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Vertical movements of frost mounds in sub-Arctic permafrost regions analyzed using geodetic survey and satellite interferometry

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Abstract

Permafrost-affected soils cover about 45 % of Canada. The environment in such areas, especially those located within the discontinuous permafrost zone, has been impacted more than any other by recorded climatic changes. A number of changes, such as surface subsidence and the degradation of frost mounds due to permafrost thawing have already been observed at many locations.

We surveyed three frost mounds (lithalsas) close to Umiujaq, northern Quebec, sub-Arctic, using a high-precision differential Global Positioning System (d-GPS) during field visits in 2009, 2010 and 2011, thus obtaining detailed information on their responses to the freezing and thawing that occurs during the course of the annual tem-

- ¹⁰ sponses to the neezing and thawing that occurs during the course of the annual temperature cycle. Seasonal pulsations were detected in the frost mounds and these responses were shown to vary with the state of degradation and the land cover. The most degraded lithalsa showed a maximum amplitude of vertical movement (either up or down) between winter and summer (thawing) of 0.19 ± 0.09 m over the study period,
- while for the least degraded lithalsa this figure was far greater $(1.24 \pm 0.47 \text{ m})$. Records from patches with little or no vegetation showed far less average vertical movement over the study period $(0.17 \pm 0.03 \text{ m})$ than those with prostrate shrubs $(0.56 \pm 0.02 \text{ m})$, suggesting an influence from the land-cover.

A differential Interferometric Synthetic Aperature Radar (D-InSAR) analysis was also completed over the lithalsas using selected TerraSAR-X images acquired from April to October 2009 and from March to October 2010, with a repeat cycle of 11 days. Interferograms with baselines shorter than 200 m were computed revealing a generally very low interferometric coherence, restricting the quantification of vertical movements of the lithalsas. Vertical surface movements in the centimeter range were recorded in the near vicinity of Umiujag.

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1 Introduction

Permafrost underlies 45% of Canada and has a significant effect on the global climate. Climate modelling suggests that increasing air temperatures are to be expected over the next 40 years, with a large increase expected in this area of up to 10° C dur-

- ⁵ ing the winter months (Allard et al., 2007). Such elevated air temperatures will affect the soil temperature, which has been modelled to increase by about 4°C (2041–2070) (Sushama et al., 2006). Such warming would increase thawing during the summer months leading to an increase in marshlands or wetlands and encouraging the formation of new lakes (Rowland et al., 2010; Smith et al., 2004).
- ¹⁰ Characteristic landforms of the discontinuous permafrost zone, such as palsas and lithalsas (Fig. 1a), are also likely to suffer as a result of increasing soil temperatures. Lithalsas are permafrost mounds; they are typical of northern Quebec and Lapland and are formed by ice segregation in a similar manner to palsas. In contrast to palsas, however, lithalsas have no insulating cover of peat (Calmels, 2008; Zoltai and Tarnocai,
- ¹⁵ 1975; Zuidhoff, 2002; Zuidhoff and Kolstrup, 2005), which makes them more sensitive to changes in temperature (Pissart, 2000; Seppälä, 1988). The morphology of lithalsas and palsas are normally low circular or oval features, around 5 m in height, 10–30 m in width and up to 150 m in length. The ice lenses of their permafrost cores are usually not thicker than 3 cm, but lenses up to 40 cm have been described (Gurney, 2001; Pissart,
- 20 2002). Their anticipated degradation with continued warming is likely to have severe direct and indirect consequences for the ecosystem, the hydrological regime, and the vegetation, and to ultimately also affect the human population (Nelson et al., 2003).

Changes in the land surface within the area covered by this study (around Umiujaq in northern Quebec) have been attributed to permafrost thawing. A number of studies

²⁵ (e.g. Laberge and Payette, 1995; Fortier and Aubé-Maurice, 2008) have shown that longer and warmer summer periods lead to degradation of these mounds (and even their disappearance) accompanied by a subsidence of the surrounding terrain.



Increasing temperature and pressure gradients in winter encourage the formation of segregation ice and cause frost heave. During the thawing period the opposite occurs and lithalsas subside (Skaven-Haug, 1959). Long-term climatic variations are expected to elicit responses to changing air temperatures that are comparable to these annual

⁵ changes. Calmels et al. (2008), for example, surveyed a lithalsa close to our own study area and recorded thaw settlement of 1 m over 5 year period.

