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A multi-sensor approach towards a global vegetation corrected SRTM DEM product

F.E. O'Loughlin [a,*], R.C.D. Paiva [b], M. Durand [c], D.E. Alsdorf [c], P.D. Bates [a]

[a] School of Geographical Sciences, University of Bristol, United Kingdom
[b] Institute of Hydraulic Research, Federal University of Rio Grande do Sul, Brazil
[c] School of Earth Science and Byrd Polar and Climate Research Center, Ohio State University, United States

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ABSTRACT

We develop the first global 'Bare-Earth' Digital Elevation Model (DEM) based on the Shuttle Radar Topography Mission (SRTM) for all landmasses between 60N and 54S. Our new 'Bare-Earth' SRTM DEM combines multiple remote sensing datasets, including point-ground elevations from NASA's laser altimeter ICESat, a database of percentage of tree cover from the MODIS satellite as a proxy for penetration depth of SRTM and a global vegetation height map in order to remove the vegetation artefacts present in the original SRTM DEM. We test multiple methods of removing vegetation artefacts and investigate the use of regionalization. Our final 'Bare-Earth' SRTM product shows global improvements greater than 10 m in the bias over the original SRTM DEM in vegetated areas compared with ground elevations determined from ICESat data with a significant reduction in the root mean square error from over 14 m to 6 m globally. Therefore, our DEM will be valuable for any global applications, such as large scale flood modelling requiring a 'Bare-Earth' DEM.

1. Introduction

Digital Elevation Models (DEMs) are used for a wide range of applications, including hydrology and water resources, geology and geomorphology, civil engineering projects, vegetation survey, glaciology, volcanology and modelling natural hazards such as flooding, landslides and coastal inundation (Bamber, 1994; Moore, Grayson, and Ladson, 1991). The accuracy of such DEMs is a key point for these applications. For example, in river hydrodynamic modelling, the DEM is one of the most important inputs as it controls the accuracy of the model outputs (Sanders, 2007), in particular flood extents and depths. With climate change, development pressures, and land-use changes generally leading to changes in flood frequencies globally (Hirabayashi et al., 2013; Milly, Wetherald, Dunne, and Delworth, 2002), accurate outputs from hydrodynamic models will become increasingly necessary to understand the risks associated with these changes and their impact on global wetlands and associated issues related to biogeochemical cycles and biodiversity.

In many developed nations accurate DEMs derived from expensive LiDAR surveys are now available, with the first LiDAR surveys flown in the 1980s (Krabill, Collins, Link, Swift, and Butler, 1984). However, these only cover a small percentage of the earth's landmass. For global or near global coverage, space based DEMs must be used. To date, the most popular near-global DEM was obtained from Shuttle Radar Topography Mission — SRTM (Farr et al., 2007). The SRTM DEM has been used by numerous scientists for a variety of science studies. However, all these studies have encountered the same issue: how to correct the vegetation bias in the SRTM DEM. Schumann, Bates, Neal, and Andreadis (2014) noted the importance of an accurate 'Bare-Earth' DEM for flood-modelling and related industries. Baugh, Bates, Schumann, and Trigg (2013) noted that correcting the vegetation error in the SRTM DEM for a region of the Amazon Basin increased the accuracy of modelled inundation extents from 25% to 94%.

Carabajal and Harding (2005) validated the SRTM DEM using ICESat, a satellite laser altimeter, and discovered that the errors in SRTM increased with increasing tree cover. This was because the C-band radar used by SRTM could not fully penetrate the vegetation canopy to the ground. This finding was also supported by another study that utilized satellite radar altimeters to validate the SRTM DEM (Berry, Garlick, and Smith, 2007). While these errors can clearly be attributed to vegetation, their correction requires knowledge about canopy heights and radar penetration depths. The first widely used global vegetation height map was only published in 2010 (Lefsky, 2010), followed by a more accurate vegetation map the following year (Simard, Pinto, Fisher, and Baccini, 2011). Prior to this, the correction of vegetation biases in SRTM could only be undertaken on small areas using either in-situ measurements or national datasets (Gallant, Read, and Dowling, 2012; Wilson et al., 2007). In hydrologic and hydrodynamic modelling, vegetation errors in the SRTM have generally been ignored except in

* Corresponding author.
E-mail address: fiachra.oloughlin@bristol.ac.uk (F.E. O'Loughlin).

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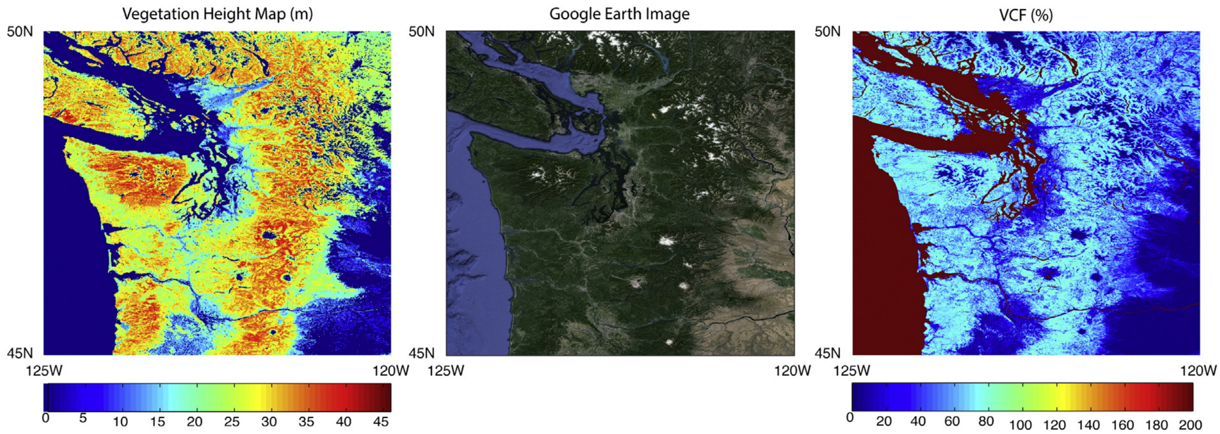

