument was built in December 1999 with an along-track stereoscopic capability using its nadir-viewing and backward-viewing telescopes to acquire stereo image data with a base-to-height ratio of 0.6 [59]. Since 2001, these stereo pairs have been used to produce single-scene (60 × 60 km^2) DEM based on a stereo-correlation matching technique using a WGS84 geodetic reference. The GDEM imaged the Earth's landmass between 84ºN and 84ºS latitudes offering greater coverage than SRTM Mission. The original ASTER mission specifications called for DEMs to have a vertical accuracy within the ± 7 m to ± 50 m range depending on the number and quality of GCPs and tie points [60]. In 2011, jointly, NASA and Japanese partners made the validation and the accuracies assessment of ASTER-V2.1 GDEM products (version-2.1). The results of this study showed that the absolute geometrical rectification accuracies, expressed as a linear error at the 95% confidence level, are ± 8.68 and ± 17.01 meters for planimetry and altimetry, respectively [61]. Overall, the ability to extract elevations from ASTER stereo-pairs using stereo-correlation techniques meets expectations. Studies were conducted by a large group of international investigators, working under the joint leadership of U.S. and Japan ASTER project participants, to validate the estimated accuracy of the new ASTER-V2.1 Global DEM product and to identify and describe artifacts and anomalies found in the GDEM product [62]. The ASTER-V2-1 DEM data over the study region were downloaded from USGS data explorer gate [63] and were preprocessed using ArcGIS [67].

3.3 SRTM-V4.1 Data

The SRTM is an international project managed by the JPL (Jet Propulsion Laboratory) and sponsored by NASA, the NGIA (National Geospatial-Intelligence Agency) of the U.S. Department of Defense, the German Aerospace Center (DLR) and the ISA (Italian Space Agency). It collected the most complete high-resolution digital topographic database over 80% of the Earth's land surface from 60ºN to 56ºS during 11 days mission; which was flown aboard the space shuttle *Endeavour* between 11 and 22 February 2000 [65]. The used radar systems are the C-band (5.6 cm) Space-borne Imaging Radar (SIR-C) developed by NASA and the X-Band Synthetic Aperture Radar (X-SAR, 3.1 cm) developed by DLR with ISA participation [66]. They were flown for tests on two *Endeavour* missions in April and October 1994, then modified for the SRTM mission to collect single-pass interferometry (InSAR) data using two signals at the same time from two different radar antennas. The first one was located on board the space shuttle and used as a transmitter and receiver, and the second receiver antenna was at the end of a 60-meter (baseline) mast that extended from the payload bay [61, 67]. Obviously, the differences between the two signals allowed the calculation of surface elevation using stereo-photogrammetry methods [48]. The fundamental objectives of the SRTM Mission are to provide important information for NASA's Earth Sciences Enterprise, which is dedicated to understanding the total Earth system and the effects of human activity on the global environment [61, 67, 68].

Since 2000, the SRTM data have been provided in 30-m pixel size only within U.S. territory, while for the rest of the world the data were available for public use at 90-m pixel size. On September 23, 2014, the U.S. government announced that the highest resolution elevation data generated from NASA's SRTM in 2000 would be released globally over the next year with the full resolution of the original measurements, 30-m pixel size. This new version (V4.1) named SRTM-V4.1 was released in September 2014 for Africa and its surrounding areas. Then, in November 2014, it was released for south and North America, most of Europe, and islands in the eastern Pacific Ocean. The most recent release, in January 2015, includes most of continental Asia, the East Indies, Australia, New Zealand, and islands of the western Pacific [61, 67].

The data are projected in a geographic coordinates system using a WGS-84 geodetic reference and EGM-96 vertical datum. According to Ref. [63], at 90% confidence level, the absolute vertical height accuracy is equal or less than ± 16 m, there is a relative vertical height accuracy of less than ± 10 m, there is a circular absolute planimetric error of less than ± 20 m, and a circular relative planimetric error of less than ± 15 m. These data have been planned to meet the needs of the scientific applications (geology, geophysics, hydrologic modeling, etc.), civilian applications (navigation safety and warning systems for aircraft, civil engineering, land use planning, better locations for cell phone towers), and military applications (flight simulators, logistical planning, traffic-ability, missile and weapons guidance systems, and battlefield management, tactics). Moreover, for any other projects that requires accurate knowledge of shape and height of the land, such as small-scale modeling and solar radiation calculations, landscape ecology, classifications improvement, better 3D illustration and analysis in GIS environment [67]. The SRTM-V4.1 DEM data used in this research were downloaded from USGS data explorer gate [63] and were preprocessed using ArcGIS [64].

3.4 Topographic Contours Data and DEM Derivation

The generated DEM-5 with 5 m pixel size was based on contour lines extracted from accurate topographic map with a very large scale (1:5,000) which was established from photogrammetric stereo-preparation and restitution exploiting optico-mechanic stereo-plotter. According to the photogrammetric theory, the vertical accuracy of contour lines depends on the base-height ratio, and the relationship of the ground distance between successive exposures of photographs to the flying height [69]. It depends also on the precision of GCPs incorporated in stereo preparation and stereo-pairs model calibration (internal and external orientations). Thus, the vertical RMSE ($RMSE_{Vertical}$) of generating contour lines from photogrammetry can be computed using the following equation [70, 71]:

$$RMSE_{Vertical} = \pm 0.304 * \text{Contours Interval} \quad (1)$$

Since the used map contour lines interval is 2.5 m, the calculated elevations accuracy of this map ($RMSE_{Vertical}$) is ± 0.76 m. Nevertheless, based on error propagation theory, we must consider the digitalization and interpolation method errors. As well, the output pixel size specifications which determine the derived DEM details must be taken in consideration depending on the richness of contour lines and their spatial distribution [72, 73]. However, this last error is insignificant since the contours lines integrated in the interpolation process are very dense with excellent spatial distribution over study site. Indeed, during the Kriging interpolation process, the statistical nearest neighbor analysis regarding the density and distribution of integrated contours showed an excellent precision (RMSE = 0.1%). Moreover, the contour lines elevation values have been introduced manually in the attributes table immediately after the digitalization of each vector, thus eliminating the probable altimetry error. But for planimetric coordinates position error, based to the map scale and the digitizing table characteristics (± 0.249 mm accuracy), has been estimated at ± 12.5 cm which is insignificant vis a vis the desired output pixel size (5 m) after interpolation.

Likewise, it has been demonstrated that DEM accuracy can vary to a certain degree with different interpolation algorithms and interpolation parameters [73]. Several interpolation methods existent in ArcGIS [64] and other mapping software's, and the best and appropriate DEM interpolation method must reproduce as close as possible the terrain shape [74]. Zimmerman et al. [75] and Arun [76] revealed that Kriging approach adjusts itself to the spatial data structure and provides better estimations of altitude than other interpolation methods. However, due to specific shape of Bahrain island topography, after many tests exploring several methods simple Kriging with linear model was chosen. According to Gao [77], the accuracy of a derived raster DEM using interpolation method ($RMSE_{Interpolation}$) is related to the contour density and the DEM pixel size output, and it is formulated as follows:

$$RMSE_{Interpolation} = \pm (7.274 + 1.666\ S)\ D/(1000 + \varepsilon) \quad (2)$$

where, S stands for resolution in meters; D stands for contour density expressed as km/ km^2; ε is an error term related to D. Contour density was calculated by dividing the total length of contour by the size of the study area. Based on these research variables, this accuracy is estimated at ± 16 cm. Therefore, the total DEM-5 elevation error in terms of RMSE can be formulated as follow:

$$RMSE_{Total} = \pm\sqrt{(RMSE_{Vertical})^2 + (RMSE_{Interpolation})^2} \quad (3)$$

Finally, considering all the error sources propagation, the total obtained RMSE ($RMSE_{Total}$) on the derived DEM-5 using simple Kriging is ± 0.78 m. In other word, it is the tolerance or the maximal error which must not be exceeded in comparison with the reference points for validation i.e. DGPS.

3.5 DGPS Surveying Data for Elevations Validation

In Bahrain, the GPS ground control segment station is one among the 6 National Geospatial Agency Stations receiving signal from the GPS satellites constellation. It computes the correction for their positions based on geodetic network measurements and atomic horologe [78]. Consequently, in this study, the used DGPS real time recording and correcting takes advantage of differential corrections from the known and accurate fixed geodetic locations (benchmarks) as well from the satellite signal which is updated by Bahrain ground control segment in real time. Prior to DGPS deployment for validation purposes, GCPs were selected based on the topographic variability and inter-visibility between receivers without any obstruction. Then, 400 points have been measured with DGPS assuring accuracies of ± 1 cm and ± 2 cm, respectively, for planimetry and altimetry. These points were uniformly distributed over the study area considering all existents topographic terrain variabilities (different slopes, orientations, elevations, roughness, etc.).

