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Artefact detection in global digital elevation models (DEMs): The Maximum Slope Approach and its application for complete screening of the SRTM v4.1 and MERIT DEMs

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ABSTRACT

Despite post-processing efforts by space agencies and research institutions, contemporary global digital elevation models (DEMs) may contain artefacts, i.e., erroneous features that do not exist in the actual terrain, such as spikes, holes and line errors. The goal of the present paper is to illuminate the artefact issue of current global DEM data sets that might be an obstacle for any geoscience study using terrain information. We introduce the Maximum Slope Approach (MSA) as a technique that uses terrain slopes as indicator to detect and localize spurious artefacts. The MSA relies on the strong sensitivity of terrain slopes for sudden steps in the DEM that is a direct feature of larger artefacts. In a numerical case study, the MSA is applied for globally complete screening of two SRTM-based 3 arc-second DEMs, the SRTM v4.1 and the MERIT-DEM. Based on 0.1° × 0.1° sub-divisions and a 5 m/m slope threshold, 1341 artefacts were detected in SRTM v4.1 vs. 108 in MERIT. Most artefacts spatially correlate with SRTM voids (and thus with the void-filling) and not with the SRTM-measured elevations. The strong contrast in artefact frequency (factor ~12) is attributed to the SRTM v4.1 hole filling. Our study shows that over parts of the Himalaya Mountains the SRTM v4.1 data set is contaminated by step artefacts where the use of this DEM cannot be recommended. Some caution should be exercised, e.g., over parts of the Andes and Rocky Mountains. The same holds true for derived global products that depend on SRTM v4.1, such as gravity maps. Primarily over the major mountain ranges, the MERIT model contains artefacts, too, but in smaller numbers. As a conclusion, globally complete artefact screening is recommended prior to the public release of any DEM data set. However, such a quality check should also be considered by users before using DEM data. MSA-based artefact screening is not only limited to DEMs, but can be applied as quality assurance measure to other gridded data sets such as digital bathymetric models or gridded physical quantities such as gravity or magnetics.

1. Introduction

Since the beginning of the 21st century, remote sensing from dedicated space-borne platforms has revolutionized our knowledge of the Earth topography. Notably the (1) Shuttle Radar Topography Mission (SRTM; Farr et al., 2007), the (2) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; Tachikawa et al., 2011), the (3) Advanced Land Observing Satellite with the Panchromatic Remote-sensing instrument for Stereo Mapping (ALOS/PRISM) and associated ALOS World 3D (AW3D) DEM, cf. Tadono et al. (2015) and the (4) TerraSAR-X Add-on for Digital Elevation Measurements (TanDEM-X; Wessel et al., 2016) have sampled the Earth surface geometry with unprecedented resolution and spatial coverage. As a result of these missions, digital elevation models (DEMs) as geometric representations of the surface relief have been produced with spatial resolutions of 1 to 3 arc-seconds (~30 to ~90 m in latitudinal direction) or better and near-global coverage (Hirt, 2015). Today, DEM data sets form a critical backbone in several applications in engineering, geo- and environmental sciences. DEMs have become a common good, e.g., as base layer for personal navigation systems, OpenStreetMap and Google Maps.

In light of the widespread use, a realistic assessment of the DEM quality (that is, how closely the digital model represents the actual terrain surface) is important. DEMs may be subject to imperfections, such as vertical and horizontal errors, speckle-noise, voids (unobserved areas, also denoted as holes) and biases (offsets) that can vary regionally. Also, artificial features that misrepresent the actual terrain surface may be encountered in DEM data sets. Examples include artificial spikes, sinkholes, steps, pixel defects, line and masking (clipping) errors. Among all imperfections in DEM data sets, artefacts may be the

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most crucially problematic error source for DEM applications (Brown and Bara, 1994; Lecours et al., 2017). In areas such as hydrology, hydrodynamics and flooding analysis (Wechsler, 2007; Yamazaki et al., 2017), geostatistics, geomorphology, and geomorphometry (Pike et al., 2009; Reuter et al., 2009), geometrical and physical geodesy (Torge and Müller, 2012; Hirt et al., 2014) these unwanted features may falsify the outcome of DEM-based analyses.

Over the years progress has been made with the production of improved DEM data sets, particularly based on SRTM and ASTER mission products. NASA's Jet Propulsion Laboratory (JPL) and the National Geospatial Intelligence Agency (NGA) have post-processed the initial ("unfinished") SRTM DEM release v1 (2003/2004) to remove some artificial error sources (pits, spikes) and fill minor voids in the "finished-grade" second version (Slater et al., 2006) that was released as v2.0 in 2004/2005 and v2.1 in 2009 (Crippen 2017, pers. comm.). A third model generation with improved void-filling based on ASTER elevation data has been released as Version v3 (2015), cf. NASA (2015) report. As far as ASTER is concerned, some of the spurious vertical artefacts (e.g., spikes representing clouds instead of the terrain) contained in the first "research-grade" release GDEM v1 (2009) have been removed in release GDEM v2 (2011) through inclusion of additional remote sensing data, and better delineation of water bodies has been achieved in GDEM v3 Abrams (2016) that is expected to be released in 2018 (Abrams 2017, pers. comm.). Further, research institutions have released post-processed SRTM versions that differ from the agency products in view of the void filling procedures and removal of additional errors. Examples include the SRTM v4.1 release by CGIAR-CSI (Reuter et al., 2007; Jarvis et al., 2008), the Altimetry Corrected Elevation (ACE2) DEM (Berry et al., 2010), the EarthEnv-DEM90 (Robinson et al., 2014), and the Multi-Error-Removed Improved-Terrain (MERIT) DEM by Yamazaki et al. (2017).