In this study we have investigated the seasonal dynamics of lithalsas on the eastern shore of Hudson Bay, in the Nunavik region of northern Quebec, Canada, using a differential system (d-GPS).

- ¹⁰ The d-GPS has been successfully used for a wide range of scientific applications, although its use for geocryological purposes only really started in the mid 1990's. For example Theakstone et al. (1999) generated maps and a DEM for a glacier in central Norway, stating a vertical accuracy of 0.1 m, Kaufmann (1998) evaluated the stability of reference points on a rock glacier in the Austrian Alps, Tait and Moormann (2003)
- found a d-GPS to be the best approach for monitoring topographic movements in continuous permafrost regions, and Sheng et al. (2004) and Tait et al. (2005) used a d-GPS to survey frost mounds within the continuous permafrost zone. A number of research teams have also successfully used a d-GPS to monitor frost heave and thaw subsidence. For example, Little (2006), Little et al. (2003) and Nelson et al. (2001) collected
- d-GPS measurements in flat areas of northern Alaska, where they recorded heave and subsidence movements of up to 0.06 m. Shiklomanov et al. (2013) used a d-GPS to quantify isotropic thaw subsidence in permafrost areas of northern Alaska, and Wirz et al. (2015) derived the temporal variability of mountain permafrost slopes using d-GPS measurements.
- In addition to field measurements, remotely-sensed radar data has also been used to detect vertical movements in permafrost regions from space, by means of differential interferometry. Differential Interferometry Synthetic Aperture Radar (D-InSAR) uses the phase content of a complex radar signal to detect land surface deformations by transforming the phase difference between two acquisitions into a displacement figure (e.g.



Bamler and Hartl, 1998). Changes of the order of centimetres, or even millimetres, can be observed depending on the sensor's wavelength. Such an analysis requires at least two scenes of the area of interest, recorded by the same sensor but at different times, and an appropriate digital elevation model (DEM). D-InSAR has mainly been used to

- ⁵ detect large-scale deformations caused by earthquakes (e.g. Yen et al., 2008) or by seismic and volcanic activities (e.g. Ge et al., 2008; Amelung et al., 2000), but it has also been used to monitor glacier velocity (e.g. Goldstein et al., 1993). The first extensive studies of permafrost thawing and freezing in the Arctic (North Slope of Alaska) using D-InSAR were based on data from the ERS SAR sensor (C-band, 5.7 cm wave-
- length) (Liu et al., 2010, 2011). Data has also been available at a higher spatial res-10 olution since 2006 from COSMO-SkyMed (ASI, 2007), based on shorter wavelengths (X-band 3.6 cm) and since 2007 from the TerraSAR-X satellite (DLR, 2010). A number of studies have since been initiated using TerraSAR-X data to investigate vertical movements caused by permafrost thawing within the Arctic region (Larsen et al., 2009,
- 2011; Lauknes et al., 2010a, b; Short et al., 2011, 2014; Strozzi et al., 2012).

Study area description 2

The study area covers about 60 km² and is located near the Inuit village of Umiujag (56°33' N, 76°33' W), close to the eastern shoreline of Hudson Bay in Nunavik, northern Quebec, Canada (Fig. 2).

- The study area is located in the transition zone between the sub-Arctic and the Arctic, 20 where a high sensitivity to climatic changes is expected making it an ideal region in which to conduct a climate change impact study. The permafrost is mainly scattered (Fig. 2) and the study area covers the northern timber line; the mean annual ground temperature (MAGT) at a depth of 10 m is about -2.5 °C (Smith et al., 2010).
- There are currently only 60 to 80 frost-free days per year in the study area (Envi-25 ronment Canada, 2004) and the annual average air temperature is about -5.5°C but, due to the proximity of Hudson Bay, the region is characterized by high temperature

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variability throughout the year. From June until mid-December the climate has a maritime character with little diurnal variation in temperature and moderate temperatures of about 8 °C. In contrast, when Hudson Bay freezes over during the winter temperatures can reach to below -30 °C due to continentality. In addition, the annual average wind speeds in this area are between 20 and 24 km h⁻¹ (Gagnon and Ferland, 1967), resulting in wind-chill temperatures down to -60 °C (Environment Canada, 2004). The average annual precipitation is approximately 500 mm (Phillips, 1984), of which 37 % falls as snow (Environment Canada, 2004).