3.6 DEMs Accuracies Assessment

In the section 3.4 above, the accuracy of derived DEM-5 based on topographic contour lines and Kriging method is calculated. For both space born DEMs (SRTM and ASTER), the end user has no control on the preprocessing steps or the elevation errors correction methods, except some marginal operations such as fill or sink. However, in this section we discuss the errors propagation for SRTM and ASTER. Then, we present the mathematical relations to calculate the accuracy for each DEM independently by reference to DGPS *in situ* measurements.

Uncertainty on a measured DEM is the sum of the uncertainties caused by platform, sensor, external environment and the target characteristics as discussed before. For instance, errors are propagated in the measurements acquired by SRTM mission because of several sources. These included to the shuttle position, astronauts activities, uncertainty of the baseline (the length and orientation of mast) which is the most significant error source, timing error, multipath, phase measurement error, thermal distortions and noise of the radar system as the Shuttle moves around the Earth in orbit, and going in and out of sunlight [25, 68]. Farr et al. [66] elaborated all these error sources in detail with their mathematical equations and they quantified the effects of each one individually. As discussed previously, USGS [63] estimated the global SRTM-V4.1 absolute vertical height accuracy is equal or less than ± 16 m. Nevertheless, for Bahrain island which was considered with African continent and Middle-East region when SRTM-V4.1 errors were compensated by NASA using least-square adjustment, this absolute vertical height accuracy was estimated to ± 5.6 m [66].

Furthermore, METI et al. [62] found that the ASTER DEM contains significant anomalies and artifacts, due to sensor radiometric sensitivity and calibration, atmospheric variability, clouds, stereo-pairs images geometry, and the automated algorithm used to generate the final DEM based on stereo correlation procedures. In addition, quality of the used GCPs for calibration, human errors and mistakes, as well the target characteristics (vegetation cover, bare soil, snow, ice, terrain morphometry i.e. elevation, slope, aspect, surface roughness, etc.) affect the derived DEM accuracy. Moreover, other scientists believe that orbital parameters of the TERRA-Platform might have an impact on ASTER DEMs data acquisition [79]. As discussed previously, the ASTER-V2.1 version GDEM accuracy was estimated at ± 17.01 meters [80].

In this research, the errors of DEMs derived from three different sources (SRTM-V4.1, ASTER-V2.1 and Topographic contours DEM-5) are completely independent and we assume them normally distributed. The used DEMs were validated by reference to elevation data acquired with DGPS representing the elevation truth. According to the American Society for Photogrammetry and Remote Sensing [71], the height accuracy of each DEM should be expressed by the root mean square error ($RMSE_{DEM\text{-}j}$) given by the following relation:

$$RMSE_{DEM}\text{-}j = \pm\sqrt{\frac{\sum_{i=1}^{n}(H_{Ref} - H_{DEM-i})^2}{n-1}} \quad (4)$$

where, H_{Ref} is the reference DGPS elevation data (in situ measurements), $H_{DEM\text{-}i}$ is the elevation data from the three considered sources (SRTM, ASTER and topographic contours DEM-5), and "n" corresponds to the total number of DGPS GCPs used for validation, i.e. 400 points.

4. Results Analysis

The quality assessment of the used DEMs and the produced thematic maps is critical for information extraction and analysis; it is based often on statistical methods. In contrast, visual methods are generally neglected despite their potential for derived product quality assessment. Certainly, the complementarily between visual and statistical methods would result in a more efficient improvement of the derived product quality.

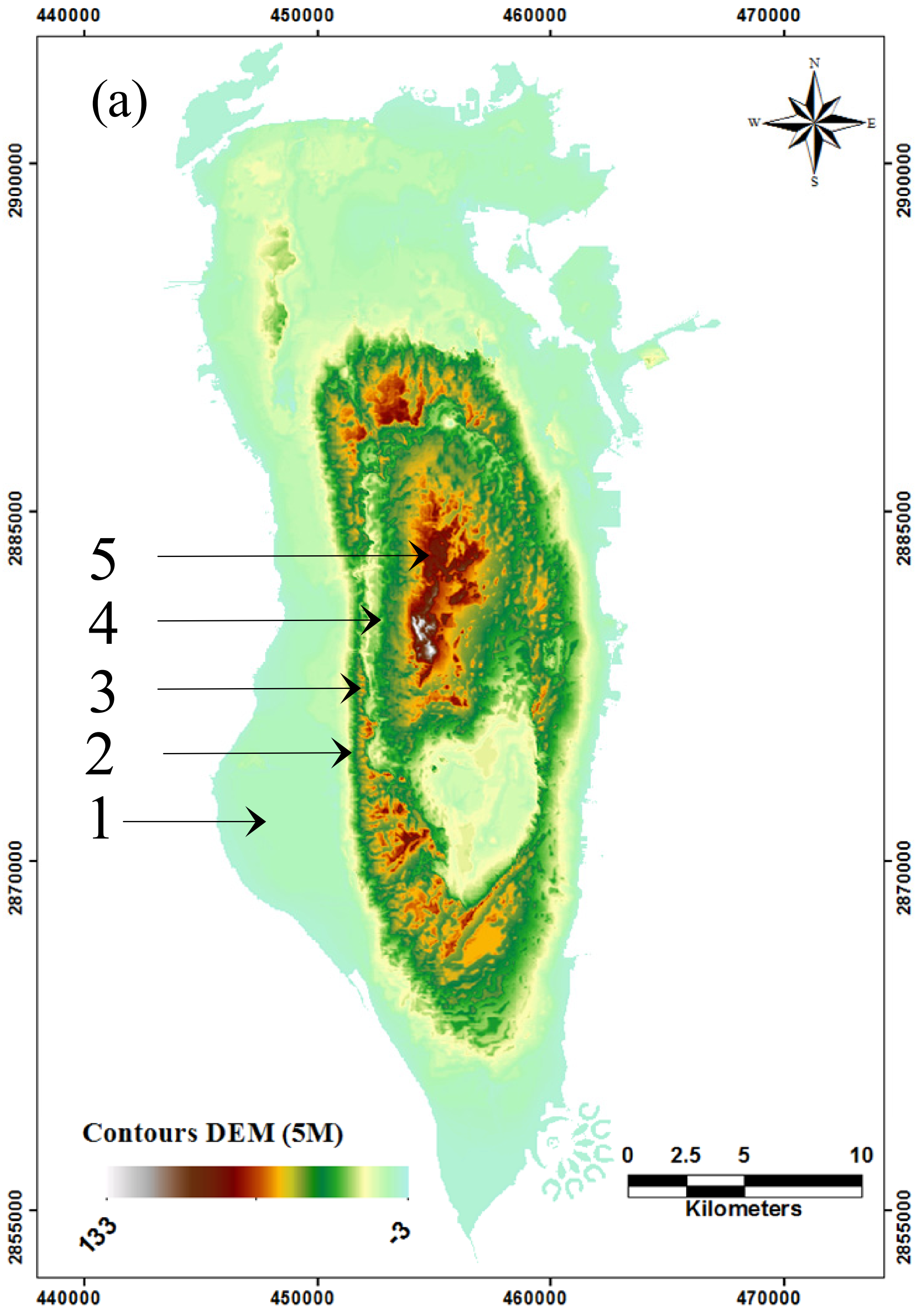
4.1 Elevation

Fig. 2 illustrates the derived DEMs from space-bone (SRTM and ASTER) and topographic contour lines. By reference to the ground and terrain truth, the topography of Bahrain is not so variable, over half of the surface laying is below 20 m, and composed mainly of low angle slopes. It is possible to identify five major physiographic regions, which occur as concentric units of variable width. The first region is the coastal lowlands (number 1 in Fig. 2a) with elevation less than 5 m above mean sea level and slopes less than 0.5%. It is characterized with water table levels only 30 to 60 cm below the surface. The second region is the upper Dammam back-slope (number 2 in Fig. 2a) which reflects the general asymmetrical shape of the main Bahrain dome with elevation between 10 and 20 m, and slopes less than 5.4%. The third region is the multiple escarpment zones surrounding the interior basin of the island (number 3 in Fig. 2a); it is a continuous belts of low multiple enfacing escarpments. From the north-west to the south-west of this region, the elevation and slopes vary significantly, respectively, from 20 to 34 m and from 5.4 to 14%. The fourth region is the interior basin (number 4 in Fig. 2a) which looks as an asymmetrical ring of lowlands surrounds the central plateau region (fifths region) with relatively height elevation and strong slopes classes, respectively, 34 to 51 m and 14 to 29.5%. Finally, the fifth region is the central plateau with upstanding residual hills and mountain (number 5 in Fig. 2a). In this region, the elevations and slopes vary significantly between 51 and 134 m for Jabal-Dukhan (the highest point in Bahrain) and 30 to 81%, respectively (Fig. 2). According to this analysis, it is possible to distinguish among four major groups of drainage (catchments) zones which are mimicking the major topographic areas: the coastal lowland, the upper Dummam backslope, the multiple escarpment zones, and the interior-basin and central plateau.

