Ice surface changes in Eisriesenwelt (Salzburg, Austria) based on LIDAR measurements between 2017 and 2020

ABSTRACT

Based on highly accurate laser detection and ranging (LIDAR) surveys in the show cave part of Eisriesenwelt in 2017, 2019 and 2020, areal and mass-related comparisons of the ice cover were carried out. The results show that within this three-year period the total ice surface of about 11,100 m² remained nearly constant and a slight increase in ice volume occurred. Detailed three-dimensional visualisations of the dynamics of the ice surface within the study period are shown and discussed.

ZUSAMMENFASSUNG

Veränderungen der Eisoberfläche in der Eisriesenwelt (Salzburg, Österreich) anhand von LIDAR Messungen zwischen 2017 und 2002

Basierend auf hochexakten Vermessungen des Schauhöhlenteils der Eisriesenwelt mittels Laser-Scanner in den Jahren 2017, 2019 und 2020 wurden flächenhafte und massenbezogene Vergleiche der Eisbedeckung angestellt. Es zeigte sich, dass über diesen Zeitraum von drei Jahren die Gesamteisfläche von etwa 11.100 m² nahezu gleich blieb, und ein geringer Eisvolumenzuwachs zu verzeichnen war. Detaillierte dreidimensionale Visualisierungen zur Dynamik der Eisoberfläche werden für den Untersuchungszeitraum gezeigt und diskutiert.

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INTRODUCTION

Eisriesenwelt, located approximately 50 km south of the City of Salzburg at an elevation of 1640 m, is one of the largest ice caves on Earth.

In order to monitor the ice masses in times of global warming, a series of three-dimensional ice-surface mapping campaigns have been carried out since 2010. After an initial interval of three years (2010, 2013, 2016), the most recent campaigns were performed in 2017, 2019 and 2020, in order to obtain detailed spatial data for a better understanding of the relationship between climate and ice dynamics. For information about the ice cave and the three-dimensional mapping by means of terrestrial laser-scanning the reader is referred to Buchroithner et al. (2011), Milius & Petters (2012), Petters (2012), and Buchroithner (2015).

DATA ACQUISITION

The data presented in this paper were acquired in 2017, 2019 and 2020 always at the end of April using a *RIEGL* VZ-400i LIDAR instrument mounted on a tripod (Fig. 1), taken from approximately 350 scan positions during each measurement campaign. With a diameter of 206 mm and a height of 308 mm the scanner, which weighs 9.7 kg, uses a laser source in the near infrared (wavelength of 1550 nm), which means that the laser light is invisible and eye save. Data acquisition can be done in absolute darkness. Each data set was scanned with a spatial sampling resolution of 9 mm at 10 mdistance (equalling 0.05° resolution in azimuth and elevation). The acquisition of the LIDAR data of a full 360° scan takes 30 seconds. Every 10 m such a full 360° scan was taken on the visitor walkway. Each scan contains approximately 15 million measurements, which result in a point cloud of around 5 billion measurements for each campaign.

Automatic on-board registration aligned each newly acquired scan position with respect to all previously

Fig. 1: The RIEGL VZ-400i terrestrial laser-scanner mounted on a tripod on the visitor walkway of the Eisriesenwelt.
Abb. 1: Der *RIEGL* VZ-400i terrestrische Laserscanner, montiert auf einem Dreibein, platziert auf dem Besucherweg der Eisriesenwelt.
Foto: Thomas Gaisecker

acquired data. Thus, the registration did not require any user interaction as long as the data of the newly acquired scan position overlapped sufficiently. At the end of each measurement campaign, i.e. after approximately 15 h inside the cave, all data were already registered within the correct coordinate system (Figs. 2, 3).

DATA PROCESSING AND VISUALISATION

After transferring the data to *RIEGL's* postprocessing-software *RiSCAN PRO* a comprehensive report on the project was automatically generated. Additionally, *RiSCAN PRO* provides easy-to-use tools for rapid and expressive visual inspection of data accuracy (Fig. 4) which allowed to verify at a single glance that the data of all scan positions are consistent within a few millimetres. The data in Fig. 4 show a voxel dataset colourised by the standard deviation attribute of each voxel. In three-dimensional computer graphics, a voxel represents a value on a regular grid in three-dimensional space, e.g. a cube.