Unfortunately, despite these multiple year-long post-processing efforts by space agencies and research institutions, contemporary global DEMs are not free of artefacts, as the DEM user might be tempted to assume. A good statement was made by Wechsler (2007, p1482) that [modern digital data sets such as DEMs] may "*lure users into a false sense of security regarding the accuracy and precision of the data. Potential errors, and their effect on derived data and applications based on that data, are often far from users' consideration*".

As we demonstrate in this paper, current global DEMs may contain spurious artefacts, such as pixel, line and edge defects, steps, pits and spikes as well as unfilled voids, and most of these unwanted features are a result of the DEM editing processes applied by the producers. The somewhat surprising presence of serious artefacts in current DEMs suggests that artefact testing procedures are not yet routinely applied prior to the release of DEMs.

1.1. Artefact detection in the literature

Methods for artefact detection and their removal have been discussed in several papers. Polidori et al. (1991) proposed to study the fractal geometry of a DEM to detect artefacts. Brown and Bara (1994) detected DEM systematic errors based on semivariance and fractal analysis. Oimoen (2000) investigated the detection and removal of production artefacts (mostly line errors) and emphasized the detrimental role of such features on derived DEM products "*such as slope, aspect and hydrology*". Albani and Klinkenberg (2003) describe a spatial filter for stripe removal in DEMs, while Arrell et al. (2008) tackle the problem of stripe removal with spectral techniques. Feng et al. (2004) presented a technique for removal of cloud-related spikes in ASTER elevation data. Lindsay and Creed (2005) study the removal of artificial depressions in DEMs in the context of hydrodynamic modelling, and Lindsay and Creed (2006) studied techniques to distinguish between artificial and natural depressions in DEM data sets. Reuter et al. (2009) state that because artefacts are "*distinct erratic features, most of them can be detected visually in 3D views, by using sun shading or simple GIS operations*" and note that [handling of artefacts is] "*especially important for land-surface parameters derived from second order derivatives (curvatures), aspect map and/or hydrological parameters*" (Reuter et al., 2009, p91). Villa Real et al. (2013) presents an algorithm for detection of vertical artefacts in DEMs that relies on comparisons against reference data. Polidori et al. (2014) noted the dependency of elevation derivatives on artefacts and tested the directional distribution of slopes that could possibly reveal artefacts in the data. Hirt et al. (2014) used extreme gravity values derived from topography to detect artificial depressions in SRTM elevation data. Merryman Boncori (2016) reports local shifts in SRTM DEM data that can be interpreted as artificial steps between DEM data tiles and Lecours et al. (2017) assess the influence of artefacts in digital bathymetry models on habitat maps. From the literature overview, geomorphometric quantities (Pike et al., 2009) such as horizontal gradients and slope (maximum inclination) are particularly sensitive for artefacts in DEM data sets: This dependency can be exploited, as shown in the present paper, to develop an approach for artefact detection in contemporary DEM data sets.

1.2. This study

The primary goal of the present paper is to detect and investigate spurious artefacts in current global DEM data sets that might be an obstacle in DEM applications requiring realistic terrain derivatives, such as hydrology and hydrodynamics, geomorphology, topographic mapping and gravity modelling. As secondary goal, the paper shall increase awareness in the producer and user community for the artefact problem that may even affect the most recently released products incorporating edited SRTM data.

We introduce the Maximum Slope Approach (MSA) as a technique that uses slopes as indicator to detect and localize spurious artefacts (Sect. 2). The MSA exploits the strong sensitivity of terrain slopes for sudden steps in the DEM that are a direct feature of larger artefacts. We apply the MSA for globally complete screening (inspection) of two selected 3-arc second resolution SRTM releases (Sect. 3) in a numerical case study (Sect. 4). The chosen data sets are (i) the widely used SRTM v4.1 by CGIAR-CSI (Jarvis et al., 2008) and (ii) the new SRTM-based MERIT-DEM (Yamazaki et al., 2017), that can be considered a substantially edited elevation product where error sources have been reduced or removed. In the numerical case study, large terrain slopes will be automatically detected and localized in both SRTM data sets (Sect. 4.1), and semi-automatically classified into natural terrain features and artefacts (Sect. 4.2). The frequency of artefact occurrences in both products and their geographic distribution is analysed in Sect. 4.3 and discussed in Sect. 5.1. To exemplify artefacts and natural slopes we visualize selected DEM samples (see geographical location map in Fig. 1).

Our MSA-based artefact detection procedure is simple. It can in principle be applied with the DEM data itself; however, comparisons with a second DEM product increase the performance of the approach (Sect. 5.2). The MSA can easily be applied on all global DEMs, e.g., from the ASTER, ALOS/PRISM and TanDEM-X sensors, to ensure that spurious artefacts – if contained in the data – are detected before the public data release or application of the DEM. Application of the MSA on other gridded geodata products that may potentially contain artefacts, like planetary topography, Earth bathymetry, magnetics or gravity is possible as well (Sect. 6).

2. Methods

2.1. Definition, cause and examples of artefacts

The term artefact, as aimed at and used in this study, denotes distinct step-like disruptions of the DEM-represented terrain surface that