Anonymous Referee #2

Received and published: 12 December 2015

Reply: We would like to thank the reviewer for providing these valuable comments that helped us to significantly improve the quality of our publication.

Samsonvov et al. reported surface uplift at a growing pingo on the Arctic coast of the Canadian NW Territories. This paper is innovative in three aspects: being the very first InSAR study of pingo uplift, using a flexure model to fit and explain the InSAR-observed uplift rates, and using a permafrost thermal dynamics model (i.e., NEST) to simulate permafrost aggradation and pingo growth. But the clarity of this paper should be improved before published on The Cryospere.

Reply: Thank you very much for your favorable evaluation.

Major comments:

1. More detailed information about the InSAR data and methods are needed. Where is the reference point? Consider to present the ascending and descending interferograms in two perpendicular-baseline vs. time plots, from which readers can tell what Radarsat-2 scenes used, temporal and spatial baseline of each interferogram.

Reply: Additional details about DInSAR processing were added to section 2.2. Reference points were plotted in Figs 6-7. Perpendicular-baselines vs. time were plotted in Fig 3.

Also explain the MSBAS approach, how this is different from the conventional SBAS approach? It appears that the authors upsampled interferograms from 20 m to 10 m in this MS-BAS processing (page 6400, line 19). How reliable are the 10-m results, since they are derived from 20-m interferograms?

Reply: We provided additional information about MSBAS algorithm. For details two references to manuscripts describing MSBAS methodology are provided. Original resolution of SAR data is 1.6x2.8 m, after applying 3x3 multilooking the resolution becomes 4.8x8.4 m. During DInSAR analysis 20 m DEM is resampled to ~8.4 m resolution (to match multilooked SAR data) and computed interferograms have similar ~8.4 m resolution. For MSBAS processing interferograms are further resampled to a coarser 10 m resolution, which reduces their size and makes MSBAS processing faster. Therefore, no loss of quality due to reduced resolution is observed, except when DEM is resampled from 20 m to ~8.4 m. However, this is not a significant reduction since only small baseline interferograms are used (therefore, sensitivity to topography is minimal) and because the topographic relief of the area is nearly flat.

2. Time series model

In the result section, it appears that the authors used a time series model consists of a linear plus ‘harmonic functions’ (page 6402, line 11). Due to a lack of clear definition and description, I found it very hard to understand this model and the time series results. Is it different from linear-trend uplift model stated in the method section (page 6400, lines 22-25). If so, the authors should revise relevant text in the method section to point out that two different time series models are used. What exactly are these ‘harmonic functions’? Why they are used and capable of describing the seasonal changes of uplift rate? Add a modelled uplift curve by interpreting the uplift rate curve, so that we can directly compare the model with the InSAR-observed uplift. Seasonal settlement and heave due to thawing/freezing of active layer could occur (page 6408, line 2; and Liu et al 2014, Seasonal thaw settlement at drained thermokarst lake basins, Arctic Alaska, The Cryosphere, doi:10.5194/tc-8-815-2014). How would this influence the interpretation of measured surface uplift and its seasonal changes?

Reply: We improved description of modeling by providing equation (1) with corresponding values. Harmonic function is a sine function. The output of MSBAS processing are time series of vertical ground deformation. These time series are computed without any model assumption, they represent realistic motion (precisely similar to SBAS). In post-processing it is common to fit linear trend to time series to capture a linear component of the motion, this also helps to visualize the results since only one image is required. Such results are, for example, shown in Fig 6 and 8 (top). In addition to time series for the point experiencing maximum motion we simultaneously fitted linear and sine functions and these results are shown in Fig 9(top). The usual seasonal surface processes act in the opposite way that is observed here - during summer the ground subsides (but we observe fast uplift) and during winter the ground uplifts (but we observe slow uplift). These evidences suggest that process described in this manuscript is originated at depth. Since reference point is subjected to similar surface processes (subsidence in the summer and uplift in the winter) this component of the signal is not captured in shown time series.

3. InSAR results

It appears (not stated explicitly) that standard deviation of deformation rates from the entire study area is used to represent the precision of InSAR-measured rates (Page 6401, line 22, line 26). This only works if the deformation rates are expected to be zero. But surface deformation of various types (e.g. thaw settlement, thermokarst) could also occur in this arctic lowland region. How the non-zero deformation affect the use of standard deviation to quantify precision? InSAR maps on Fig 6 and 7 include residual ponds, which should show no InSAR coherence. How areas of low coherence are treated in MSBAS? It looks they are masked out on Fig 5 (again, not explicated explained what are the white areas within InSAR coverage). But why they are not masked out on Fig 6 or 7? The first SAR image was taken in June 2011. Then why the Fig 6 time series starts from August 2011?

