The TanDEM-X 30m DEM Change Maps: applications and further developments

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Abstract

The TanDEM-X mission has been acquiring continuously bistatic data from which DEM are derived since 2010. The outstanding quality of these DEMs enables the observation of changes that occur on the whole Earth's landmass. This paper presents the new product of the TanDEM-X mission, the TanDEM-X 30m DEM Change Maps, which is available for free for scientific and non-commercial use since November 2023. Various applications which are primordial for climate change monitoring are introduced and show how the DEM Change Maps can be a very useful input to derive information about e.g. glacier melting, mining monitoring or deforestation globally. Finally, the next developments towards building DEM Change Maps time series are explained.

1 Introduction

Since 2010, the TanDEM-X mission flies two very similar satellites in a close formation to provide bistatic interferometric imaging for digital elevation models. In 2016 the first global TanDEM-X DEM, generated from two coverages of the entire landmass of the Earth, was released. Already at the time of its creation, it became clear that the Earth's surface is dynamic in many areas and that these changes could be recorded using the TanDEM-X DEMs since changes in glaciers or forests, but also agricultural activities or infrastructural changes leave well visible traces in the X-band DEMs. Therefore, in 2017, the TanDEM-X mission decided to acquire an additional complete coverage of the Earth's landmass. The goal was to create an independent dataset within a well-defined period from 2017 to 2020 to observe topographic changes. This data is used to create a new global DEM, the TanDEM-X DEM 2020 [1], but also to produce a new global product called the TanDEM-X 30m DEM Change Maps. The aim of this product is to show the DEM changes in the newly acquired data w.r.t. the first global DEM on a global scale. This can also help to understand climatic changes. Note that the newly acquired overlapping DEMs are not averaged together during the mosaic generation before calculating the difference, as it is the case with TanDEM-X DEM 2020, so that the crucial temporal information is preserved.
In a first step, the global TanDEM-X DEM was edited in a 30-metre grid, i.e. gaps were filled with elevation data from external sources and water areas that appear noisy due to the low radar backscatter were smoothed [2]. Both the edited DEM, the TanDEM-X 30m Edited DEM and the TanDEM-X 30m DEM Change Maps are freely available for scientific and non-commercial users since November 2023 [3].
This paper starts with a short description of the TanDEM-X 30m DEM Change Maps product, and raises attention to its limits when it comes to straightforward usage for volume change computation. Afterwards, some applications are shown and finally an outlook on the future extension of the DEM Change Maps to DEM Change Maps time series is provided.

2 TanDEM-X 30m DEM Change Maps Product Description

2.1 Main characteristics

The TanDEM-X 30m DEM Change Maps product aims to provide global terrain change information that is particularly useful for various fields, including mining, glaciology, and forest monitoring. The product shows changes between the DEM generated with data collected between 2016 and 2022 (yet, most of the data were taken between 2017 and 2021) and the TanDEM-X 30m Edited DEM [2]. In order to be able to monitor terrain changes, it is important to know precisely the acquisition time of the used data. Therefore and since some parts of the world were acquired more than once during the considered acquisition phase, two DEM Change Maps are provided per geographic cell in order to keep the respective unique timestamp for each pixel. One DEM Change Map (DCM) shows changes between the reference DEM and the oldest pixels of the new dataset – or first DEM changes -, and the second DCM exhibits changes between the reference and the newest pixels from the new dataset – or latest DEM changes (Figure 1). Thus, the two maps differ when there are multiple coverages. In the case of a single coverage, both maps contain the same information.
This product is a first step for visualizing temporal changes in glaciers, ice sheets, coastlines and forests on a global scale which is important for understanding the impacts of

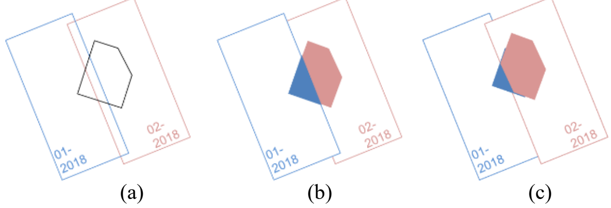

Figure 1 First and latest TanDEM-X 30m DEM change maps: (a) Two adjacent scenes taken at different times, where the terrain has changed across both scenes; (b) DEM change map - first change: the pixels of the oldest acquisition are taken in the overlap area; while for the (c) DEM change map - last change, the pixels of the newest data are selected in the common area

climate change. Therefore, it is planned to extend the TanDEM-X 30m DEM Change Maps locally to provide detailed information on changes to the Earth's surface over time in form of a stack or times series containing all available and future TanDEM-X DEM acquisitions.