The study area can be divided into a coastal region with gently sloping topography and the Lac-Guillaume-Delisle graben (Fig. 2). The two landscape units are separated by ridges of outcropping bedrock (consisting of volcanic sediments) known as "Cuestas" (Kranck, 1951). The entire study area is experiencing a heterogeneous postglacial rebound that averages about 1.0 cm year⁻¹ (Lajeunesse and Allard, 2003; Tait and Moorman, 2003).

Temperatures in the region around Umiujaq are expected to increase by up to 10°C over the next 40 years, with the rate of increase expected to be highest during the winter months (Allard et al., 2007). Such an increase in air temperature would have an impact on the soil temperature, which would in turn be expected to increase by approximately 4°C (until 2070). These modelling results obtained by Sushama et al. (2006) suggest
 a significant future deepening of the active layer, which would be likely to result in

thaw-related settlement (Calmels, 2008).

3 Data and methods

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The data used for this study consisted of information collected during field visits in 2009, 2010 and 2011, together with remotely sensed data acquired by the German TerraSAR-X satellite. The in situ measurements provided detailed information on the seasonal variations in lithalsas at specific locations and were also used to validate the results obtained from analysis of the remote sensing data. Table 1 shows the acqui-



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sition dates for the d-GPS and TerraSAR-X data, as well as details the dates of the useable differential interferograms.

3.1 Field data

The three lithalsas investigated (identified as I, R, and M) are located to the south-east of the community of Umiujaq (Fig. 3)

They are each about 40 m in diameter and between 5 and 10 m high. They comprise a mixture of patches of bare ground and areas covered by lichens or prostrate shrubs, with their slopes being covered in small shrubs. A detailed soil map (1 : 10 000 scale) by Doyon et al. (2010) identifies the three features as ice-rich frost mounds ("Buttes cryogènes riche en glace"). Lithalsas I and R lie within a zone of aeolian sediments dominated by sand, sandy silt, sandy gravel and gravel ("Sable, silt sableux, sable graveleux et gravier"). Lithalsa M is further to the south-east in an area of marine and littoral sediments consisting mainly of sand but including beds of heavy minerals and shell fragments ("Sable moyen à grossier avec présence de lits de minéraux lourds et de fragments de coquillages"). Adjacent to the southern slope of this lithalsa lies a poorly drained wetland area (Doyon et al., 2010).

The three lithalsas all exhibit clearly different states of degradation. A 220 m² pond on the eastern side of Lithalsa R provides evidence that this lithalsa is in the process of breaking up, with additional evidence coming from the presence of numerous cracks and small-scale solifluction features (Fig. 1b). A pond has also formed on the east-

- and small-scale solitluction features (Fig. 1b). A pond has also formed on the east-facing slope of Lithalsa M, but its dimensions are smaller (Fig. 3) and there are far fewer cracks than at Lithalsa R. Degradation at Lithalsa M is therefore interpreted to be less advanced than at Lithalsa R. There is in contrast no evidence of degradation at Lithalsa I, which has no pond and no visible cracks.
- Seven field visits were made between August 2009 and April 2011, covering the full range of seasons. The three lithalsas were surveyed using a Pro-Mark 3 GPS from Magellan with a NAP100-L1 antenna. The d-GPS technology allows accurate measurement of vertical movements (at centimeter or even



sub-centimeter scales) within a worldwide geodetic coordinate system. This is achieved using normal code-based GPS technology, which acquires coordinate positions through triangulation by defining the interspace between at least four satellites and receiver (http://www.unavco.org/projects/project-support/polar/base_
stations_and_survey_systems/base_stations_and_survey_systems.html). This kind of GPS only has an accuracy of a few meters, but this is improved by using a differential system (d-GPS) equipped with at least two receivers. One of the two receivers serves as the base station: it has a known (fixed) position from which it tracks the satellites. The other receiver (the rover receiver) is placed at a particular point for only a limited