Reply: Our true objective is NOT to underestimate precision. By including areas that are *undergoing true motion the value of standard deviation of deformation rates slightly increases. This is acceptable since we do not want to underestimate standard deviation; small overestimation is fine for our purposes. MSBAS processes only pixels coherent in all interferograms (similar to SBAS), in previous version gaps in Figs 7-8 were interpolated by the plotting script, we corrected this in a current version – incoherent regions are now plotted in white. Thank you very much for pointing out to this inconsistency. To preserve space and improve clarity we plot only images for selected dates. This now is stated in caption of Fig 7.*

4. Elastic loading model

I like this simple flexure model described in section 4, but I don't have the expertise to judge how appropriate this can be used to describe pingo growth and if the assumed parameter values (page 6403 lines 18-20). The physics makes sense to me though. I think it would be helpful to include a simple diagram to show the geometry and symbols used in equation 1. And it seems theta refers to the azimuth angle from the North direction in the geodetic system, instead of 'tilt angle' (page 6403, line 8) The authors should state the purpose of this modelling effort at the beginning of section 4. It took me a while to figure out they want to solve for the centre location, size, direction, and delta q/D, from the InSAR data. And discuss why these values are important.

Reply: We have clarified the purposes of modeling in the first sentence of section 4. This model was initially proposed in Mackay, 1987, we just adopted it for the elliptical source, it describes signal very accurately, according to Fig 8. We provided a reference to a schematic diagram in Mackay, 1987. The symbol of tilt angle was corrected – now we use "alpha".

5. Permafrost modelling of pingo scenarios

It is unclear to me how the authors used the same strategy, i.e. saturated 99 And another related question: why permafrost thickness and deepening of freezing front (as predicted by NEST) can be used to present pingo uplift, which is driven by expelled pore water? The linkage remains unclear to me. Maybe I have missed something fundamentally.

Reply: The uplift of a pingo is due to the development of a sub-pingo water lens and its subsequent freezing (Mackay, 1979). Permafrost aggradation into the sub-adjacent lake bottom sediments and pore water expulsion continue to feed the sub-pingo water lens. The process of permafrost aggradation both maintains a pressurized water lens and, beneath the pingo, converts the water into ice. Thus, we can estimate the growth rate of a pingo based on the downward freezing of the water in the sub-pingo water lens. An increase in thickness of the pingo ice corresponds to its uplift, and in turn increases the lag between seasonal cooling cycles, permafrost aggradation at depth and pingo growth. Mackay (e.g., 1979, 1998) applied a simplified Stefan solution (Ingersoll, 1954) with a one-year time step to explain the measured growth rates of pingos in Tuktoyaktuk peninsula. To investigate seasonal variation and long-term rate of pingo growth due to permafrost aggradation, we used a process-based permafrost model, *NEST (Zhang et al., 2003). As the model was developed for terrestrial conditions, we used saturated porous material with 99% of porosity to represent sub-pingo water lens. We revised the text to further clarify the modeling strategy. We added more sentences to clarify the modelling strategy.*

6. DEMs Several DEM products have been used and presented in this study, e.g. the ones made from air photos (section 2.1), the 20-m one used in InSAR (section 2.2), the 90-m one shown on Figure 2. A brief summary of these may help to reduce confusion. And more importantly, what is the height accuracy for each DEM products? This info is essential to assess the accuracy of the differential DEM results shown on Figure 4.

Reply: We clarified the situation with DEMs. Unfortunately in this remote region, there is no single high-quality, high-resolution DEM covering entire region, so we had to use different DEMs for different purposes. In section 2.1 it is said that precision of all DEMs derived from stereo-photo analysis and Total Station surveys (Fig 5) is 0.5 m. The 5 m precision of 20 m DEM used for removing the topographic phase during InSAR analysis is reported in section 2.2. The precision of 90 m DEM is unknown, but this DEM is used only as a background in Fig 2, its precision is not important at the resolution shown in this figure.

Minor comments:

Abstract, line 9. The conclusion that this pingo is the largest in the region is not supported by the model result.

Reply: We rewrote sentence as following: "Satellite measurements suggest that this feature is one of the largest diameter pingos in the region that is presently growing." It is concluded from Fig 6.

Abstract, line 24 (and in conclusion): delete sentences about InSAR can study martian pingos, which is not supported by this study.

Reply: We removed this sentence.

Page 6400, line 16 and line 20: change software to algorithm

Reply: Corrected.

Page 6401, title of section 3: delete [0] at the end

Reply: Corrected.

Page 6401, line 10: move definition of the acronym DEM to its first appearance in section 2.1 (I think).

Reply: Corrected.

Page 6405, line 15: remove the dot after 33

Reply: Corrected.

Page 6409, line 18-20: elaborate more on how the processing method caused the failure to resolve known growing pingos.

Reply: This information is provided in the lasts sentences of section 6: "The discrepancy between long-term field measurements and these results is likely caused by the inability of our processing methodology to resolve deformation at smaller spatial scales. The DInSAR spatial resolution can be improved by using high-resolution DEM for removing the topographic phase". Another possible factor is temporal decorrelation due to ground condition changes. We will further address this issue in our following publication.

Fig 4 caption: add 2014 and date of the background radar image.

Reply: Corrected.