Fig. 1. Comparison of Vegetation Height Map, Google Earth Image and VCF product. Examples of the Vegetation Height Map and VCF datasets are shown for a smaller region in Fig. 9.

heavily-vegetated areas, such as the Amazon (De Ruyver, 2004; Pinel et al., 2015). However, here the SRTM bias can cause large errors in model results such as under predicted flood extent and too rapid flood wave propagation (Jarihani, Callow, McVicar, Van Niel, and Larsen, 2015; Paiva et al., 2013). Despite the importance of artefact removal methods to correct vegetation errors in SRTM data to date have been rather simple and have only applied static corrections, i.e. they removed a spatially uniform fixed percentage of vegetation height from the DEM (e.g. Baugh et al., 2013; Paiva, Collischonn, and Tucci, 2011). For example, Baugh et al. (2013) found that subtracting 50% of the vegetation height produced the best results in their hydrodynamic model but highlighted that this fraction may be different in other regions with other vegetation densities.

In this study we therefore introduce a first near global 'Bare-Earth' SRTM DEM product using a dynamic correction that varies with vegetation height and density, and which can be regionalized according to climatic zones or vegetation types. Our 'Bare-Earth' SRTM DEM deals only with vegetation biases and does not remove biases due to built structures.

2. Data and methodology

We use the SRTM DEM as our base data product. We then use global maps of vegetation height (Simard et al., 2011) and a canopy density proxy from MODIS data, coupled with satellite altimetry (ICESat GLAS) to develop and validate an empirical model for global DEM vegetation correction. Different correction models and parameter regionalizations are tested and to determine an optimal method, examples showing the impact of the vegetation correction on the SRTM DEM are provided. All datasets used were horizontally referenced to WGS84.

2.1. SRTM DEM

The Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007) was an international project sponsored by the National Geospatial-Intelligence Agency (NGA) and NASA and was flown in February 2000. During its 11 day mission 12.3 Tbyte of terrain data were collected covering land areas between 56S and 60N. Two InSAR instruments were used: a C-band radar provided by the Jet Propulsion Laboratory (JPL) and an X-band radar provided by the German and Italian space agencies.

Kinematic GPS transects, corner reflector arrays, ground control points (GCPs) from NGA and JPL, and optical imagery DEMs were used in system calibration and accuracy assessment (Farr and Kobrick, 2000). SRTM's vertical and horizontal linear errors at 90% confidence (LE90) were smaller than the mission specifications of 20 m and 16 m respectively (Rabus, Eineder, Roth, and Bamler, 2003). When compared with GCPs, Rodríguez, Morris, and Belz (2006) discovered that vertical errors (LE90) in SRTM were approximately 8.2 m globally, while Berry et al. (2007) found the vertical mean error globally between SRTM and ground points determined from satellite radar altimetry data to be 3.6 ± 16.16 m.

In this study, we used the 3 arc-second C-band void-filled version 4 SRTM DEM product (Jarvis, Reuter, Nelson, and Guevara, 2008) obtained from the Consortium for Spatial Information (CGIAR CSI) available at srtm.csi.cgiar.org. This product is referenced vertically to the Earth Gravitational Model of 1996 (EGM96). EGM96 has the same reference ellipsoid as WGS84, but it has a higher spatial resolution and more accurate geoid. While many different versions of the SRTM DEM exist, all of them have the same vegetation errors and the method described below is generic.

2.2. ICESat

The ICESat Geoscience Laser Altimeter System (GLAS) was the first satellite based Earth orbiting laser altimeter and was operational between 2003 and 2009. ICESat GLAS had a surface footprint of ~65 m and made observations every 172 m along its track (Schutz, Zwally, Shuman, Hancock, and DiMarzio, 2005). Mission details and data products are described by Zwally et al. (2002). In this study the ICESat GLAS GLA14 Land Elevation Product, Release 34, was used. Geodetic and atmospheric corrections have already been applied to this product. Carabajal and Harding (2005) noted that the vertical error in these data is 0.01 ± 0.04 m for flat surfaces.

ICESat data were obtained from the Reverb website (available at reverb.echo.nasa.gov) and were extracted using code provided by the National Snow and Ice Data Centre (NSIDC). The extracted data were converted to the WGS84. Suitable observations were selected by use of the elevation-use flag, and the saturation index was used to remove/correct saturated observations. This was done to ensure only undistorted ground elevations were selected. The same criteria used by Hall, Schumann, Bamber, Bates, and Trigg (2012) and O'Loughlin, Neal, Yamazaki, and Bates (2016); O'Loughlin, Trigg, Schumann, and Bates (2013) was implemented: observations with a saturation index less than two were not corrected, observations with an index of two were corrected using the saturation elevation correction field, and all other observations were excluded. The selected observations were then converted to EGM96 — the same vertical datum as the SRTM DEM. However, as a number of peaks can be found in ICESat GLA14 observations and the GLA14 elevation is given as the centroid of the Gaussian fit, to ensure that the ICESat returns are as close as possible to 'ground truth' we applied the criterion that the number of peaks detected in the ICESat observations must be equal to one. We use the centroid value as this is the best estimate of the mean ground elevation over the ~70 m ICESat return for single peak waveforms. It should be noted that the returns of single peak data over vegetation are wider than multiple peak returns. While it is known that ICESat suffers from errors due to changes in