- period of time (usually between 15 and 60 s; http://www.trimble.com/gps_tutorial/). By comparing the signals from the two receivers at the same point in time, systematic errors, such as those due to atmospheric signal delays or the variations in the precision of the orbits, can be substantially reduced.
- The records were analysed using GNSS Solution v3.10.07 post-processing software, also from Magellan. Coordinates and elevations for the 39 measurement points (R1–R12, M1–M14, and I1–I13) over the three lithalsas were determined in August 2009, March 2010, May 2010, August 2010, and April 2011. The base station was mounted about 500 m from the lithalsas, close to a trigonometric point on stable bedrock where changes in elevation caused by frost heave or thawing subsidence
- could be excluded. Unfortunately however, the trigonometric point could not be identified and due to the remoteness of the study area no permanent reference station was available. Since this introduced the possibility of errors in the recorded position of the base station, the measured coordinates needed to be manually corrected for each record date before running the post-processing software. This correction was un-
- dertaken using the online service provided by the NRCan's Geodetic Survey Division (www.geod.nrcan.gc.ca/index_e.php) in which the recorded coordinates are submitted to the system, together with information concerning the processing mode and the reference system. The Precise Point Position (PPP) is then calculated based on the Canadian Spatial Reference System (CSRS). The coordinates finally defined by the CSRS



for the base station were 56.55° N and 76.54° E. The points on the three lithalsas at which measurements were to be recorded by the mobile receiver were first selected in August 2009. It was important to ensure that they were located within snow-free areas and in either non-vegetated patches or sparsely vegetated patches (with lichens and/or prostrate shrubs). The selected points were marked with a metal-pin about 20 cm long,

hammered into the ground and wrapped with pink tape.

The Magellan user's guide states that a vertical accuracy of "up to" 1.5 cm is attainable when using a recording time of at least 15 s, and that this may be improved by using longer recording times. For this study a recording time of 60 s at each point was chosen and since there were no obstacles interrupting the signal this should ideally have resulted in an accuracy of several millimetres. However, because of the need to compute a correction for the coordinates of the base station (see details below), the vertical accuracy was reduced to within a few centimetres.

3.2 Remote sensing data

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- In addition to the ground measurements, contemporaneous records from the TerraSAR-X satellite were also examined. Launched in June 2007, this satellite acquires high-quality X-band radar images with a spatial resolution of down to 1 m whilst circling the earth in a polar orbit at an altitude of 514 km. The frequency that the X-band sensor operates at is 9.65 GHz, which corresponds to a wavelength of about 3 cm (DLR, 2010). Its repetition time is 11 days. There are several acquisition modes
- available and we based our choice of the most suitable mode on coherence images computed from more than 30 images acquired in 2009 on different passes, at different polarizations, and with different angles of incidence. We considered only images acquired in the StripMap mode, scanning the surface with a footprint of 30 km × 50 km and
- ²⁵ a spatial resolution of about 3 m (Table 2), in order to compromise the best spatial resolution and the best coverage. Our investigations indicated that data from an ascending pass, in VV polarization and with an incidence angle of 40° was the most suitable for the study (Spannraft, 2010; May 2011). Interferograms computed from winter acquisi-



tions could not be considered, because snow influenced the radar signal resulting in too few coherences to process.

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 car-

- tographie 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 2000 × 5000 pixels defined for the calculation of the differential Interferograms. The differential interferograms, which in their initial stage only contained information on the phone difference were upwrapped using the minimum cost flow all stage.
- ¹⁰ information on the phase difference, were unwrapped using the minimum cost flow algorithm in order to retrieve vertical displacement (Constantini and Rosen, 1999). The high resolution DEM was used for georeferencing.

4 Results and discussion

4.1 Field measurements – differential GPS (d-GPS)

The field measurements showed a similar pattern at most of the measurement points, with 88.9 % of these points recording uplift during freezing periods (after August 2009–March 2010: average uplift 0.44 m; August 2010–April 2011: average uplift 0.11 m) and subsidence during thawing (March–August 2010: average subsidence 0.46 m). The vertical movements at those measurement points that did not conform to this pattern
 were small (average: 0.1 m) compared to the average vertical movement of all points

of 0.4 m between August 2009 and April 2011.

Figure 4 shows the heights of the lithalsa surfaces (both an average height for all three lithalsas and separate heights for each lithalsa, averaged from all the relevant measurement points) over the 20 month period relative to the height of the base station, measured on 6 different dates (14 August 2009, 25 March 2010, 8 May 2010,

tion, measured on 6 different dates (14 August 2009, 25 March 2010, 8 May 2010, 12 August 2010, 27 October 2010, and 9 April 2011) and interpolated over the en-



tire 20 month period. It should be pointed out that for October 2010 observations were only available from Lithalsa I due to the weather conditions that did not allow further measurements.