After completion of the data registration the whole point cloud was divided into small cubes, the aforementioned voxels. For the Eisriesenwelt dataset we used a voxel size of 10 cm. Within each voxel the distribution of the scan data was analysed and a best fit plane was calculated. The standard deviation represents the noise of the data with respect to this plane. An interpretation of this standard deviation only makes sense on voxels representing almost flat areas. In the case of poor registration (i.e. if the scan data do not fit together) the standard deviation would increase significantly. Nevertheless this voxel dataset is just used

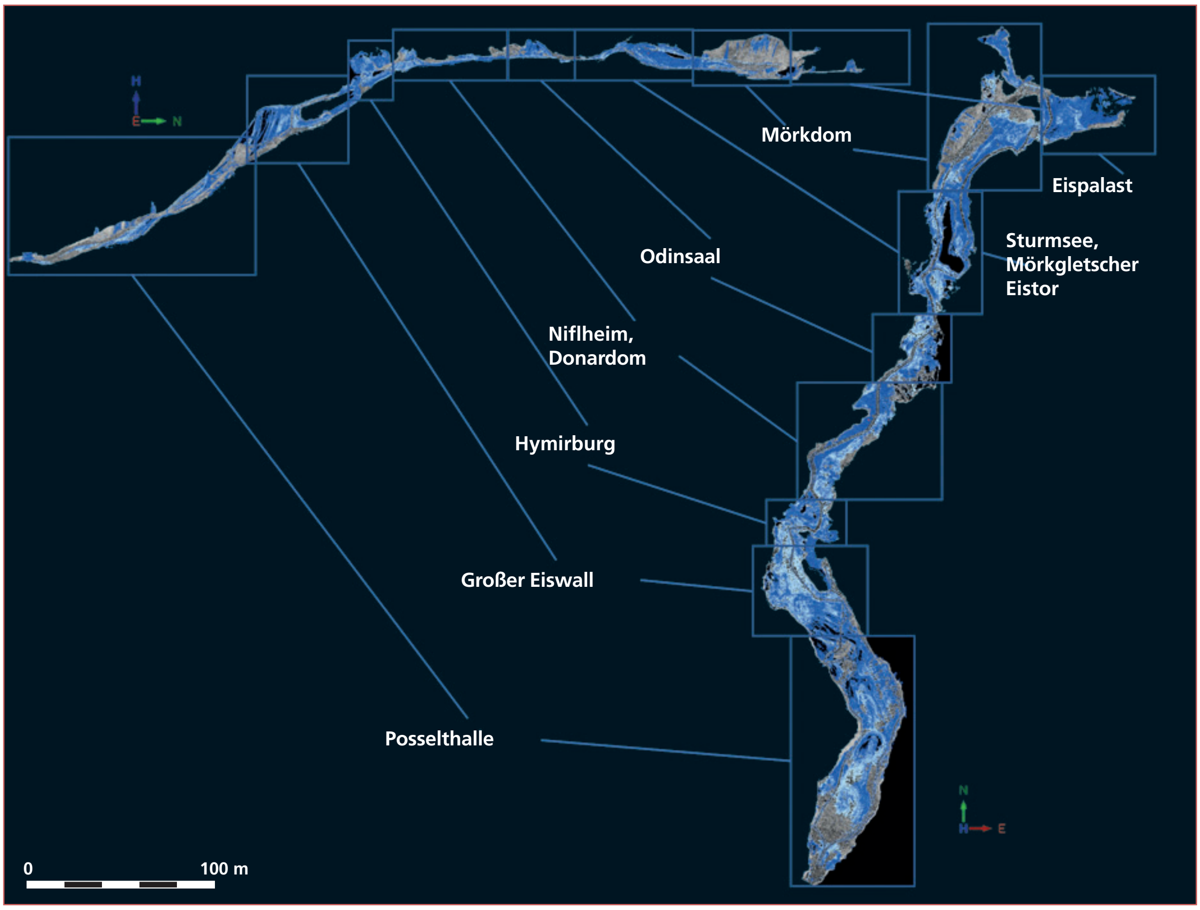

Fig. 2: Plan view and profile view of the registered scan data of the ice-bearing portion of the Eisriesenwelt colourised according to reflectance. The ice is coloured from white to blue, blue indicates the lowest reflectance values. Rock is displayed in grey.
Abb. 2: Plan- und Profilansicht der aufgenommenen Scan-Daten des eisführenden Teils der Eisriesenwelt ihren Reflexionswerten entsprechend eingefärbt. Eis wird in weißen bis blauen Farben gezeigt, wobei Blau die niedrigsten Reflexionswerte anzeigt. Fels ist grau.