2.2 Information layers

All information layers exist for multiple time intervals (e.g. first1622 and last1622) for each tile. Here first1622 stands for the first change layer between 2016 and 2022 and last1622 respectively for the last change layer. The TanDEM-X 30m DEM Change Map components, which are described hereafter are:

- DEM Change Map (DCM)
- Height Accuracy Indication (HAI)
- Change Indication Mask (CIM)
- Acquisitions Date (DATE)

2.2.1 DEM Change Map (DCM)

The DCMs are the main layers and give the DEM difference in meters. Note that this layer gives DEM differences and not necessarily physical height differences, because the reference (TanDEM-X 30m Edited DEM) is averaged over a time period. Additionally, no correction for penetration depths into snow, ice or forests is currently considered. In the product available for download under [4], coloured quicklooks with legend are provided (Figure 2) as well as a kmz file containing full resolution coloured png with various clipping of the color scale so that changes of different orders of magnitude can be observed.

Since the new images were calibrated over stable surfaces of the TanDEM-X 30m EDEM, it can be assumed that their absolute height accuracy is in the same order or slightly worse than the TanDEM-X 30m EDEM i.e. less than 2 metres. Consequently, the derived DEM Changes provide an accurate estimation of the height changes over at least bare surfaces (see Section 2.3). Jumps may occur between adjacent acquisitions if the two acquisition dates are separated by several months. In fact, a finer calibration is performed within the datatake but not between adjacent datatakes to preserve the possible large-scale terrain changes. Therefore, the DATE layers (section 2.2.4) shall always be considered together with the DCMs.

2.2.2 Height Accuracy Indication (HAI)

The Height Accuracy Indication map represents for each pixel the combination of the Height Error Map values (HEM) of the new DEM data and the TanDEM-X 30m EDEM (Figure 3). It is computed as the error propagation under the assumption of Gaussian distributions. However, this is only an approximation therefore called height accuracy indication and not height error map. Calibration or phase unwrapping errors are not represented in this layer.

2.2.3 Change Indication Mask (CIM)

The Change Indication Mask (CIM) indicates where the DCM processor found changes between the CRawDEM mosaic and the reference DEM (TanDEM-X 30m EDEM) and help users with the analysis of the reliability of DEM changes based on the local properties of the TanDEM-X 30m EDEM, the CRawDEM data and the HAI (Figure 4).

2.2.4 Acquisition Dates (DATE)

The date layer gives the acquisition date of the used CRawDEM scene for each pixel. The date is given in integer format YYYYMMDD (Figure 5). The DEM Change is therefore flagged with this date. Note however that the DEM Change is computed w.r.t TanDEM-X 30m EDEM which has no clear timestamp. Indeed, it is an edited version of the first global TanDEM-X DEM which was generated by mosaicking overlapping single-scene DEMs acquired in a time span between the end of 2010 and 2015. Consequently, the time span during which the change occurred cannot be clearly stated yet.

2.3 Warning about the usage of the DCM

Note that radar waves are able to penetrate into volumetric targets, such as vegetation and snow and ice. The amount of penetration depends on the radar frequency, the acquisition geometry and the characteristics of the target itself (e.g. vegetation structure and density or snow properties). In these cases, the estimated height from an InSAR-derived DEM (i.e. the radar reflective surface) represents the location of the mean phase center of the backscattered signal from the illuminated volumetric target and it is typically located below the real surface. Differently, no penetration occurs over bare surfaces and, in this case, the retrieved topographic height from InSAR-derived DEMs represents indeed the height of the real surface.

Moreover, the DEM differences depicted in the DEM Change Maps are evaluated with respect to an edited version of the original TanDEM-X Global DEM product, which was generated by mosaicking overlapping single-scene DEMs, called RawDEMs, acquired in a time span between the end of 2010 and 2015 (at least two acquisitions were utilized over low-relief areas, while up to about 10 acquisitions were necessary over high-relief terrain in order to achieve the specified accuracy). Therefore, the topographic height depicted by the TanDEM-X Global DEM represents an estimation of the mean height of the radar reflective surface, derived using an averaging procedure weighted by the reliability of each single input RawDEM. Temporal changes which occurred during the acquisitions time span were also averaged in the mosaicking.