The average heights (black bars) increase by 0.44 m between August 2009 and ⁵ March 2010, followed by a rapid decrease between March and May 2010 of 0.32 m, with a further decrease of 0.14 m to August 2010, followed in turn by a slight increase of 0.10 m to April 2011. The difference between the highest average elevation (March 2010) and the lowest average elevation (August 2010) was 0.47 m. Between March and May 2010 an average subsidence across all lithalsas of 0.35 m ¹⁰ was recorded, which represents 70.6% of the total subsidence over the entire year 2010. The subsequent average subsidence across all lithalsas between May and August 2010 was far less (0.12 m) even though the period was nearly 2 months longer.

These records clearly confirm the expected seasonal frost heave and thaw subsidence, and also indicate that that these processes are not linear over the whole year:

- ¹⁵ the frost heaving during the freezing period (after August 2009–April 2010) was rather slow compared to the rapid subsidence following the initial thaw in late April or May. The freezing process therefore seems to operate much more slowly than the thawing process. The very minor frost heave observed during the 2010–2011 freezing period (average across all lithalsas: 0.04 m) was not as pronounced as in the previous (2009– 2010) (2009–2000) (2009–2000) (2000) (2000) (2000) (20000) (2000) (2000) (2000) (2000) (2000) (2000) (2000) (2000) (2000) (2000) (2000) (
- 20 2010) freezing period. Possible reasons for this difference are discussed later in this section.

The relative heights of the individual lithalsas (grey bars) all show similar trends but the amplitudes of their vertical movements vary considerably: Lithalsa R shows the least variation in height over time (August 2009–April 2011), with the maximum

²⁵ recorded vertical movement being the subsidence of 0.19 m between March and August 2010. All recorded vertical movements totaled over the entire period and averaged over all measurement points on Lithalsa R amount to 0.48 m. The net movement of lithalsa R amount to 0.06 m.



The maximum recorded vertical movement averaged across all measurement points on Lithalsa M was 0.20 m (between May and August 2010), and the total vertical movement (as for Lithalsa R) was 0.57 m. Lithalsa M reached its maximum uplift two months later than the other lithalsas. Compared to lithalsa M the net-movement is with 0.03 m ⁵ less.

Lithalsa I showed much greater vertical movement over the year than the other lithalsas, with a dramatic peak in its relative height in March 2010 followed by a very rapid decrease to May 2010. The greatest vertical movement (1.24 m) occurred between August 2009 and March 2010, and the sum of all vertical movement (as above) over the entire period was 3.2 m. Lithalsa I is the only lithalsa for which records are available from October 2010. The net movement at lithalsa I is with 0.01 m again less than at the other two lithalsas.

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Analyzing the measurements from individual measurement points (Fig. 3) reveals that the smallest vertical movement occurred at a point on Lithalsa R (R3), which had less than 0.2 m total movement over the 20 months period. The largest vertical movements (summation of movements of the 20 month period) occurred on Lithalsa I, at I4 (5.7 m) and I5 (6.0 m). These high numbers on Lithalsa I are largely due the rapid subsidence between March and May 2010. Observations from the R12 point indicate continuous subsidence. This behavior is probably due to the location of R12 at the slope of the lithalsa (Fig. 3) where advanced degradation in form of cracks and solifluction occurs.

Taking into account the different trends over the 20 month period as well as the behavior at the individual measurement points, it is clear that Lithalsa I was the most dynamic lithalsa over the observation period, while Lithalsa R was the least dynamic.

Lithalsa I was not only the most dynamic at all of the measurement points but also showed the greatest amount of variation between the measurement points. Hence, as far as the seasonal behavior of the frost mounds is concerned, the lithalsa with the least evidence of degradation (Lithalsa I) is the most active of the three lithalsas while Lithalsa R, which shows the most advanced signs of degradation, is the least active.