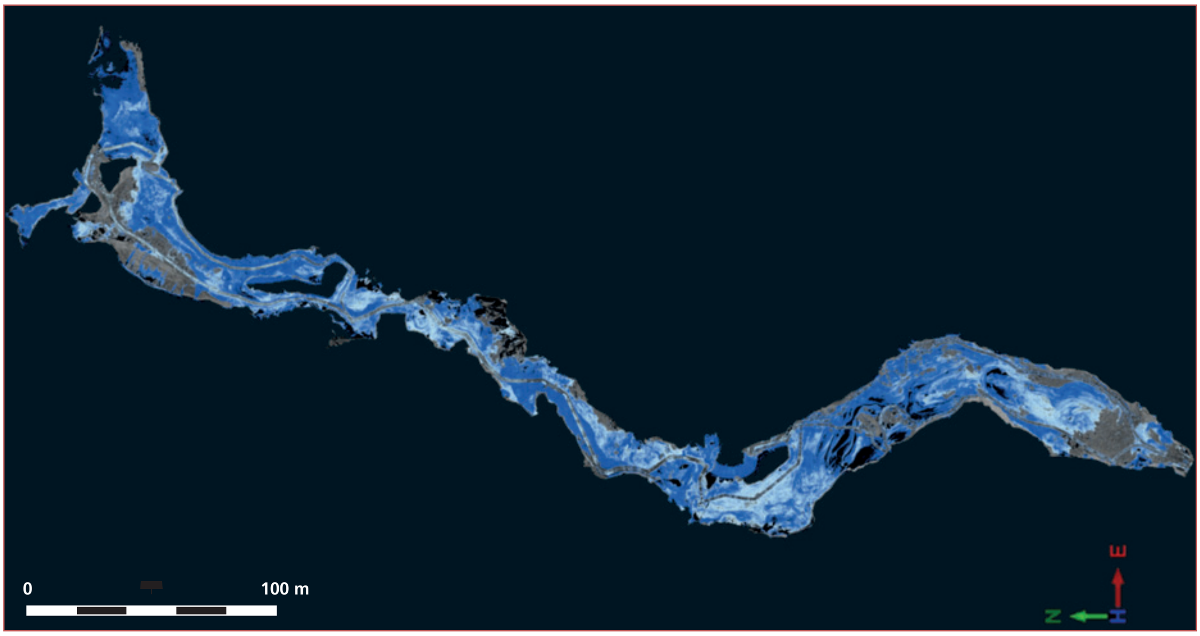

Fig. 3: Enlargement of the plan view of the show cave part of Eisriesenwelt from Fig. 2.
Abb. 3: Vergrößerung der Planansicht des Schauteils der Eisriesenwelt von Abb. 2.

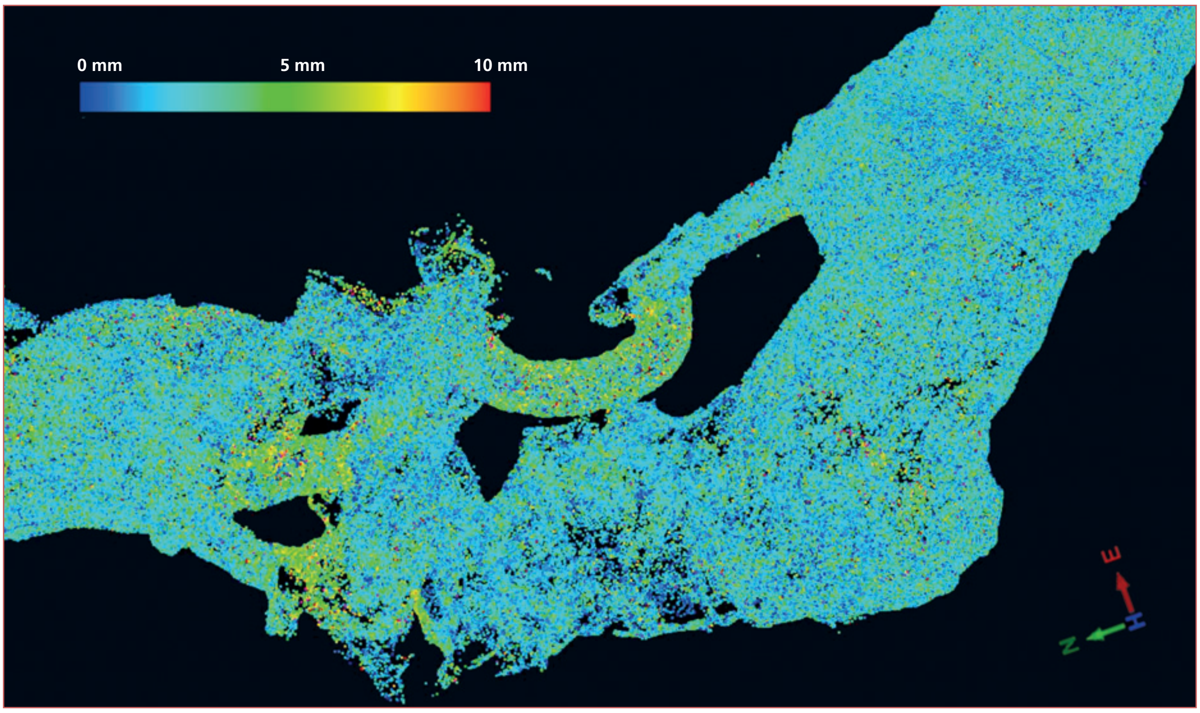

Fig. 4: Registration accuracy of LIDAR data in the region Hymirburg and Großer Eiswall (data from April 2017).
Abb. 4: Registrierungsgenauigkeit der LIDAR-Daten im Bereich Hymirburg und Großer Eiswall (Datenaufnahmen April 2017).