Furthermore, the elevation variability in Bahrain island is not so large, the maximum and the minimum are -3 and 134 m, respectively. Visual interpretation of Fig. 2 shows that the three considered DEMs illustrated generally similar terrain shapes and forms except their difference in sensitivity to terrain texture, roughness and micro-topography. Indeed, the ASTER DEM shows less detail than the SRTM, especially regarding the micro-topography regime, which includes height variations and undulations of lengths comparable to the radar wavelength (Figs. 2b and 2c). Radar wavelength ranges furnish good signal returns from the Earth's surface. Moreover, the almost total absence of vegetation cover in the study area helps the radar system to characterize the surface topography since its signal adheres very well to the micro-topography and determines the intensity and type of the backscattered signal [81]. Indeed, radar is sensitive to surface roughness since shorter radar wavelengths (X-band) are most sensitive to micro-topography, while long wavelengths (C-band) are sensitive to macro-topography. Obviously, these characteristics advantage SRTM compared to ASTER. However, the SRTM DEM range values vary between -3 and 125 m (Fig. 2b), describing correctly the topographic zones even those inland with an altitude below zero (-3 m), but it underestimated the highest point in Bahrain by 9 m (Jabal-Dukhan, 134 m). While, the ASTER range values vary from 0 (zero) for inland zones with -3 m bias (by reference to the sea level) to 139 m by 5 m overestimation to Jabal-Dukhan (Fig. 2c). Nevertheless, both space-borne DEMs characterized similarly the macro-topography (which is related to large changes in slopes and aspects of surface facets being generally related to large parts of the hydrological network), geological structures, erosion features and global terrain geomorphology. Finally, the contours DEM-5 show a smooth and clear representation of the island topography with altitude variation between -3 and 133 m (Fig. 2a). By reference to the original data introduced in the interpolation process we observe that the predicted altitude of Jabal-Dukhan was underestimated with 1 m. This bias is introduced because the Kriging method considered the spatial autocorrelation structure of elevations among the considered points.

Fig. 3 illustrates a statistical correlation between the 400 DGPS reference points for validation and their homologous in each DEM. For the contours derived DEM-5, we observe that the validation DGPS-GCPs correlate perfectly ($R^2 = 0.99$) with their homologous (Fig. 3a). This result was expected because the topographic contours lines were plotted based on accurate stereo-photogrammetry and surveying methods, and interpolated using a powerful statistical interpolation method. For the space-born DEMs, the correlation coefficients are 0.96 and 0.92, respectively, for SRTM and ASTER. These correlations indicated that SRTM perform slightly better with reference validation points than ASTER. This slight performance is expressed by Fig. 3b which depicted the distribution of validation points around the fitting axis (1:1 line). The scatter plot illustrates in general a good fit to 1:1 line (first bisectrix axis). But, depending on the land use classes the altitude values are sometime overestimated and other time underestimated. For ASTER, the scatter plot as presented in Fig. 3c reveals a good linear relationship between the two considered variables, but it overestimated the majority of validation points. We observe that the ASTER cluster datasets points fall not closely to the one-to-one line axis as SRTM cluster points. This trend is also confirmed with the derived profiles along two transects from west to east (Fig. 4a) and from north to south (Fig. 4b) of the island considering the three DEMs. Visual analysis of these profiles (Figs. 4a and 4b) reveals that in general ASTER overestimate the elevation more than SRTM in both geographic directions. In addition, they show that the slopes characteristics (west-east and north-south) of the terrain have significant impact on ASTER accuracy than SRTM.

Finally, the global height surface accuracies expressed with RMSE calculated using Eq. (4) and 400 DGPS-GCPs. The derived DEM-5 from topographic contours map exhibit the best accuracy of ± 0.65 m which is less than the tolerance or the total error (± 0.78 m) calculated based on errors sources propagation (Eq. (3)). Then, the results show satisfactory performance of SRTM with global accuracy of ± 3.00 m which is less than the absolute vertical height accuracy (± 5.6 m) advocated by NASA for African continent and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Contours DEM (5M)
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2.5
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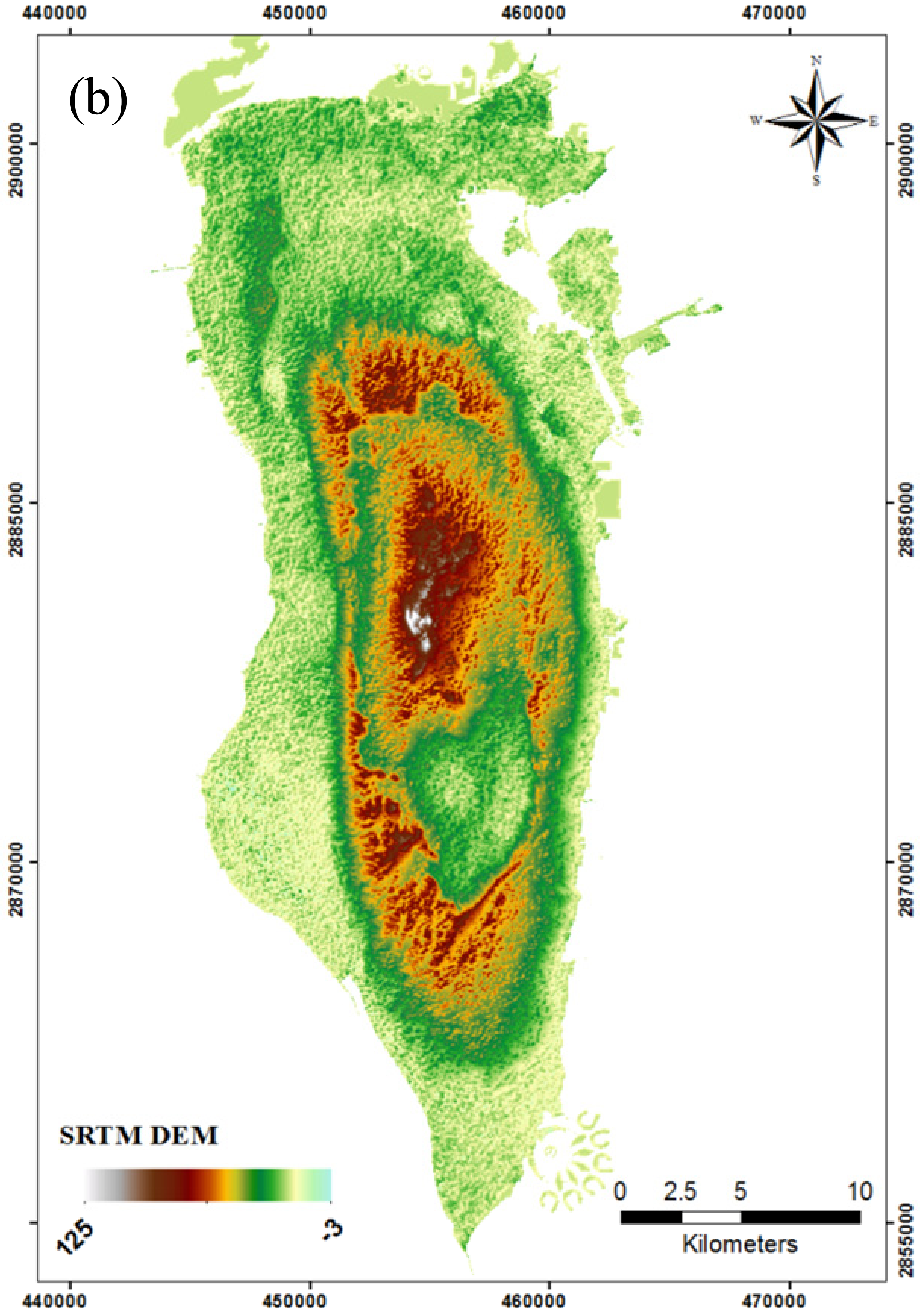
Kilometers