As a consequence:

- Precise time-stamps can only be associated to changes between pairs or stacks of DEM Change Maps.
- It is not possible to exactly time-tag the height changes in the new DEM Change Maps with respect to a specific date in the past, but they can only be referred to the overall acquisition time span of the RawDEMs utilized for the generation of the TanDEM-X Global DEM product.
- The new DEM Change Maps can only be associated to physical height changes for bare surfaces, while in presence of vegetation or snow and ice (characterized

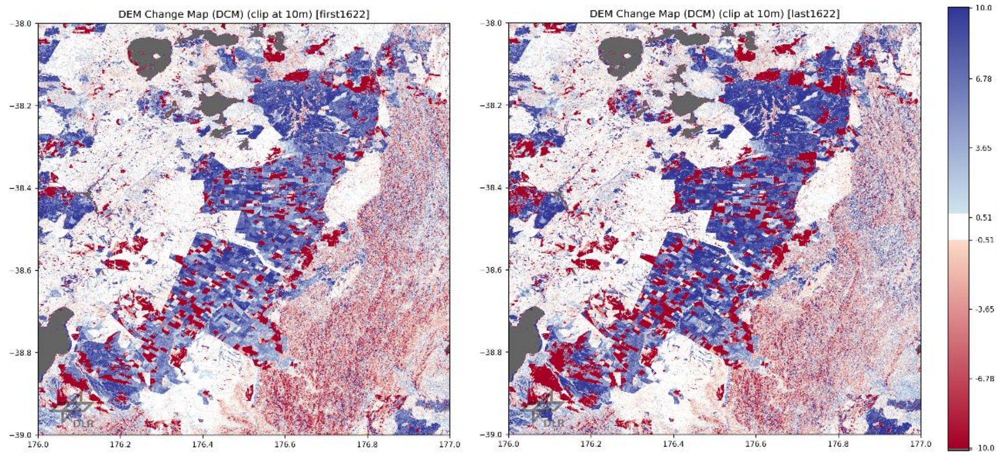

Figure 2 Coloured quicklooks of the DCMs of tile S39E176 (Northern Island of New Zealand): first change (first1622, left) and last change (last1622, right)

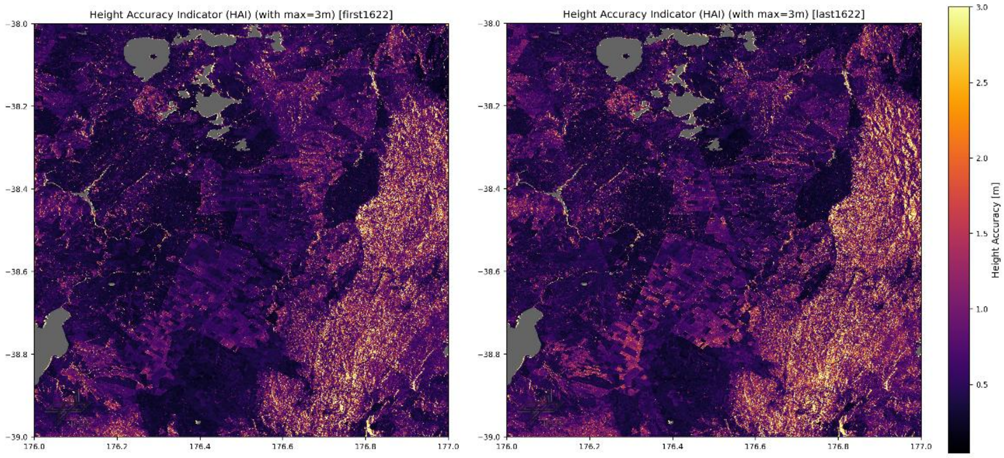

Figure 3 Coloured quicklooks of the HAIs of tile S39E176 (Northern Island of New Zealand): of the first change (first1622, left) and of the last change (last1622, right)