for a visual inspection of the three-dimensional dataset. Duringregistration plane patches were extracted from the scan data of each scan position. The software identifies common plane patches from different scan positions, links them together and minimises the errors between all these linked plane patches by using an iterative matching algorithm. Figure 5 shows a small excerpt of the statistical registration report. By analysing the full statistical report one can easily identify if a scan position is registered sufficiently against the adjacent ones. In the present study this was very well the case.

Once the registration was finished the whole point cloud of more than 5 billion points was resampled to an equalised point distance of 2 cm. This reduced the amount of data dramatically, while all details were still available (and hence visible). Due to the many scan positions and the massive overlap of all scan data from the different positions the resulting final point cloud with 2 cm-resolution showed practically no (close to zero) scan shadows or missing areas (except of very few percent of the total) and can be considered highly consistent (Fig. 6).

Finally, the datasets from the different campaigns were re-aligned against each other within official Austrian Geodetic Reporting System (BMN) with a high degree of accuracy. The purpose of the measurement campaign 2017 was to generate a new highly accurate three-dimensional dataset of Eisriesenwelt (compared to the previous ones, cf. Buchroithner, 2015). The focus on the following campaigns (2019, 2020) was to analyse changes of the ice bodies. *RIEGL's* postprocessing-software offers a powerful tool called “voxel comparison”. This tool allows a real three-dimensional surface comparison. In a first step we automatically extracted voxels of equal size from the reference dataset (2017). For this we used a voxel size of 25 cm. The scan data within each voxel were analysed and subsequently a principle component analysis delivered an estimated plane with a normal vector for every voxel.

The distinction between ice surface and rock surface is based on the intensity of the recorded reflectance signal and was automatically carried out by the software.

For the ice-covered area, which extends for a distance of about 500 m behind the entrance of the cave, an area of approximately 8.300 m² was calculated (whereby distance refers to a vertical nadir projection). Above this (basal) area there exists a total of approximately 161.000 voxels resulting in about 11.100 m² of total ice surface. Based on experience with other surface calculations based on LIDAR data using the same approach, we assume that the latter value represents the correct size of the actual ice surface in 2020. The significant difference of this ice-surface value compared to estimates obtained during previous