(b)
SRTM DEM
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-3
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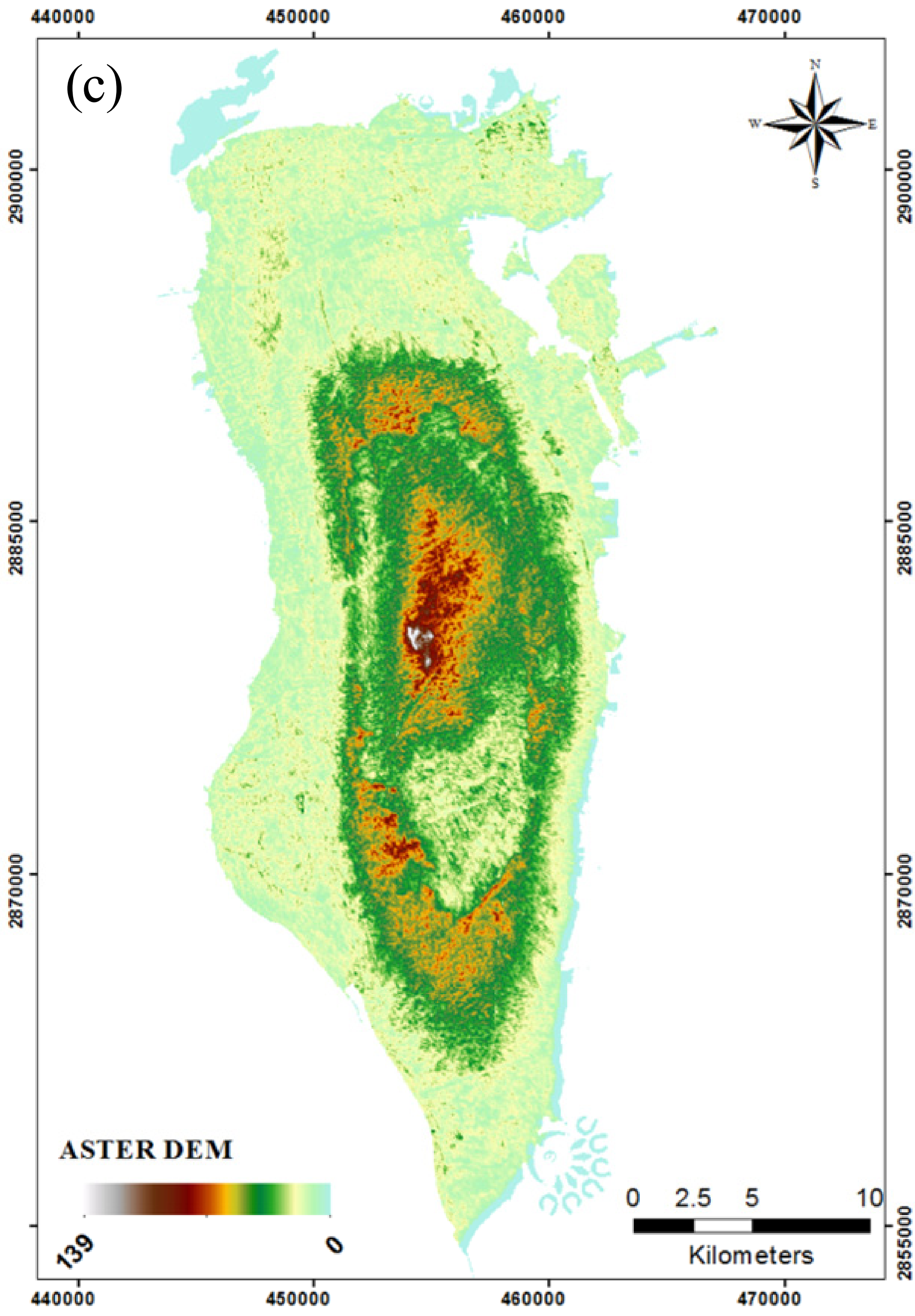


Fig. 2 DEMs maps derived from contours (a), SRTM (b) and ASTER (c).

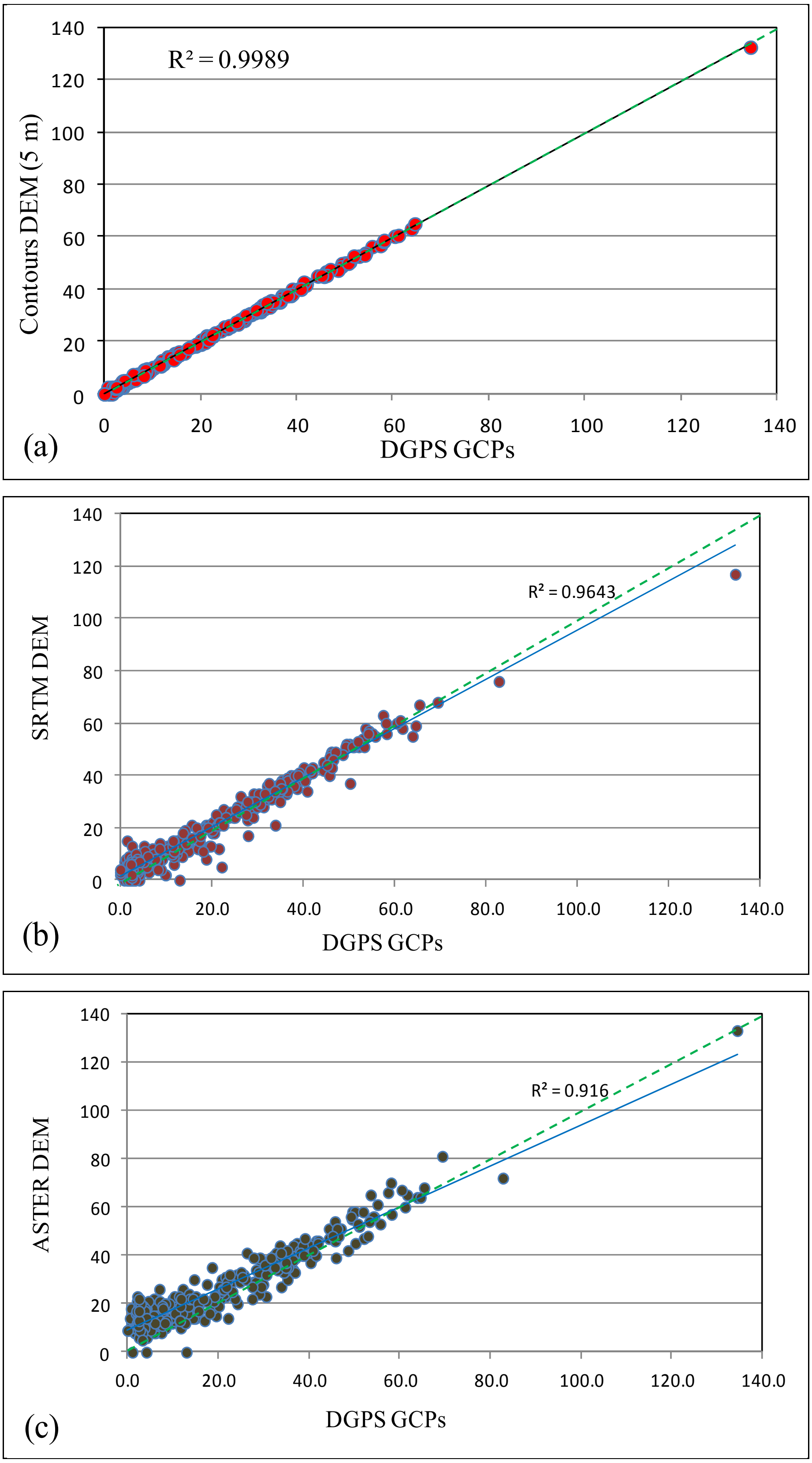


Fig. 3 Relationship between the 400 validation GCPs measured by DGPS and their homologous in each DEM, DEM-5 (a), SRTM (b), and ASTER (c).