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Our results all conform to the expected seasonal variations in the elevation of lithalsas over the course of a year; they also reveal the correlation between a lithalsa's degradation and its seasonal variations. However, the relatively small amount of uplift in all three lithalsas between the fall of 2010 and April 2011 requires some explana-

- tion. The possibility of early thawing in 2011 having already resulted in any subsidence by April can be discounted as air temperatures were still well below 0 °C (the average air temperature for January to April 2011 was –16 °C; CEN, 2013). There are, however, two other possible explanations: (i) maximum thawing had probably not yet been reached in August 2010, which would mean that the lithalsas were still in the process
- of subsiding (as suggested by the observations from Lithalsa I in October 2010, which show further subsidence of 0.03 m since August 2010), and (ii) the late initiation of freezing in 2010, when air temperatures did not drop permanently below 0°C until the 17 November which is almost one month later than in 2009 (20 October: CEN, 2013), is likely to have delayed the uplift process, which was therefore not yet completed in April 2011.

A detailed analysis of each individual measurement point yielded additional information: the low average increase in elevation recorded between August 2010 and April 2011 is due to 35 % of the measurement points actually experiencing subsidence rather than elevation. Five of these points in particular (R6, R9, R11, M4, and M13) showed a great deal of subsidence (averaging -0.19 m) and were therefore largely responsible for the low average uplift. The seasonal uplift (frost heave) trend is thus dampened by just 13 % of the measurements that exhibit high counter-trends (i.e. subsidence). If these 5 points are ignored the average uplift amounts to almost 0.1 m.

In order to better understand the behavior at individual measurement points we also took into account the vegetation and noted that 93 % of the subsiding points were either vegetation-free or covered only with a small amount of lichen. Thirteen of the fourteen measurement points that recorded subsidence between August 2010 and April 2011 also experienced below-average frost heave in the preceding winter of 2009–2010. Overall, 85 % of the points with least uplift were either mostly covered with lichen or



non-vegetated. Those measurement points with above average uplift (> 61 % of all measurement points in the winter of 2009/10 and > 83 % of all measurement points in the winter of 2010/11) were covered with prostrate shrubs. A similar observation can be made for the summer thawing process (May–August 2010): 78 % of the points

- with below average subsidence (14 out of 39) were either covered with lichen or nonvegetated, while (88%) of the points experiencing above average subsidence (25 out of 39) were covered with prostrate shrubs. Between March and May 2010 none of the nonvegetated or lichen-covered measurement points showed above-average subsidence, but most (80%) of these points showed either continuing uplift or minor subsidence.
- Patches with prostrate shrubs therefore clearly start to subside earlier than those with little or no vegetation. In view of the weather in the spring of 2010, at least temporal early thawing is a real possibility as there had already been 17 days, with temperatures of up to 6 °C (reached on 31 March 2010; CEN, 2013), before the survey was conducted (8 May 2010).
- The lower overall dynamics at non-vegetated measurement points is not surprising since records of the active layer depth in the same year (2010) indicate that non-vegetated areas had very thin (< 5 cm) thaw depths in the summer (August) compared to patches covered with shrubs or trees (Beck et al., 2015). This is due to the absence of any insulation during the winter (i.e. no insulating cover of either vegetation or snow), resulting in lower ground temperatures (e.g. Beck et al., 2015; Clebsch and Charles 1002; Macharl 1074; Demonsular and Octarles 1005; Macharl 1007).
- Shanks, 1968; Mackay, 1974; Romanovsky and Osterkamp, 1995; Nelson et al., 1997). It can therefore be assumed that subsidence at these points starts much later than elsewhere. The relationship between the different vegetation types and the elevations changes is shown in Fig. 5.

25 4.2 Remote sensing – differential Interferometry Synthetic Aperture Radar (D-InSAR)

Out of the 11 TerraSAR-X acquisitions in 2009 and 2010, only six interferograms showed a reasonable coherence with values greater than 0.3; all other interferograms



were largely decorrelated. Areas covered by water bodies, vegetated areas, and pixels located within shadows are particularly affected by decorrelation and show coherence values below 0.3. However, although the average coherence value of the six interferograms is high enough for further analysis (Carballo and Fieguth, 2002; Hanssen, 2001)
 ⁵ coherence over the three lithalsas (Table 3) is too low to be considered adequate for further analysis.