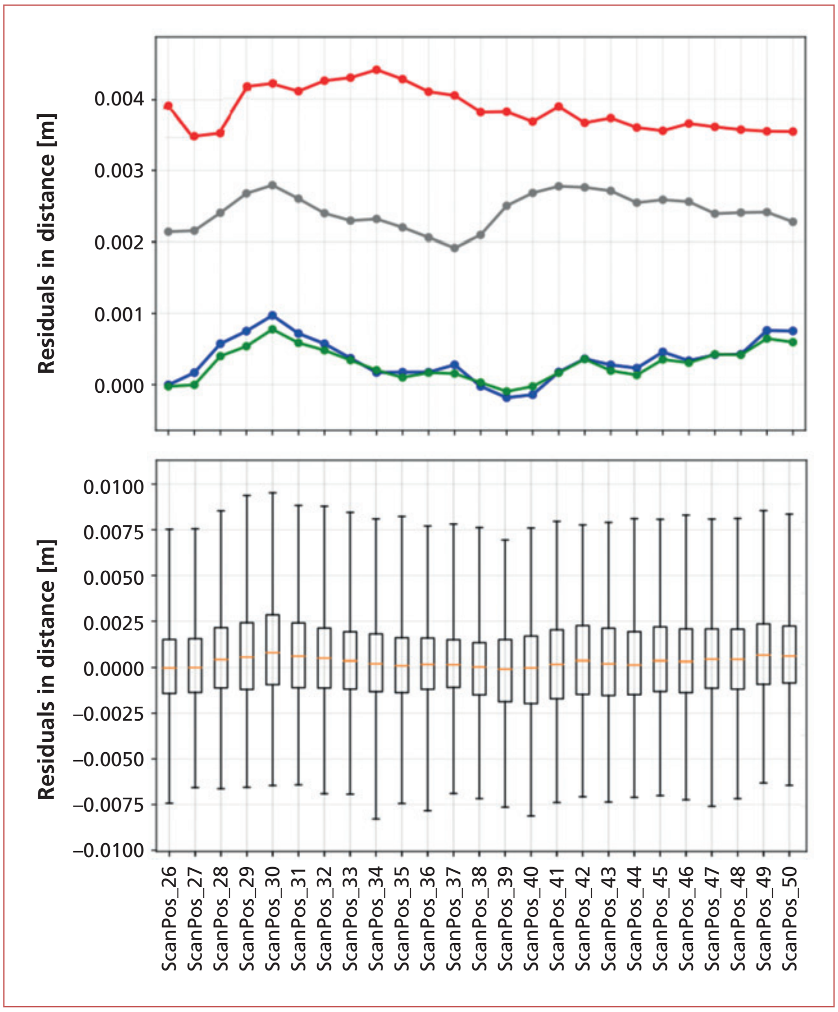

Fig. 5: A small excerpt of the statistical registration report. Upper diagram: Standard deviation and standard deviation MAD (mean absolute deviation; this type of the standard deviation is robust against outliers) of plane matches for each scan position. Lower diagram: Standard deviation of plane matches with 50% quantile (boxes) and 95% quantile (whiskers) for each scan position.
Abb. 5: Ein kleiner Auszug des statistischen Registrierungsberichts. Oberes Diagramm: Standardabweichung und Standardabweichung-MAD (mean absolute deviation; dieser Typ der Standardabweichung ist robust hinsichtlich Ausreißern) für die Oberflächen-„Passung" jeder Scan-Position. Unteres Diagramm: Standardabweichung der Oberflächen-„Passung" mit 50%-Quantilen („boxes") und 95%-Quantilen („whiskers") für jede Scan-Position.

mean
median
std.dev.
std (mad)

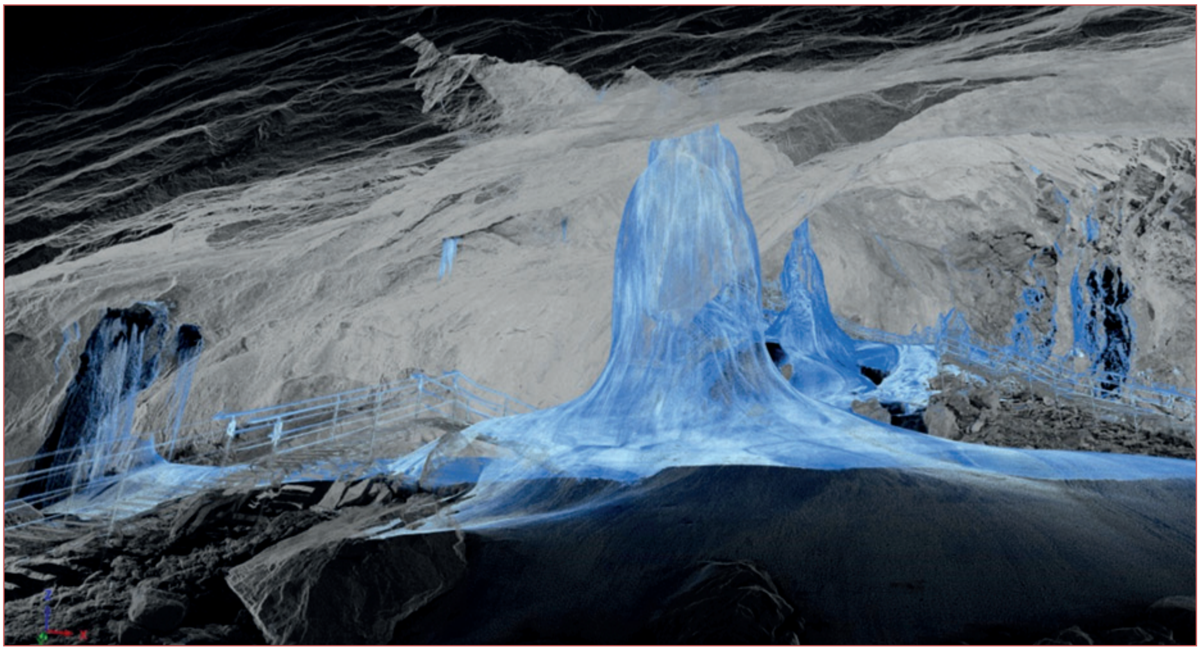

Fig. 6: Posselthalle with ice columns (resampled point cloud with 2 cm resolution; data taken in April 2017).
Abb. 6: Posselthalle mit Eissäulen (homogenisierte Punktwolke mit einer Auflösung von 2 cm; Datenaufnahme April 2017).