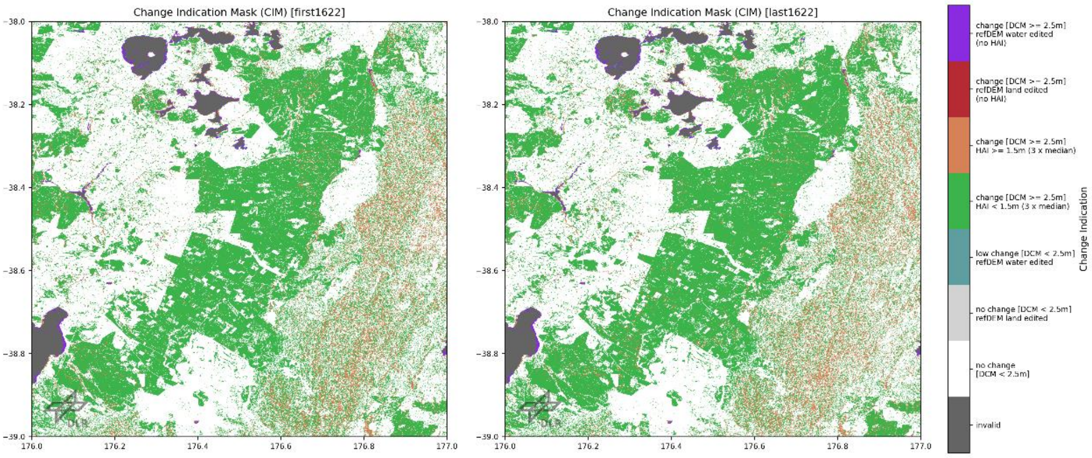

Figure 4 Coloured quicklooks of the CIMs of tile S39E176 (Northern Island of New Zealand): of the first change (first1622, left) and of the last change (last1622, right). Blue-green and green depicts changes that can be considered as reliable and orange, red and purple are changes that are non-reliable.

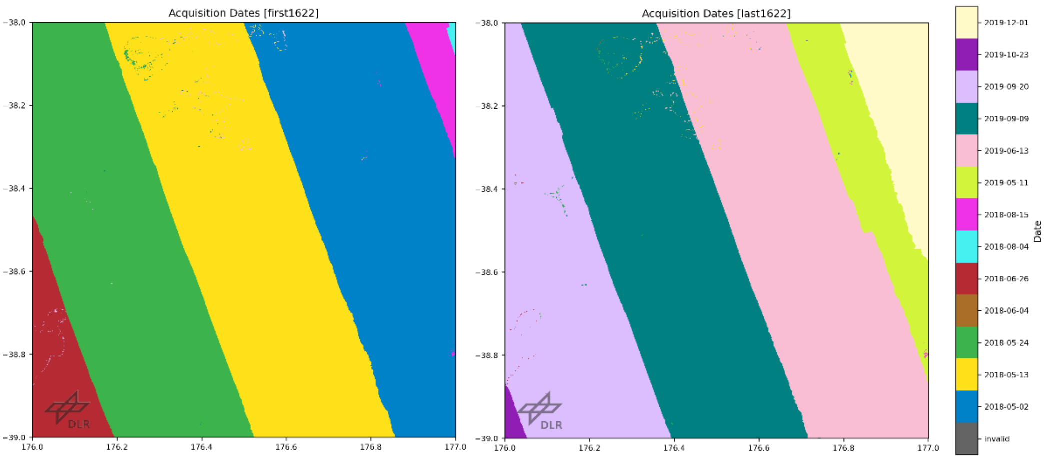

Figure 5 Coloured quicklooks of the DATEs of tile S39E176 (Northern Island of New Zealand): of the first change (first1622, left) and of the last change (last1622, right)

as an indicator of possible changes, but they should not be used for a precise estimation of vegetation and snow/ice height changes. Obviously, seasonal changes (e.g.: leaf-on / leaf-off, snow-free / snow-covered, non-frozen / frozen) have to be considered as well.

3 Applications

The DEM Change Maps, which are provided with an exact recording date provide the DEM changes with respect to the TanDEM-X 30m EDEM. The addition of the temporal component (i.e. the one of the newer acquisitions) significantly increases the information content of the interferometric recordings and creates globally unique data sets that are not only highly interesting for science, but also provide valuable contributions to socio-political issues and questions of climate change in all four spheres of the Earth.