Decorrelation in these areas is not surprising considering the large, rapid vertical movements (several decimeters in less than half a year) measured with the d-GPS. Amplitudes of movements of several decimeters in less than half a year exceeds by far

- the amount that can be quantified with TerraSAR-X data, where a phase cycle corresponds to 1.6 cm and the time interval between acquisitions is 11 days in the best case. Such problems caused by large changes due to freeze up processes were also identified by Short et al. (2011) when they tried to co-register TerraSAR-X and RADARSAT-2 data of Herschel Island from May, October and November. The outcomes from the dif-
- ¹⁵ ferential interferograms (Fig. 6) for the lithalsa area were therefore not subjected to any further analysis. The possibility of temporal decorrelation related to the land cover type can be discounted because the lithalsas are only covered with very sparse vegetation or none at all. Effects caused by differences in the moisture of the surface cannot be excluded, but studies in a Canadian permafrost region (Pangnirtung and Iqaluit) by Short et al. (2014) examined soil moisture unlikely to be a significant source of error.

Nevertheless the six differential interferograms (computed for the six image pairs; 7 May/14 August 2009, 14 August/30 August 2009, 14 August/30 October 2009, 5 May/12 August 2010, 12 August/28 August 2010, and 12 August/28 October 2010) reveal an interesting signal on a large scale. 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, it is an area of rock with only sparse vegetation (such as lichens and mosses). In this area a corner reflector was fixed on solid rocks by INRS for a RADARSAT-2 study and oriented for descending orbit. The signal in the TerraSAR-X interferograms might be related to the localized movement of the corner reflector, to



the relative displacement of the terrain with respect to the corner reflector, which is based on solid rocks, or to thermal dilation related to the structure where the corner reflector is installed. Without any further local information it is not possible for us to be more precise on the cause of the detected movement. West of the lithalsas (around

- ⁵ 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 belongs to the Cuestas (solid rock) but land cover classifications based on an IKONOS image (2005) and a GeoEye image (2009) present vegetated (prostrate shrubs) patches (May 2011) interspersed with temporary pool. Following the signals from the differential interferogram are very likely
- to be related to a temporary ponding. This suggestion 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 August 2009 and 30 August 2009), whereas it was very dry (only 5.8 mm precipitation) over the seven days prior to the first acquisition date.

15 5 Conclusion

The d-GPS records confirmed the expected vertical movements of lithalsas relatively to the unfrozen environment around them. The average uplifts during the two freezing periods (winter 2010 and winter 2011) measured with d-GPS are 0.4 and 0.1 m. The average measured subsidence during the thawing period (summer 2010) is 0.5 m.

- The results also indicate different patterns of behavior for each of the three lithalsas, reflecting their degradation status: maximal movements were recorded for the less degraded lithalsa (21 % above the average) and minimal movements were recorded for the most degraded lithalsa (40 % below the average). With regard to the vegetation cover, patches with prostrate shrubs cover experienced greater uplift and subsidence then there with little or ne vegetation.
- than those with little or no vegetation. The amount of movements also shows that permafrost features in this region are currently undergoing active degradation. Furthermore the d-GPS implications and experiments in sub-Arctic permafrost regions



and the achieved results are very important for the planning of D-InSAR experiments and the understanding of D-InSAR in sub-Arctic regions. As in-situ subsidence data in this environment is very rare, D-InSAR analysis is often performed without a-priori knowledge. Though, these movements could not be detected with D-InSAR due to decorrelation. It could be shown that large displacements can occur which makes the application of D-InSAR in this regions very challenging. This became evident by capturing the lithalsas' dynamics in the differential interferograms based on the X-band data of TerraSAR-X: this trial revealed the limitations of this method, as the range of movements (several cm) could not be represented in the D-InSAR products. However,

¹⁰ slow movements could be identified in the general vicinity north of Umiujaq and east of the lithalsas. These findings are of high importance as they confirm the usability of D-InSAR based on X-band to detect vertical dynamics in sub-Arctic regions.

Author contributions. I. Beck was responsible for the design of the experiments, the field work, the generation of the D-InSAR products as well as the analysis and interpretation of the results. R. Ludwig and M. Bernier were supervising her work and assisted her during the study. S. Tazio was supported the preparation of the D-InSAR products and the analysis. J. Boike was responsible for the interpretation of the permafrost processes. All co-authors supported I. Beck with the preparation of the manuscript.

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 Table 1. Acquisition dates for the d-GPS and TerraSAR-X data and details of the useable differential interferograms considered in this study.