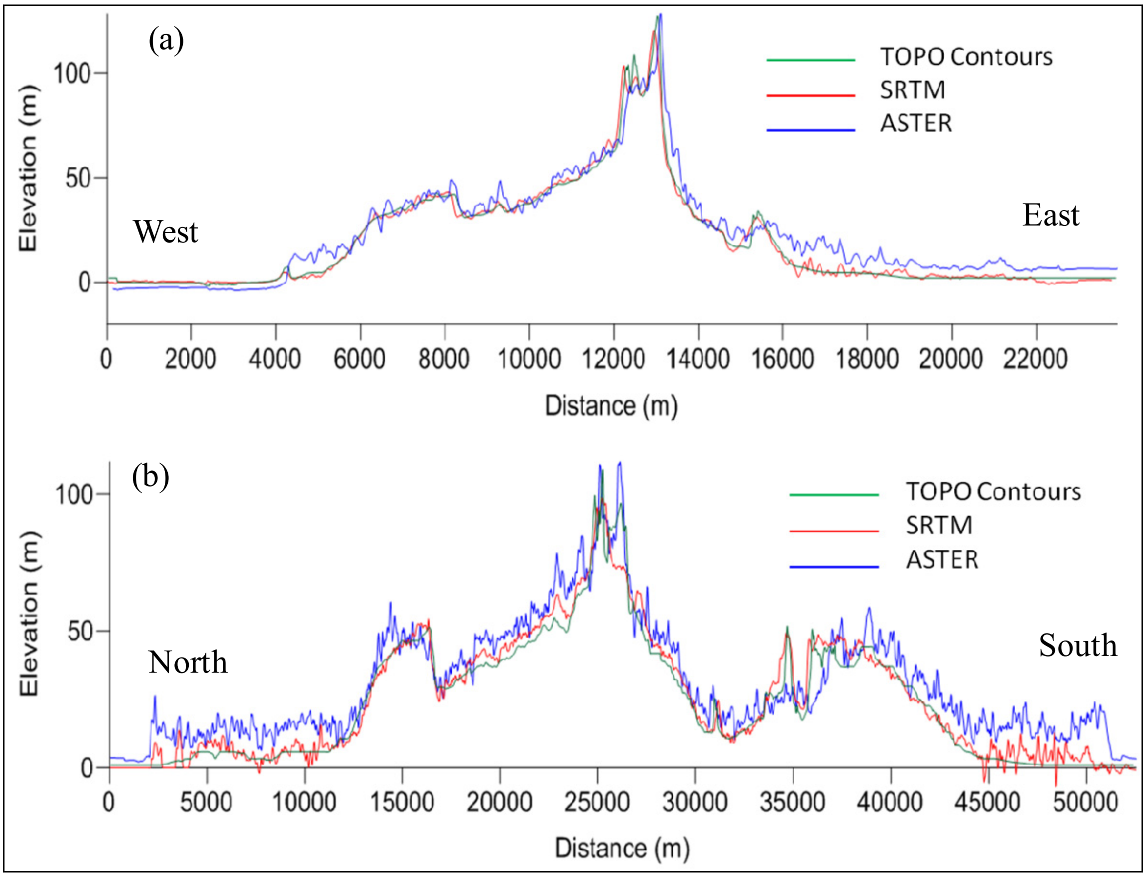


Fig. 4 Comparison of profiles derived from west-east (a) and north-south (b) directions considering the three used DEMs.

Table 3 RMSE analysis considering different land use classes.

Ground target	RSME of DEMs (± m)		
	Topo-Contours	SRTM	ASTER
Agricultural field and Palm trees	0.65	3.01	7.74
Urban/housing	0.58	2.06	7.51
Urban/high building (Skyscraper)	0.65	5.78	14.30
Mixt environment	0.56	2.55	8.26
Low slope	0.42	1.29	6.12
Relative strong slope	1.12	4.60	8.5
Global-RMSE	0.65	3.00	8.40

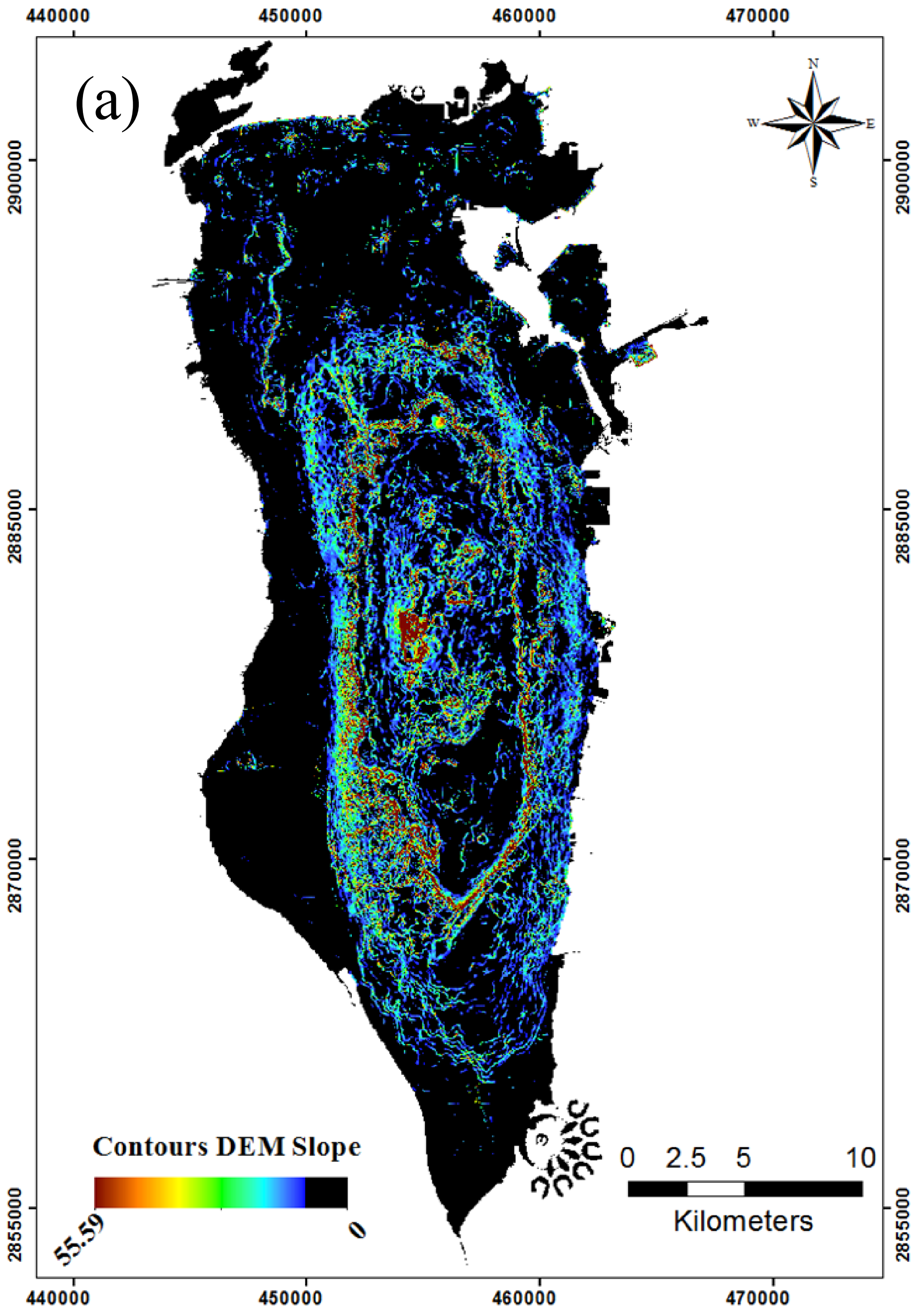
Middle-East regions. As well, the achieved ASTER accuracy was ± 8.40 m compared to the estimated error (± 17.01 m) by USGS and JAXA. Also it concurs with those published by Hirano et al. [59] who estimated an RMSE in elevation between ± 7 m and ± 15 m; and those published by EDC [82] which yield an RMSE of ± 8.6 m. Nevertheless, these accuracies are significantly influenced by the nature of the land use classes and slopes as showed in Fig. 4 and summarized in Table 3. Topography and high building (Skyscraper) in urban environment significantly influence accuracies; errors are larger for high to medium altitude with relative strong slopes, while they are smaller in the low relief areas with low slopes. These results are in agreement with other previously published results [48, 83, 84].

4.2 Slope

Slope is a primary topographical attribute, which is derived from the topographical surface. The output slope map represents the degrees of inclination from the horizontal. It has a significant influence on the velocity of surface and subsurface flow, soil water content, erosion potential, soil formation and several other Earth surface processes [85] and hence an important parameter in hydrologic and geomorphologic studies [86]. Fig. 5 illustrates the range values of slopes derived from DEM-5 (0° to 55.59°), SRTM (0° to 45.53°) and ASTER (0° to 33.59°). The slope map derived from contours DEM-5 shows an accurate description of slope network that is mimicking correctly the topographic classes (Fig. 5a). In fact, the 5-m pixel size describes correctly the topography as well the drainage network. Consequently, continuing sequence of slopes is very well described within pixels. Then, it is possible to distinguish among five major classes, such as the coastal lowlands region with slopes less than 0.45°. The upper Dammam back-slope with slopes less than 4.86°. The multiple escarpment zones surrounding the interior basin of the island, respectively, from the north-west to the south-west of this class; the slope varies significantly from 4.86° to 12.6°. The interior basin lowlands, which surrounds the central plateau region with relatively strong slopes classes, 12.6° to 26.55°. Finally, the central plateau with upstanding residual hills and mountain. In this last class, the slope varies significantly between 27° to 73° for Jabal-Dukhan (the highest point in Bahrain). Although the derived slope map from SRTM describe the major shape of slopes especially the steeper slopes in the interior basin (central plateau) and Jabal-Dukhan, it does not reflect in detail the slopes classes as those retrieved from contours DEM-5 (Fig. 5b). Indeed, we observe when the pixel size increases a considerable underestimation of slope value occurs for SRTM (approximately 10°). However, SRTM is very sensitive to the low slopes in the north-east and south-west of the island since the radar signal adheres very well to the micro-topography and determines the intensity and type of the backscattered signal. Likewise, ASTER slopes are underestimated by 22° and 12° compared to DEM-5 and SRTM slope maps, respectively. In addition, the ASTER slope map shows fragmented information with less accuracy than SRTM slopes map. The steeper slopes related to Jabal-Dukhan are identified with a cluster of red pixels in the middle of the slope map (Fig. 5c), and it is not obvious to identify the slope classes or to relay them to the topographic variability. Moreover, the highway network was associated with medium slopes ASTER map. The topography of Bahrain is not so variable and the drainage system is not well developed, then for a passive system as ASTER with 30-m pixel size, it is difficult to characterize geo-morphometric attributes accurately. Therefore, we conclude that when the pixel size increases, the generate slope values get smaller and less accurate. The medium resolution of ASTER means a more severe terrain morphology generalization, which preserves only the major relief features. In fact, as pixel size increases, a single DEM pixel value reflects more land area by averaging values within the pixel. For example, one SRTM or ASTER 30-m pixel size has a single elevation value, while the same area is represented by 36 elevation values in DEM-5 with 5-m pixel size. The effects of averaging elevation values for medium resolution DEMs make them inherently less able to accurately model smaller variations found within the terrain. Thus, for small islands with topographic features not higher than 134 m, DEMs with 30-m are not able to identify steep slopes successfully, especially ASTER. These results corroborate the finding of Ref. [40] over Grenada island in the southeastern Caribbean using SRTM-90, ASTER-30 and contours DEM-10, and other scientists who worked on mainland [77, 87].