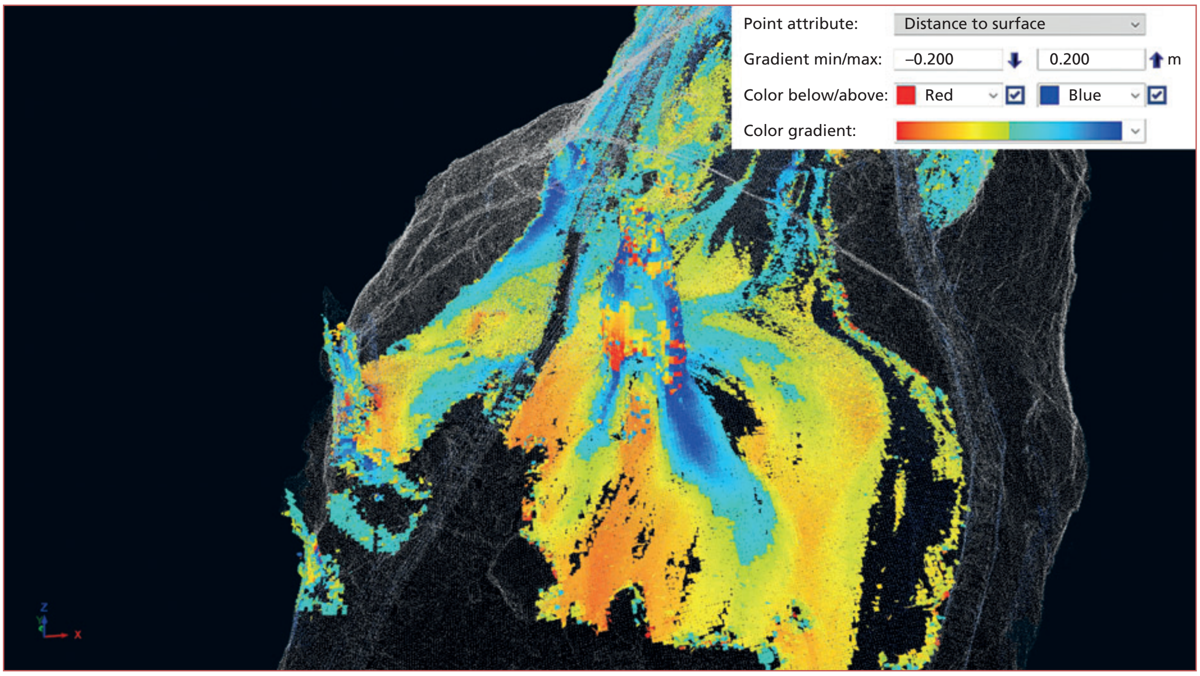

Fig. 7: Oblique view from above showing the increase and decrease of the ice surface between 2017 and 2019 in the central part of the Posselthalle with its prominent central ice column. Turquoise-blue: ice increase, yellow-red: ice decrease. Visitor walkway visible on the left side.
Abb. 7: Schrägansicht von oben, welche die Zu- und Abnahme der Eisdicke zwischen 2017 und 2019 im zentralen Teil der Posselthalle mit ihrer markanten Eissäule in deren Mitte zeigt. Türkis-Blau-Töne: Zunahme. Gelb-Rot-Töne: Abnahme. Links erkennt man den Besucherweg.

LIDAR surveys (e.g., Milius & Petters, 2012) can be explained by (i) the erroneously included surface of the *Eistunnel*, (ii) changes in the laser wavelength, and (iii) the considerable increase of the measurement range (now several hundred metres) of the new LIDAR instrument. The latter results in an improvement of the signal energy for the average scanned surface distance. This is due to the fact that in 2019 and 2020 we used a LIDAR instrument with a maximum range of 600 m for distances which only extended up to some tens of metres.
In a next step voxels of the same size were extracted from the comparison datasets (2019, 2020). Every voxel of these datasets finally got a new data attribute named "distance to surface" which shows the distance along the normal vector of the reference data set to the closest voxel of the reference data set. This attribute can be interpreted as increase or decrease of the ice thickness within every voxel. Figure 7 shows an area within *Posselthalle* colourised according to ice growth and ice decrease. This method allowed a real three-dimensional data comparison with just a few mouse clicks. Prior to our study, there were only a few points within the cave measured by ice stakes, showing the decrease respective increase of the ice cover at these individual points (Schöner et al., 2011).

CONCLUSIONS

The most recent LIDAR surveying campaign in the Eisriesenwelt end of April 2020 resulted in a total ice surface of roughly 10,100 m². Compared to 2017, an area of 2660 m² remained more or less constant, i.e. the average ice thickness changed by less than 3 cm. Approximately 3860 m² showed an ice decrease of up to 30 cm (locally even more), whereas for about 3500 m² an increase of the same amount was measured. The comparison of the overall mass balance of the Eisriesenwelt between the two survey campaigns (April 2017 and April 2020) yielded an ice increase of 59 m³ (Fig. 9). This has to be seen in relation to the total ice mass calculated by Kaidong (2018) based on ground-penetrating radar measurements taken in April 2017, i.e. approximately 63,300 m³.
The flat area of the cave between *Niflheim* and *Mörkdom* shows minor ice changes with smaller maximum decreases and increases (Fig. 8, 9). We assume that the reason is the flat topography with just a few small water inflows. The mass balance of this flat area