			Detailed dates of useable interferograms		
Year	D-GPS acquisitiondates	TerraSAR-X acquisitiondates	Dates	Temporal baseline [d] ^a	Perpendicular baseline [m] ^b
2009	20 Apr 14 Aug	7 May 14 Aug	7 May/14 Aug	99	125.36
		25 Aug 27 Sep	14 Aug/25 Aug	11	-66.79
		30 Oct	14 Aug/30 Oct	55	12.78
2010	25 Mar	22 Mar			
	8 May 12 Aug	5 May 12 Aug	5 May/12 Aug	99	0.43
		23 Aug	12 Aug/23 Aug	11	-159.00
	27 Oct	28 Oct	12 Aug/28 Oct	77	-195.41
2011	9 Apr				

^a Time delay between the aquisitions.

^b Separation in meters between two antenna positions.



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Table 2. Characteristics of the TerraSAR-X sensor and the acquisition mode used for this study (based on CAF, 2009).

Spatial resolution:		Acquisition mode:	
Swath width	~ 15 km	Sensor mode	Stripmap
Slant range resolution	1.2 km	Polarization mode	Dual (VV) ^a
Ground range resolution		Pass & look direction	Ascending/Right
– Incidence angle: 40°	1.8 m	Product type	SSC ^b
Range pixel spacing	0.9 m	Local acquisition time	6.46 p.m.
Azimuth pixel spacing	2.5 m	Processing level	L1B

^a VV: vertical/vertical; ^b SSC: Single Look Slant Range Complex.



Table 3. Average coherence over the three lithalsas for the six interferograms.

	2009			2010		
	14 Aug–7 May	14–25 Aug	14 Aug–30 Oct	12 Aug–5 May	12–23 Aug	12 Aug-28 Oct
Lithalsa R	0.36	0.12	0.06	0.15	0.16	0.21
Lithalsa M	0.12	0.41	0.34	0.25	0.30	0.08
Lithalsa I	0.21	0.33	0.11	0.06	0.20	0.06



Figure 1. (a) One exemplary lithalsa within the study area, Umiujaq, northern Quebec, with a diameter of 20 m. The picture has been taken in April 2009 east of the Cuestas ($56^{\circ}33' N 76^{\circ}28' W$). **(b)** Thermokarst pond and eroding slop of lithalsa R. **(c)** Cracks at slope of lithalsa R. They are up to 0.5 m high.





Figure 2. Location of the study area in the vicinity of Umiujaq, northern Quebec, Canada (left), and the distribution of the two main landscape types (right): the coastal region to the west of the Cuestas and the Lac Guillaume-Delisle graben to the east of the Cuestas. The approximate boundary between widespread discontinuous permafrost to the north and scattered permafrost to the south (based on Allard and Séguin, 1987) is shown in red.





Figure 3. Left: location of the surveyed lithalsas and the base station, south-east of Umiujaq (background: GeoEye image from 25 September 2009). Right: enlargement showing the three lithalsas I, R and M and the locations of the individual measurements points. The identified measurement points (R3, R12, I4, I5) are specifically discussed in Sect. 4.





Figure 4. Heights of the three lithalsas (grey bars) and the average of their heights (black bars), relative to the base station, on the 6 measuring dates spread over a 20 month period. The heights represent the average of heights from all measurement points within each individual lithalsa. The accuracy of the records amounts to several centimeters. The lithalsas were not covered by snow during the measurements. The temperatures at the top are the mean monthly air temperatures of the specific year provided by Environment Canada (2004).





Figure 5. Box plots of surface cover and elevation changes for the three lithalsas, measured between August 2009 and March 2010, between May and August 2010, and between August 2010 and April 2011, based on all 39 measurement points on the three lithalsas.





Figure 6. The six interferograms (**a**: 7 May–14 August 2009, **b**: 14–25 August 2009, **c**: 14 August–30 October 2009, **d**: 5 May–12 August 2010, **e**: 12–23 August 2010, and **f**: 12 August–28 October 2010). Left: broad area around Umiujaq, northern Quebec, Canada. The dashed arrow to the north of Umiujaq indicates the fringes of slow movements; the dotted circles indicate the area of signals east of the lithalsas. Right: the area of the three lithalsas of interest; the amount of movement exceeds the amount that can be quantified with TerraSAR-X data.





Figure 6. Continued.

