Comments from referee #1 and responses of the authors concerning manuscript I.Beck_esurf-2015-7

We thank the reviewers for their criticism and suggestions, which have made us evaluate the scientific soundness of our attempt to define the vertical movements of frost mounds in sub-Arctic permafrost regions using geodetic survey and satellite interferometry'.

Our responses to reviewers' comments are shown in bold font.

Changes made within the manuscript are shown in italics.

Page numbers and lines refer to the *.pdf document I.Beck_esurf-2015-7_review

Please note, that we also proofread the manuscript again in terms of language. The changes made are also 'tracked' in the manuscript.

Comments to the authors from Reviewer 1

The authors study the vertical heave and subsidence of three lithalsas in Quebec during a period of two years using two geodetic techniques (dGPS, DInSAR). The spatial and temporal patterns of these movements are analysed, as is the suitability of the two observational techniques. The magnitude and temporal dynamics of the vertical movements were found to be related to the state of degradation and the surface cover. I find the presented work (observations & analyses) highly relevant and interesting. I thus think that the manuscript is certainly suitable for publication in EDS, provided several points are clarified.

1. Gist of the manuscript

The manuscript is generally very pleasant to read but it could benefit from a structural revision. In particular the introduction does not make sufficiently clear

- why this work is interesting/relevant
- how it relates to previous studies
- what the open questions, aims and hypotheses are; which ones the authors want to address

We agree with the reviewer that these points could indeed be clarified. We are grateful to the reviewer for these suggestions and have added the following paragraphs to provide further information:

[…] northern Quebec, Canada, using a differential system (d-GPS) and satellite-based differential SAR interferometry (D-InSAR) (page 3, line15)

[…]Little is known about the surface movements of frost mounds (lithalsas), in particular about their responses to the freezing and thawing that occurs during the course of an annual temperature cycle, or the relationship between these movements and the state of degradation of the frost mounds or their vegetation cover. We therefore surveyed three lithalsas in the Canadian sub-Arctic using d-GPS technology to obtain more detailed information. In order to investigate the use and effectiveness of new and innovative technologies we also used D-InSAR data which, to the author's best knowledge, has not previously been used to investigate this type of permafrost landform. We analyzed TerraSAR-X images acquired between April 2009 and October 2009 and between March and October 2010, with a repeat cycle of 11 days, from which we obtained valuable information concerning the possibility of using D-InSAR in this kind of environment. (page 4, line 22)

2. Description of dGPS measurements, processing methods and uncertainties

These descriptions are not clear and the reproducibility thus questionable. The impact on the results/interpretation should be discussed more transparently. If I understand the measurement and processing strategy correctly, the authors used kinematic stop-and-go differential GPS with one fixed base station (Berber et al.). As the coordinates of the location of the latter were not well known, they estimated them by PPP (Bisnath & Gao), and these estimates were then used in the dGPS processing. However, no detailed technical description is given and neither are references to the scientific literature.

Was the position of the base station always the same (if so, how was that point marked)?

To clarify these queries the following sentence has been added:

[…]The base station was mounted, always mounded at the same location, about 500 m from the lithalsas, at a marked trigonometric point on [..] (page 7, line 24)

Which initialization was used to fix the ambiguities?

What is the uncertainty (Hofmann-Wellenhof et al.) of the observed elevations at the lithalsas i) in absolute terms, ii) relative to the base station, iii) relative to each other?

Which numbers are reported by the software?

We are grateful to the reviewer for raising these valid points. The following information and citations have been added to the text:

[…]For this the "kinematic stop-and-go d-GPS method" (Berber et al., 2002) was used. Hofmann-Wellenhof et al. suggested that the best accuracy was achieved with this method if the phase ambiguities were resolved before starting the survey. This we achieved through the use of a static initialization process provided by Magellan in their initialization equipment. The numbers recorded by the d-GPS were stored in RINEX (Receiver Independent Exchange) format. The data were analysed using the GNSS Solution v3.10.07 post-processing software (Magellan), with the data being imported into the software and then processed by adjusting vectors in relation to a fixed control point received from the base station. […] (page 7, line 11)

[…]The Precise Point Position (PPP) is then calculated based on the Canadian Spatial Reference System (CSRS) (Bisnath and Gao, 2009). The coordinates finally defined by the CSRS for the base station were 56.55° N and 76.54° E. These coordinates then served as a control point for the processing described above. Both horizontal and vertical uncertainties were calculated during post-processing. The horizontal error was found to be between 0.001 cm (Lithalsa M) and 0.098 cm (Lithalsa R), and the vertical error between 0.001 cm (Lithalsa M) and 0.123 cm (Lithalsa I).(page 7, line 35).