3.1 Mining monitoring

Our first example of the use of the change maps is the Garzweiler open-cast lignite mine in North Rhine-Westphalia. The destruction of the village of Lützerath caused quite a stir in Germany earlier that year.
Looking at a TanDEM-X DEM Change Map over the Garzweiler lignite mine (Figure 6), the major changes are already visible at first glance. The new image over this area was taken in May 2018. The reference images for the first TanDEM-X elevation model were taken in this area between 2011 and 2013. If you add up the negative changes in elevation (in red), i.e. the total excavation, over this area, you get the amount of extracted lignite and the overburden volume. This total volume is -490 ± 6 million m^3. In this

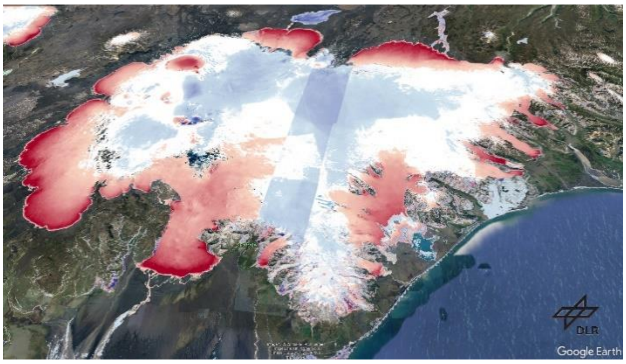

Figure 7 DEM Changes (between -30m (in red) and +30m (in blue)) over the Vatnajökull, the largest ice cap in Iceland: acquisitions are from November/December 2017 and the bluer one is from April 2019, so that different DEM changes are visible. On the top, the lava flow of the Bardabunga eruption can be seen in blue.

case, the given error refers only to the combined elevation error maps of the reference elevation model and the new data. In addition, it must be noted that the calibration of the new elevation data as well as the different recording times could of course introduce additional inaccuracies. Despite these limitations, the order of magnitude of the measured volume is consistent with the coal production of 30 million tonnes and overburden output of 100 - 120 million m^3 per year stated by the energy supply company RWE [5].

3.2 Volcanic activity

In addition to man-made changes, there are elevation changes in the geosphere caused by geological phenomena such as earthquakes or volcanic eruptions.
The next example shows the effects of the eruption of the Bardarbunga volcano in the northwest of Iceland's largest ice cap, Vatnajökull, between late August 2014 and late February 2015.

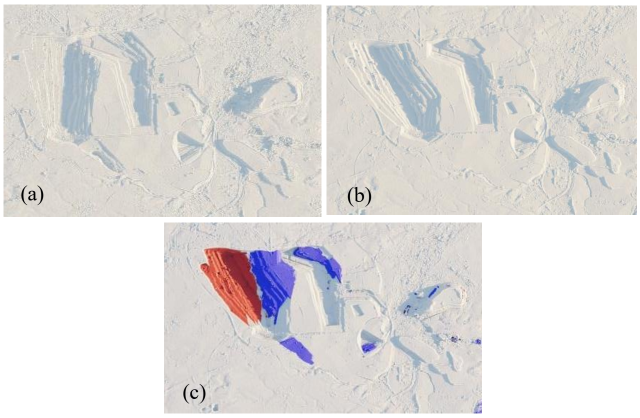

Figure 6 DEM Changes over the mine of Garzweiler in Germany: (a) extract from the first global TanDEM-X DEM with data acquired between 2011 and 2013; (b) mosaic of the new DEM scenes taken in may 2018 (c) DEM Change Map overlaid on the newer mosaicked DEM. Red emphasizes the part which was extracted.

The lava flow significantly changed the terrain elevation and a large lava field formed as it can be seen north of the TanDEM-X DEM Change Map in Figure 7. This lava field has an area of 85 km^2 with an average height of 14 metres and a maximum height of about 40 metres. Summing up the increase over the area of the lava field, a volume change of 1.47 ± 0.03 km3 was derived. The uncertainty only contains the combination of the height errors due to the coherence of both measurements. Further sources of error such as calibration and seasonality have not yet been considered. Yet, this estimate fits very well results of previous study by Dirschel et al [6], which determined a volume of the lava field of 1.44 ± 0.03 km3.