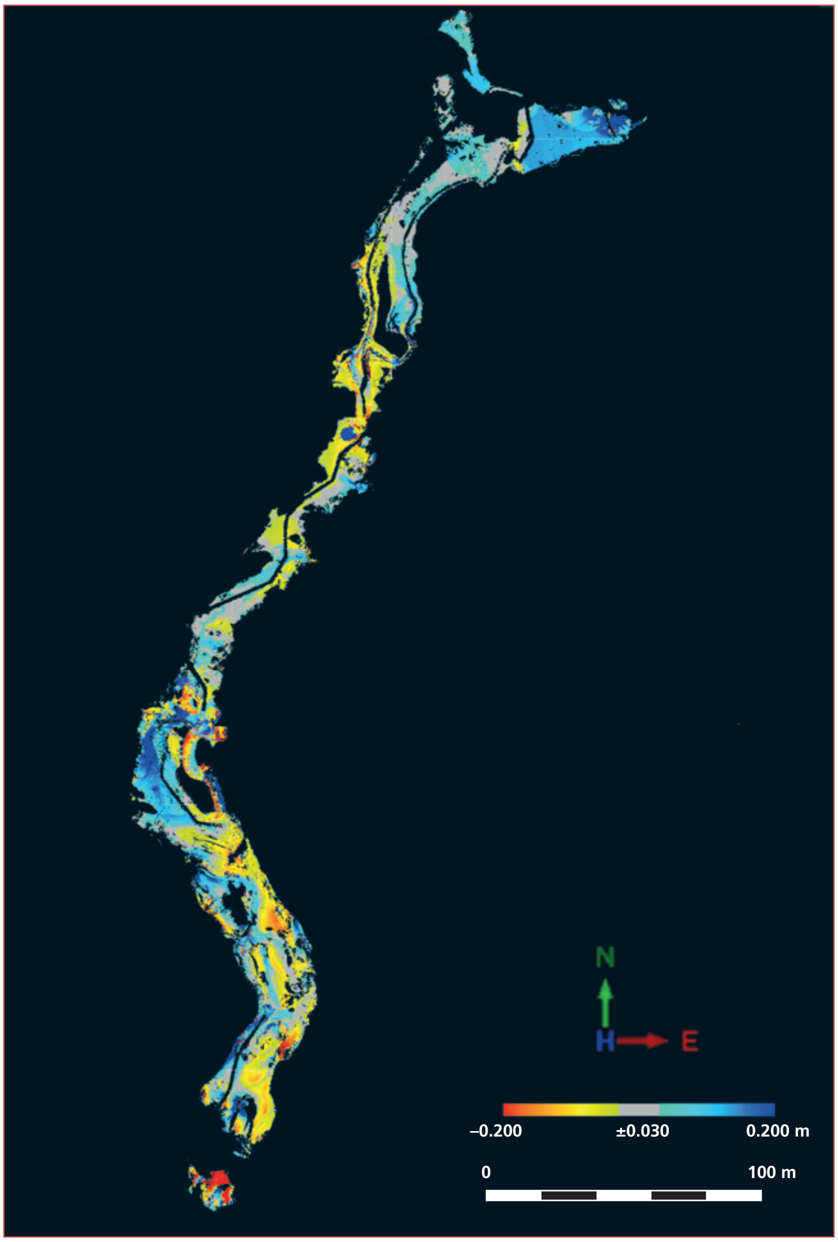

Fig. 8: The ice-bearing part of the Eisriesenwelt and comparison of the ice surface height between 2017 and 2020.
Abb. 8: Der eisbedeckte Teil der Eisriesenwelt mit dem Vergleich der Eisoberflächen zwischen 2017 und 2020.

yielded an ice decrease of 21 m³. The rearmost ice-filled part of the cave, *Eispalast*, is also a flat area, but interestingly it shows a strong ice growth of 88 m³ (Fig. 8, 9).

The first half of the show cave including *Posselthalle*, *Großer Eiswall* and *Hymirburg* shows a highly pronounced relief. From the entrance to *Hymirburg* the terrain is continuously ascending. At *Hymirburg*, just before the terrain turns flat, the maximum water inflow occurs and is responsible for almost the whole ice growth within this steep southern half of Eisriesenwelt. *Hymirburg* and the upper part of *Großer Eiswall* show a total of 64 m³ ice growth (Fig. 8). The ice increase in this area is a delayed gravity-driven reaction and is also responsible for the very local ice growth areas in the lowest part of the cave, the *Posselthalle*, which is close to the cave entrance. Overall, however, the *Posselthalle* is dominated by ice decrease. Only the already mentioned gravitational influence from ice growth in the more northern, higher areas (*Großer Eiswall* and *Hymirburg*) supports the overall mass balance in this lower part of the cave.