4.3 Aspect

Aspect is an anisotropic topographic attribute, i.e., depends on a specific geographical direction, such as to the Sun’s azimuth. Also, it has a significant influence on vegetation cover distribution, biodiversity


(a)
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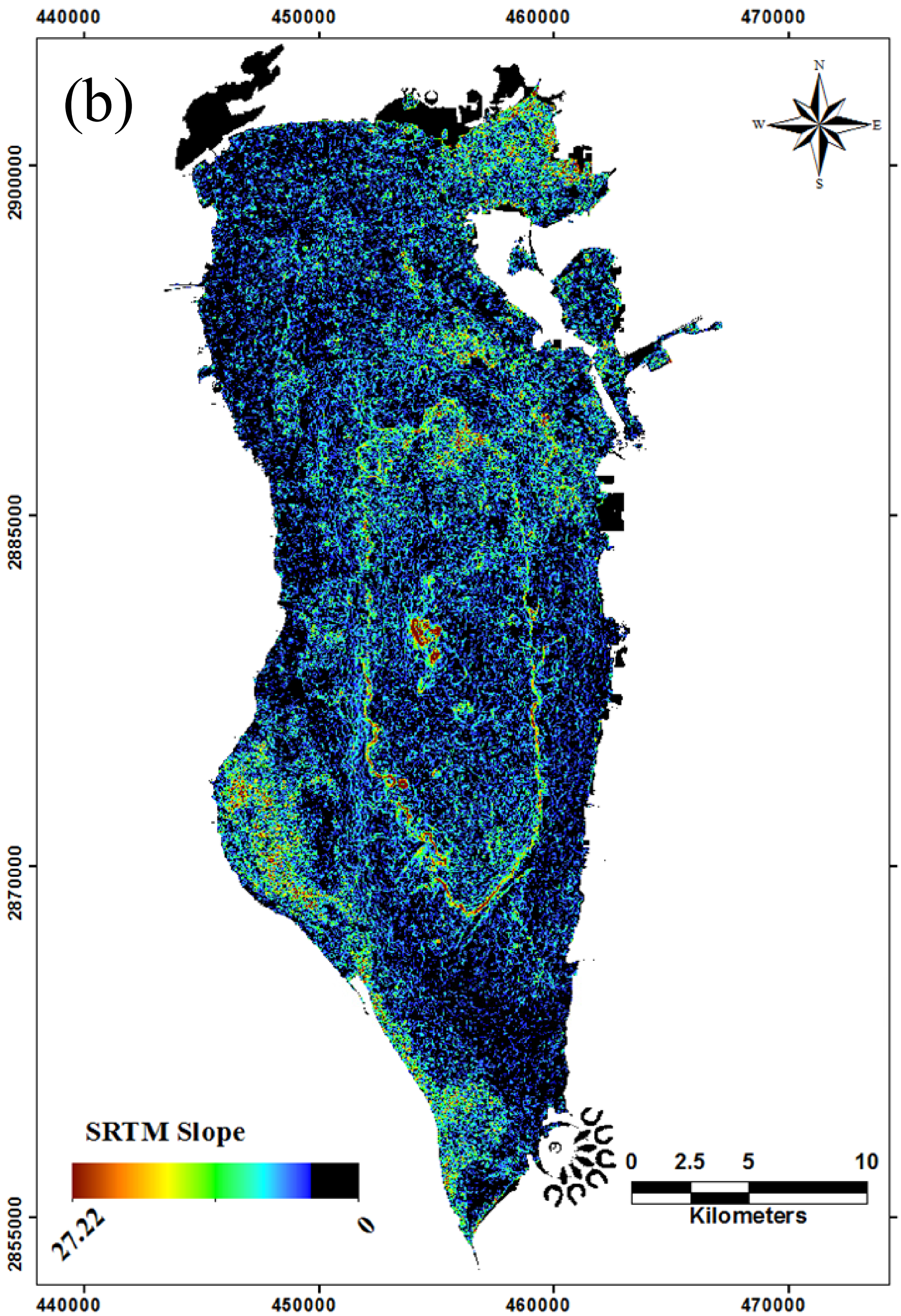
(b)
SRTM Slope
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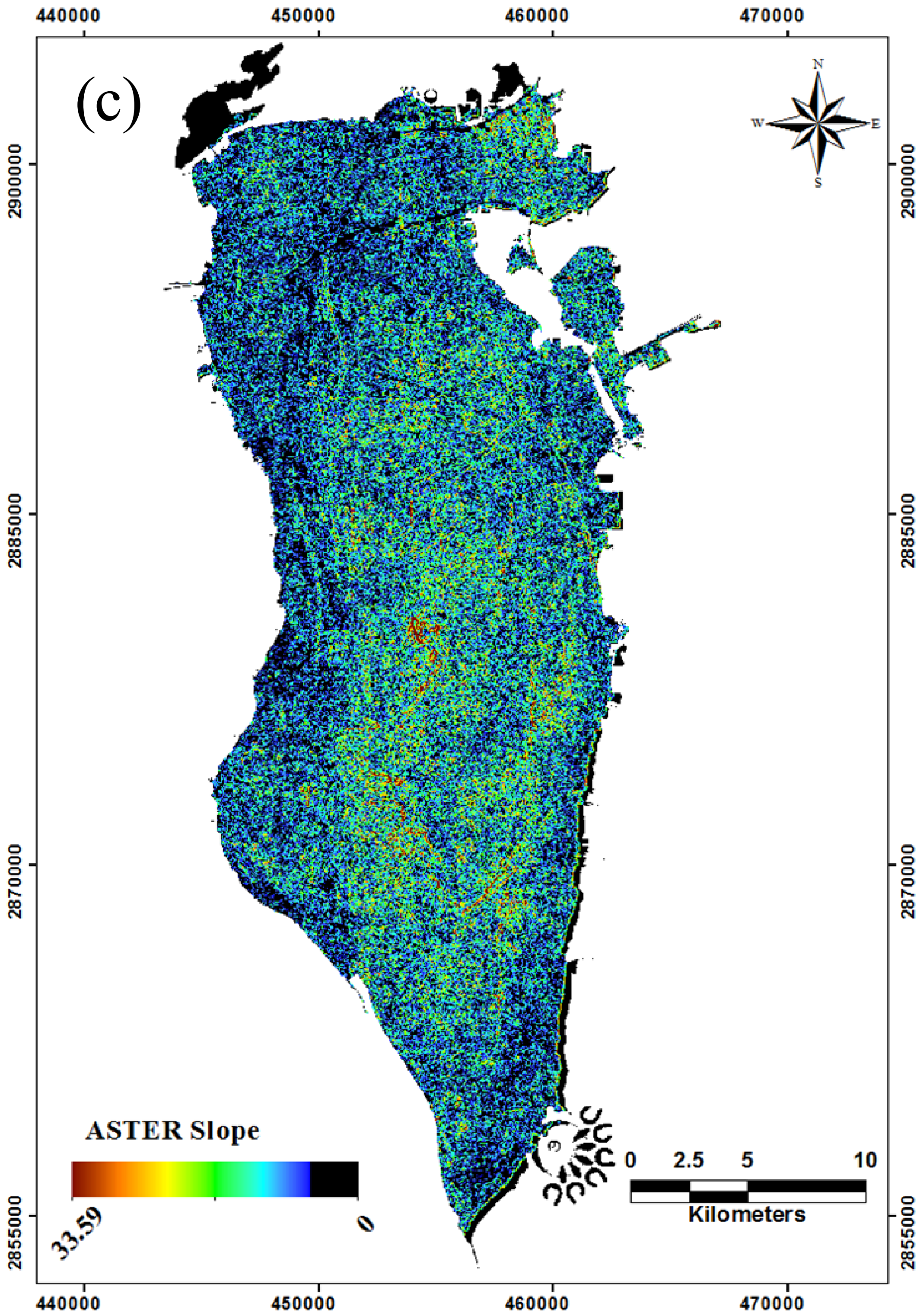