How do errors in the coordinates of the base station affect these three uncertainties?

The errors are in the coordinates of the base station reduced the vertical accuracy to within a few centimeters as mentioned in the last part of this section.

3. DInSAR analyses

Also here several aspects of the processing and the observations could be made clearer:

Was the phase unwrapping successful? If so, were there obvious errors? Fig. 6 only shows the wrapped phase. How were the coherences and phases estimated (window size, number of looks; spectral filtering)? A figure displaying these coherences would be useful.

The window size (and also the height of ambiguity, not given in Tab. 1, only the baseline) might be important for interpreting the coherences: It is claimed (p 265, lines 9-16) that the size of the movement compared to the wavelength leads to decorrelation, whereas I would expect the variation of movements within the window to be the determining factor [cf. glaciology: ice movements can be hundreds of metres but strain*window size is smaller than the wavelength, potentially keeping the coherence high].

Similarly, I do not quite follow the inference that the vegetation (owing to its sparseness) does not play a major role here. Relevant non-dimensional quantities are (Zebker & Villasenor): the height compared to the height of ambiguity; the size of the movements (of leaves, say) compared to the wavelength. Changes in the dielectric properties (soil and vegetation moisture) might also influence both the coherence and the phase:

Barrett, B., Whelan, P., and Dwyer, E. (2012) 'The use of C- and L-band repeat-pass interferometric SAR coherence for soil moisture change detection in vegetated areas'. The Open Remote Sensing Journal, 5 (1):37-53

Zebker, H.A., and J. Villasenor, Decorrelation in interferometric radar echoes, IEEE´Trans. Geo. Rem. Sensing, Vol 30, no. 5, pp 950-959, September, 1992.

S. Zwieback, S. Hensley, I. Hajnsek. Assessment of soil moisture effects on L-band radar interferometry. Remote Sens. Environ., 164, 77-89, 2015.

We appreciate this criticism and the reviewer's suggestions. Additional aspects of the processing of the TerraSAR-X interferograms are now included in Section 3.2.

[…]TerraSAR-X interferograms were computed using a 1-look in "range" and 1-look in "azimuth", in order to achieve the best possible resolution over the lithalsas. A very high resolution DEM was used for the differential interferometry, in a two-pass approach (Bamler and Hartl, 1998). The DEM was produced by the Direction de la cartographie topographique du ministère des ressources et de la faune à Québec (MRNF) from stereoscopic analysis of aerial photographs, and has a spatial resolution of 1 m. GAMMA Software (GAMMA Remote Sensing AG, 2008) was used for the processing and an area of 6000 x 2000 pixels defined for the calculation of the differential interferograms. In order to support phase unwrapping and as a measure of the quality of the interferograms, coherence was estimated using an adaptable window from the 1-look differential SAR interferograms (Wegmüller and Werner, 1996). The coherence was first estimated using a fixed, relatively small window size of 15 pixels. The window size was then determined from the irst estimate, applying successively larger windows up to 45 pixels in order to estimate lower coherence. This procedure enabled us to obtain reliable coherence values without compromising too much on the spatial resolution. […] (page 8, line 32).

Section 4.2. has been changed as following. Some of the reviewer's suggested publications have also been included as citations.

Results

Out of the 11 TerraSAR-X acquisitions in 2009 and 2010, only six interferograms showed a reasonable coherence with coherence values greater than about 0.25 computed over the whole area of interest (i.e. 0.23 for the 7 May/14 August 2009 image pair, 0.40 for the 14 August/30 August 2009 pair, 0.29 for the 14 August/30 October 2009 pair, 0.27 for the 5 May/12 August 2010 air, 0.53 for the 12 August/28 August 2010 pair, and 0.28 for the 12 August/28 October 2010 pair). All other interferograms were much less correlated. Areas covered by water bodies, vegetated areas, and pixels located within shadows are particularly affected by decorrelation with coherence values below 0.3, while built-up areas are by far the most coherent class, with coherence values greater than 0.9. However, although the average coherence value from the six interferograms is high enough for generalised further analysis (Carballo and Fieguth, 2002; Hanssen, 2001), the coherence values over the three lithalsas (Table 4) is too low to be considered adequate for further analysis. In this case, if phase unwrapping is performed without using a coherence threshold it will yield phase values approaching zero, which would be typical of noisy regions. However, these values show no correlation with the large displacements measured using d-GPS technology and have therefore not been subjected to any further analysis.