To sum up, the ice volume in Eisriesenwelt has increased slightly even in recent years of increased global warming. Future LIDAR surveys will show whether this is a multi-annual trend, providing important highly resolved data for a better understanding of the long-term ice mass balance in this cave.

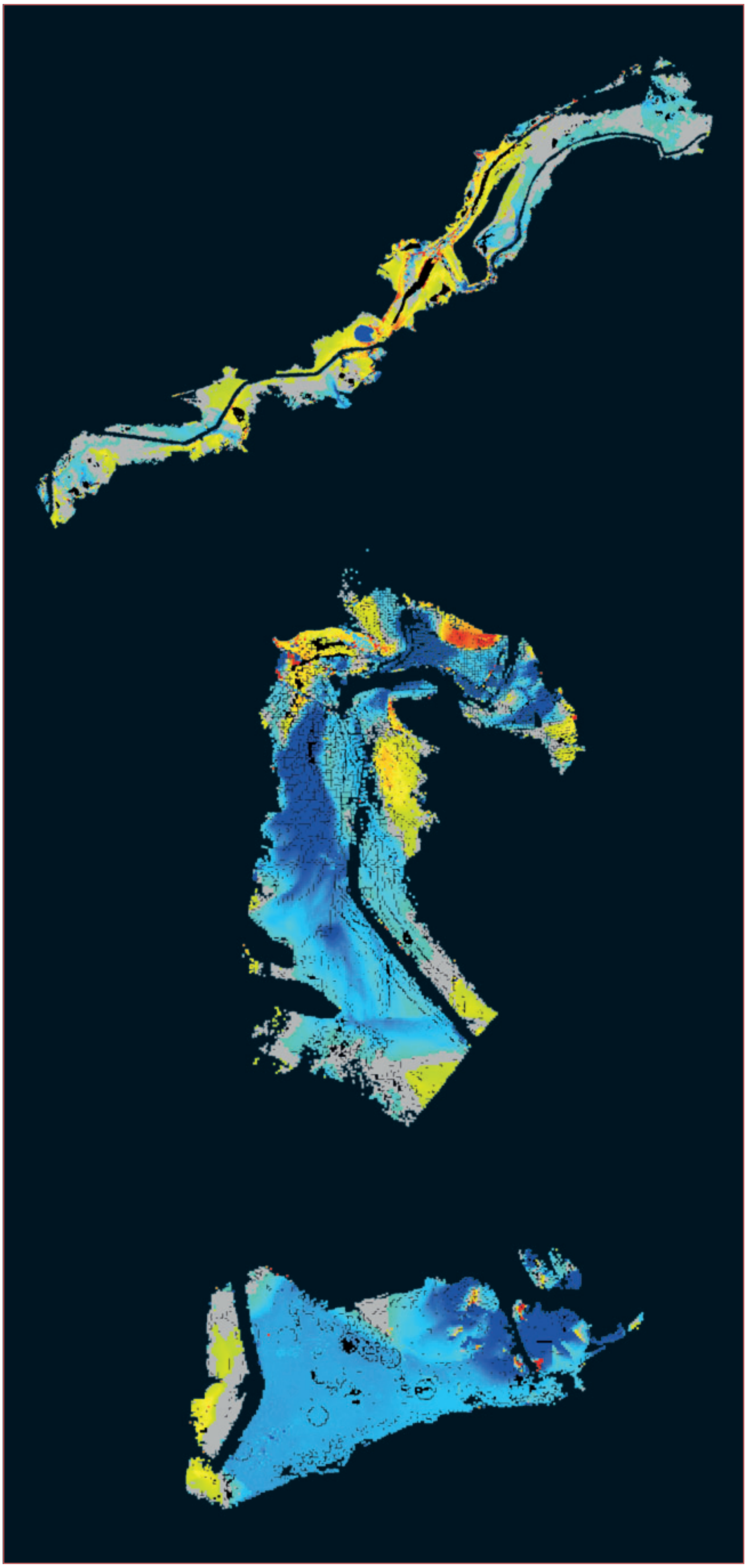

Fig. 9: Detailed visualisation at different scales. From top to bottom: Eispalast, area between Niflheim and Mörkdom, and Hymirburg and upper part of Großer Eiswall. For scale comparison and colour explanation see Fig. 8.
Abb. 9: Detaildarstellung in verschiedenen Maßstäben. Von oben nach unten: Eispalast, Gebiet zwischen Niflheim und Mörkdom, und Hymirburg und oberer Abschnitt des Großen Eiswalls. Maßstab und Farblegende wie in Abb. 8.

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ZUSÄTZLICHE ELEKTRONISCHE DATEN

Unter dem link **https://www.youtube.com/watch?v=yxVWNjO12Og** ist ein Video zum Laserscanprojekt in der Eisriesenwelt abrufbar.