Fig. 5 Slope maps derived from contours DEM-5 (a), SRTM (b), and ASTER (c) DEMs.

and agricultural productivity because solar radiation received at a location on the terrain depends on the aspect and shadows cast by the terrain [86]. Moreover, aspect characterizes the topographic curve changes (concave and convex), which control the flow direction and accumulation. Indeed, it plays a very significant role in delineating the flow-lines and subsequently the flow accumulation in sub-catchment areas. The derived aspect maps (Fig. 6) indicate the direction of slope gradients and the aspect categories represent the number of degrees of East increasing in a counter-clockwise direction, and an aspect value of -1 is generally assigned for flat areas. The discrepancies and similarities between the aspect values derived from contours, SRTM and ASTER DEMs can be determined using rose diagrams (Fig. 6). The latter are circular histogram plots, which displays geographic directional aspect classes (0° to 360°) and their frequencies as a function of the length of the radius of the rose. It is commonly used in sedimentary and structural geology, topography, erosion and hydrology for directional features characteristics interpretation. Visual interpretation showed significant difference between the derived aspect maps from the three considered DEMs. Indeed, the aspect map obtained from topographic contours DEM-5 shows a rose diagram more pronounced in west direction and very less aspects in the northeast direction. Moreover, the coastal lowland regions, the interior basin, and the manmade land (or reclamation) are mapped as flat areas (Fig. 6a). This illustration is conforming to the terrain truth. While, the rose diagrams acquired from SRTM and ASTER are relatively similar expressing the majority of aspect orientations in west and west-north directions; however their respective maps look different (Figs. 6b and 6c). In fact, the SRTM aspect map reflects significant similarity with DEM-5 aspect map classes, as well with the terrain truth (Fig. 6b). On the other hand, ASTER aspect map does not show homogenous and uniform aspect classes reflecting the truth, but rather fragmented pixels that are not informing about the real aspect orientation (Fig. 6c).

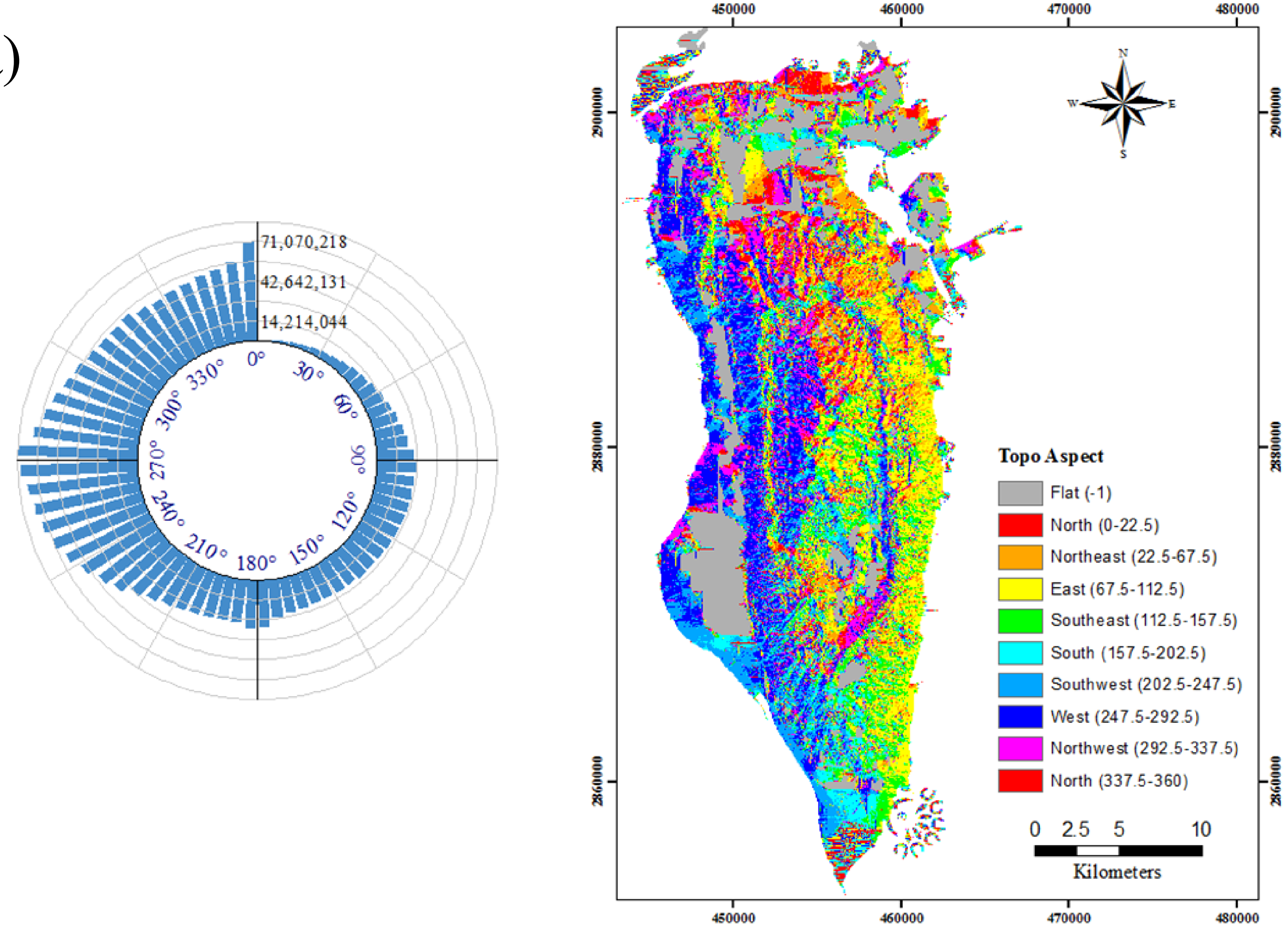
5. Conclusions

Accurate characterization of the topography based on DEM must be considered with high importance in SLR scenarios prediction and hydrology modeling, especially over small islands. Each source of DEM is subject to inaccuracies based on the data acquisition mode, its pixel size, and the topography characteristics. The elevation value measured in a pixel represents an average elevation for several elevation values within that pixel area in the real world. This research compares absolute surface heights accuracies retrieval from three independent DEMs datasets. The Shuttle Radar Topographic Mission (SRTM-V4.1) and the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER-V2.1) with 30-m pixel size, and a DEM-5 of 5 m spatial resolution generated from high topographic contour lines map at scale of 1:5,000 using simple Kriging interpolation method. In addition, topographic attributes (slope and aspect) have been retrieved and compared. For the elevations validation purposes, a datasets of 400 GCPs measured by DGPS and uniformly distributed over the study site were used.

The obtained results show that the derived DEM-5 from high topographic contours map with 5-m pixel size exhibit the best accuracy of ± 0.65 m that is less than to the tolerance or the total error (± 0.78 m) calculated based on errors sources propagation. Decidedly, this DEM-5 is more accurate to evaluate coastal zones vulnerability to SLR, flooding and the detection of topographic features and the magnitude of hydrological processes. The only problem is the DEM data at this scale are often controlled by economic factors, availability and easy accessibility.

The SRTM-V4.1 with 30-m pixel size shows a satisfactory performance with ± 3.00 m accuracy that is less than the absolute vertical height accuracy (± 5.6 m) advocated by NASA for African continent and