Discussion

Decorrelation in the TerraSAR-X differential interferograms over the lithalsas (Fig. 7a) is not surprising considering the large, rapid, vertical movements (several decimeters in less than half a year) *measured using d-GPS technology (Zebker & Villasenor). There are also large variations in movement within each of the lithalsas. Amplitudes of several decimeters in lithalsa movements were recorded over less than half a year, with variations of several centimeters between individual measurement points within each of the lithalsas (which are only about 40 m in diameter); these amplitudes far exceed the the range that can be quantified with TerraSAR-X data, where a phase cycle corresponds to 1.6 cm and the time interval between acquisitions is, at best, 11 days. Decorrelation due to large displacements resulting from freeze-up processes has also been identified by Short et al. (2011), when they tried to co-register TerraSAR-X and RADARSAT-2 data from Herschel Island, acquire in May, October and November. The possibility of temporal decorrelation associated with the land cover type can be discounted because the lithalsas have only very sparse vegetation cover, or none at all, as is also the case in surrounding areas that are characterized by much higher coherence values (Fig. 7b). Changes in the dielectric properties (soil and vegetation moisture) can also influence both the coherence and the phase (Barrett et al., 2012). However, investigations in Canadian permafrost regions (Pangnirtung and Iqaluit) by Short et al. (2014) examined the influence of soil moisture and found that it was unlikely to be a significant source of error Nevertheless the six differential interferograms reveal two interesting large scale signals. Firstly, to the north of Umiujaq (56°33.6' N, -76°32.94'E) fringes increase with time and may be an indication of localized slow movements in a rocky area with only sparse vegetation (such as lichens and mosses). A corner reflector was fixed on solid rock in this area by INRS for a RADARSAT-2 study, oriented for a descending orbit. The signal in the TerraSAR-X interferograms could be related to localized movement of the corner reflector, to the displacement of terrain relative to the corner reflector, or to thermal dilation associated with the structure on which the corner reflector is located. It is not possible to make any further interpretations concerning the cause of the detected movement without additional local information. Secondly, to the west of the lithalsas (around 56°33.18'N, -76.30.96'E), widespread slow movements can be identified over the 11 day period from 14 to 23 August 2009. This area is part of the Cuestas (solid rock) but land cover classifications based on an IKONOS image (2005) and a GeoEye image (2009) show vegetated patches with prostrate shrubs (May, 2011), interspersed with temporary pools of water. Following the signals from the differential interferogram are therefore very likely to be associated with temporary ponding. This interpretation is supported by the precipitation records: 63% of the total precipitation for August (total: 64.4 mm) fell between the two acquisition dates (i.e. between 14.08.2009 and 30.08.2009), whereas it was very dry (only 5.8 mm precipitation) over the seven days prior to the first acquisition. (page 13, line 22 – page 15, line 22).*

Minor points:
p 253 l15-16: The morphology of lithalsas and palsas are ...
[…]Lithalsas and palsas normally form low circular or oval features that are about 5 m high, 10-30 m wide, and up to 150 m long. […] (page 2, line 28).

p 254 l9, l10 and several additional points in the manuscript: use of dGPS with definite or indefinite articles seems a bit odd
d-GPS has been changed into d-GPS technology and the definite and indefinite article has been deleted.

p 257 l1: The first sentence refers to phase observations, the second one to ones using only the codes. Please clarify
Unfortunately this comment is not clear to us.

p 259, l12: (see details below) where?
We appreciate this comment. Actually it should say 'see details above', as the installation and correction of the base station data was explained earlier in this section. This sentence has therefore been deleted **Following this sentence has been deleted.**

p 267, l4: though: usually put at the end of a phrase

[…] However these movements could not be detected with D-InSAR due to decorrelation […](page 15, line 32).