3.3 Glaciers melting

Figure 7 shows also ice formations in the glacier, so-called kettles, which are formed by volcanic activity. Vatnajökull has lost part of its volume. Volcanic activity but primarily global warming are the main reasons for the retreat. The TanDEM-X Change Maps can therefore also provide information on questions concerning the cryosphere.
Using these maps which are globally accessible, it is possible to observe the development of glaciers and polar regions on the entire surface of the Earth and to get an idea of the extent of the changes and especially the melting of glaciers within 6 to 8 years. In contrast to the previous examples from the geosphere, however, it is not possible to

precisely determine the volume of ice or snow that has disappeared. This is due to several factors.
On the one hand, the averaging of several recordings in the reference DEM (the TanDEM-X 30m Edited DEM, edited version of the global TanDEM-X DEM) has the disadvantage that neither precise information on the time nor the acuiqistion geometry of the data can be given. On the other hand, in the presence of snow- or ice-covered surfaces, the radar waves penetrate the snow cover, so that the estimated topographic height is below the real surface. Considering the short wavelength of the X-band, this phenomenon is (only) in the order of few meters, yet it must be carefully considered when interpreting the change maps.
Changes in glaciers and ice fields are highly sensitive indicators of climate change. Figure 8 shows an overview of the massive melting over the southern Patagonian ice field since the acuiqistions for the first TanDEM-X elevation model.

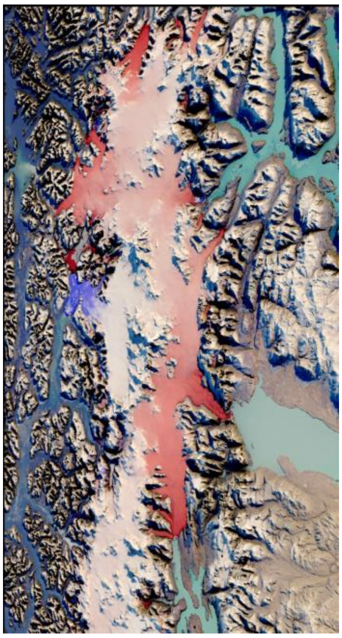

Figure 8 DEM Changes (between -30m (in red) and +30m (in blue)) over the Patagonian ice field. Massive melting of the glaciers can be observed. The only part in blue is the Pio IX glacier which is one of very few areas

Looking at the Jorge Mott Glacier in the northwest in detail, the strong melting and thus the decrease in height can immediately be noticed. In order to limit the calculation to the glacier, only all changes greater than 10 m in absolute terms were considered and added up. On the ice field itself, a smaller but nevertheless negative height trend is recognisable, which is not considered for this calculation. Over the Jorge Mott Glacier, this results in a total volume decrease of 10.7 ± 0.2 km3 between December 2010 to August 2014 and June 2018. Depending on the reference date, this means a melting of 1.4 to 2.6 km3/yr. For an earlier period, a melt rate of -2.59 km3/a could be determined [7]. This rough estimate is in the same order of magnitude and thus shows the potential that DEM change maps have with appropriate acquisition time knowledge and penetration compensation. Particularly striking is the Pio XI (or Brüggen) glacier, which in contrast to the rest of the area shows a blue colouration and thus an increase in elevation. Recent studies show that local conditions such as calving, fjord topography and sediment budget, as well as climate, have led to the unusual increase over the past decades.

3.4 Deforestation

Changes in forests can also be observed in TanDEM-X DEM Change Maps. Deforestation and the associated significant decrease in elevation is clearly visible and shows up in dramatic deforestation patterns, especially in tropical rainforests. Figure 9 depicts a scene east of Lake Taupo on New Zealand's North Island showing the elevation change to the global TanDEM-X DEM for data taken in mid-2018 or mid-2019. In the upper left corner is a protected forest area that has changed little as the natural forest grows slowly. To the right of this is a heavily managed forest area where progressive deforestation but also regrowth is evident. Comparing 2018 to 2019, darker shades of blue appear, i.e. the annual growth of these fast-growing trees becomes visible and measurable.