(a)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14,214,044
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30°
60°
90°
120°
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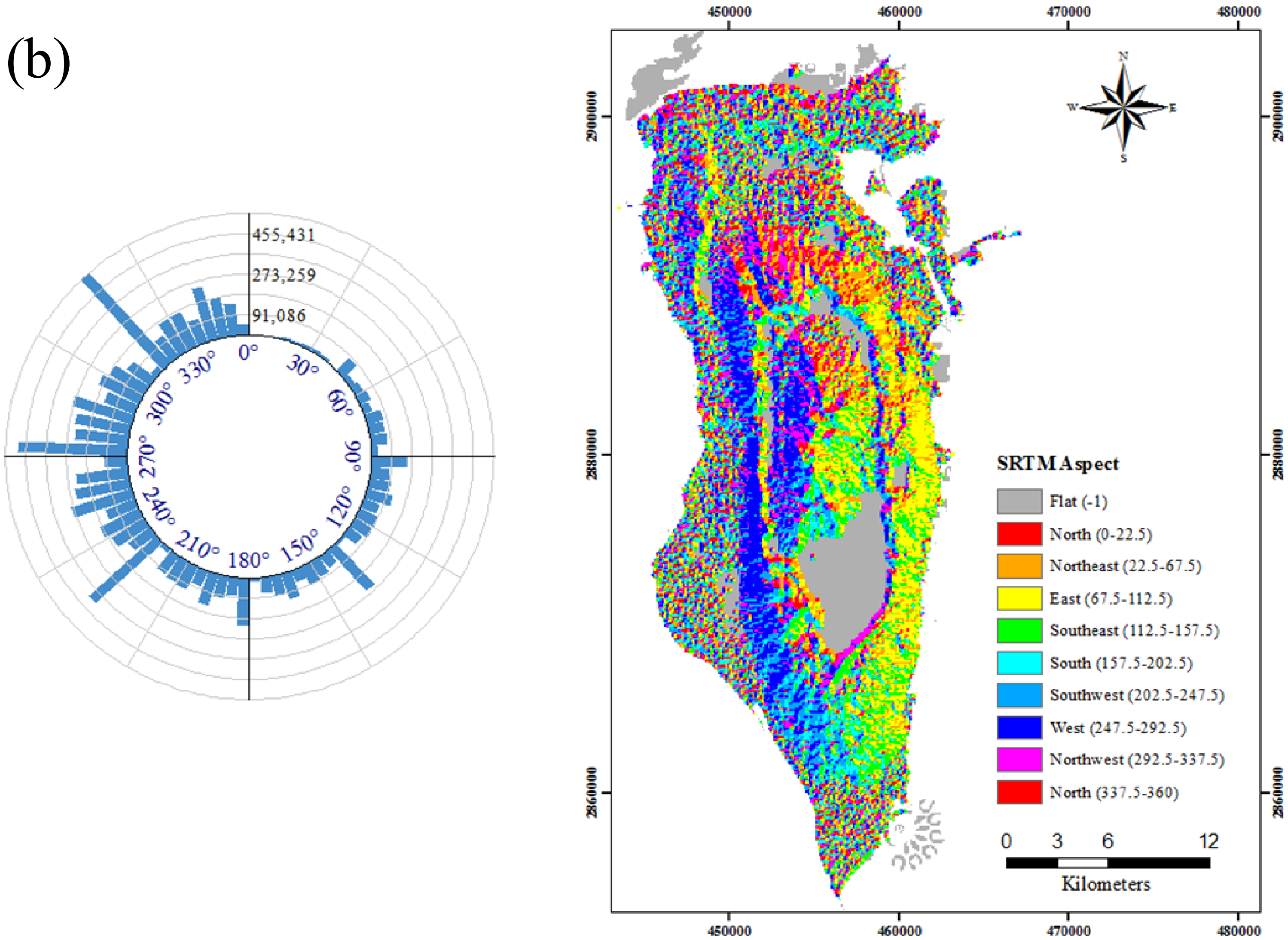
330°
450000
460000
470000
480000
2900000
2880000
2860000
N
S
W
E
Topo Aspect
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)
0 2.5 5 10
Kilometers

(b)



455,431
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SRTM Aspect
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)
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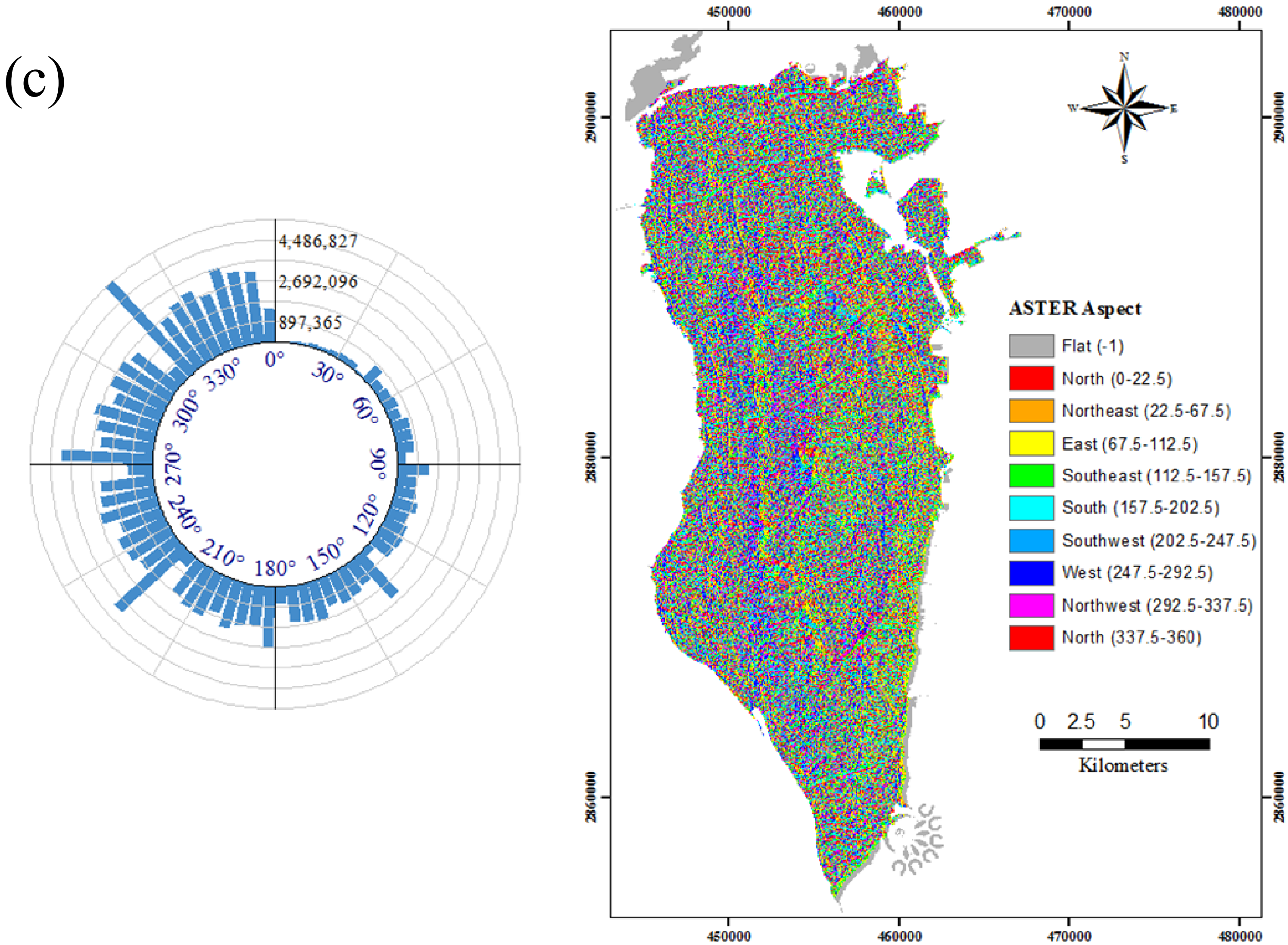

Fig. 6 **Aspect maps derived from contours DEM-5 (a), SRTM (b) and ASTER (c) DEMs.**

Middle-East regions. Obviously, this result is subject of several errors sources, which are propagated, in the raw data acquired by SRTM mission. However, according to this achieved accuracy and the ready-to-be-used, SRTM-V4.1 DEM is of great interest for morphological studies of small islands especially located in regions with frequent cloud coverage. Certainly, the height of small islands as Kingdom of Bahrain with topographic features not higher than 134 m can be estimated using SRTM-V4.1 with relatively and limited accuracy. Whereas, this DEM is not significantly consistent for SLR scenarios simulations.

The achieved ASTER-V2.1 DEM accuracy of ± 8.40 m is better than the estimated error of ± 17.01 m by USGS and JAXA. This large error can be related to many anomalies and artifacts as we discuss previously. However, ASTER provides globally an acceptable representation of the overall island macro-topography. Indeed, a medium or coarse DEM resolution means a more severe terrain generalization, which preserves only major relief features. Whereas, its practical uses are limited for small islands morphology characterization. Consequently, ASTER is not providing suitable and accurate topographic information to simulate the impact of SLR scenarios on small islands or to analyse the vulnerability of low-lying areas to inundation and flooding. Without doubt, ASTER DEM was an excellent alternative compared to SRTM with 90-m pixel size, but actually with SRTM-V4.1 full resolution (30-m) released globally, ASTER will likely see its limited uses in geosciences applications.

In this study, we demonstrated that there are significant differences between the elevation, slope, and aspect values derived from high resolution DEM-5 and medium resolution DEMs, SRTM and ASTER. These space-borne DEMs do not adequately identify the slope change points, which are important in the characterization of flow direction and accumulation processes. Thus, the DEMs with a resolution equal or greater than 30-m do not provide useful information about the real slope value. Obviously, when a DEM does not express the realistic link between the topographic attributes (elevation, slope and aspect) and the drainage system; it becomes not useful in SLR scenarios simulations, as well in hydrological modelling processes. Certainly, the small islands landscape scale plays an important role in the selection of the DEM pixel size. The latter must be less than the hill slope length, and a DEM about 5-m pixel size is required to characterise correctly the landscape hydro-morphology response, and SLR impact analysis. In fact, it was shown that the DEM pixel size must reflect the real slope and aspect values, which are vital to the hydrological response modeling.

Acknowledgements

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