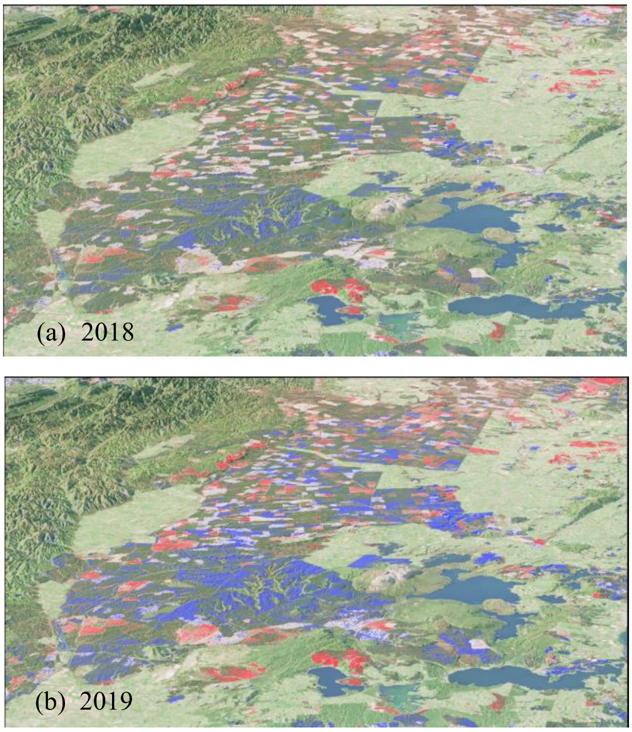

Figure 9 DEM Change Maps over a forested and agricultural area in the northern island of New Zealand: in red and blue, DEM changes from acquisitions from 2018 (a) and 2019 (b) w.r.t. TanDEM-X 30m Edited DEM.

Over forested areas, X-band radar waves penetrate very little, so TanDEM-X heights move in the canopy. This is referred to as a surface model. Density and type of forests, as well as seasonal changes and imaging geometry determine the depth of penetration into the canopy. Similar to snow and ice, a direct derivation of the changed volume is therefore not easily possible. However, if areas with similar geometry are observed at the same time of year, time series (stacks) of DEM change maps are created, which can then be compared with each other and also enable quantitative analyses and thus even the detection of emergence.

4 DEM Change Maps Stacks

The TanDEM-X 30m DEM Change Maps already represent a unique dataset with great potential for many different applications. However, they can only give the DEM change in comparison to the TanDEM-X 30m EDEM, which does not have a specific time-tag. Some pixels can even contain information from several different years. This procedure yields the great accuracy of the global TanDEM-X DEM, but it also means it is not possible to give an exact time period for the observed DEM height change.
In order to obtain a DEM Change Map with a time-tagged reference, the difference between two time-tagged mosaics of CRawDEM scenes can be calculated. Although this is already possible by combining the FIRST and LAST mosaic of the published 30m DEM Change Map product, there are not only these TanDEM-X DEM data available (Figure 10).

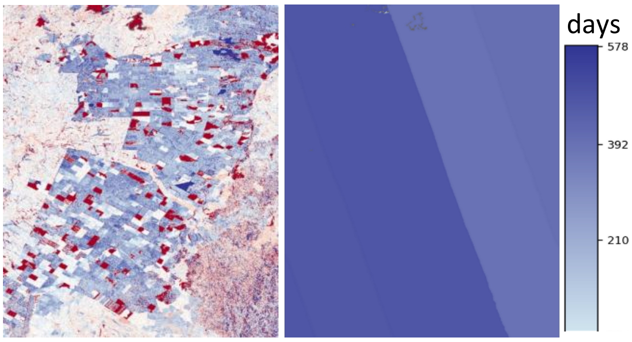

Figure 10 Difference of the two DEM Change Maps depicted in Figure 9 together with the time difference in days between both acquisitions.

Additional DEM acquisitions such as the former acquisitions used for the global DEM (2010 - 2016) and also up-to-date data (since 2022) is used for further time layers.
The older acquisitions are currently reprocessed with the TanDEM-X Processor (ITP) with delta-phase and adaptive filtering processing [8,9], in order to obtain the same quality and pre-calibration as the CRawDEM scenes used for the DEM Change Maps.
After processing all these years of TanDEM-X DEM data to CRawDEM scenes, multiple layers of time-tagged DEM changes, so-called DEM Change Map Stacks, can be computed. DEM Change Map Stacks allow the observation of DEM change velocities, as well as the determination of timely defined volume changes. These quantities are important parameters for application areas, such as open pit-mining, glaciers, forests, drying lakes, and many more.
The DEM Change Map Stacks do not have the same amount of data all over the Earth. There are at least three acquisitions globally. Over difficult terrain like mountainous regions there have been additional acquisitions for the global DEMs and therefor for the DEM Change Map Stacks. Furthermore, there were and are additional acquisitions ongoing over fast changing and areas of interest, like active volcanoes, glaciers or active mining sites.
Within this contribution, examples of DEM Change Map Stacks and their usage will be shown.

5 Conclusion

This paper presented the new product of the TanDEM-X mission: The TanDEM-X DEM Change Maps. This product is available for free in 30m posting since November 2023 and will be updated regularly in order to build time series of DEM changes. The ultimate goal is to provide these times series over the whole lifetime of the TanDEM-X mission.

6 Literature

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