Canada

Natural Resources Canada | Ressources naturelles Canada

Improved Modeling of Vertical Crustal Motion in Canada for a New North American Reference Frame

Catherine M.I. Robin[1], Michael Craymer[1], Remi Ferland[1], Earl Lapelle[1], Mike Piraszewski[1], Yanlai Zhao[1] and Thomas S James[2]

[1]Geodetic Survey Division, Natural Resources Canada

[2] Geological Survey of Canada, Natural Resources Canada

AGU

AGU Fall Meeting

San Francisco, December 12-16, 2016

Paper G21B-1002

ABSTRACT

A national-scale crustal velocity model has been developed for Canada as part of the current realization of NAD83(CSRS). It is used to propagate coordinates to different reference epochs, and to support scientific studies such as natural hazards related to earthquakes and sea level rise. The current velocity model is based solely on continuous and campaign GPS data between 1994 and 2011.3. To improve on this, a new hybrid model has been created which incorporates a new GPS velocity field with GIA and elastic rebound models for improved accuracy, particularly in northern areas with sparse GPS coverage. Several GIA models and interpolation techniques were tested. Improvements to the GPS velocity field include the addition of new stations in key areas, 5 more years of data, and the reprocessing of all data with the latest software, orbits and antenna calibrations. We include all continuous GPS sites in Canada, the northern portions of the US, all of Greenland, repeated high accuracy campaign surveys of the Canadian Base Network, and a set of global sites used to define the reference frame. Initial uncertainty estimates for the hybrid model are also provided. It is envisaged that such a hybrid model can be used to provide an improved vertical crustal velocity model for a new North American reference system.

1. GPS VELOCITIES

Continuous GPS Solutions

- Weekly solutions using Bernese GNSS Software v5.2
- 879 weekly solutions (2000-01-02 to 2016-11-05)
- CODE repro2 precise orbits
- IGS antenna calibrations in IGb08/ITRF2008
- 100 IGS stations define IGb08/ITRF2008 reference frame
- Ionospheric-free L3 baselines with tropo estimation for all baselines

Campaign GPS Solutions

- Multiple (3-4) 24 hr occupations of each site for each campaign
- Same Bernese processing methodology as for continuous sites

Canadian Base Network (CBN)

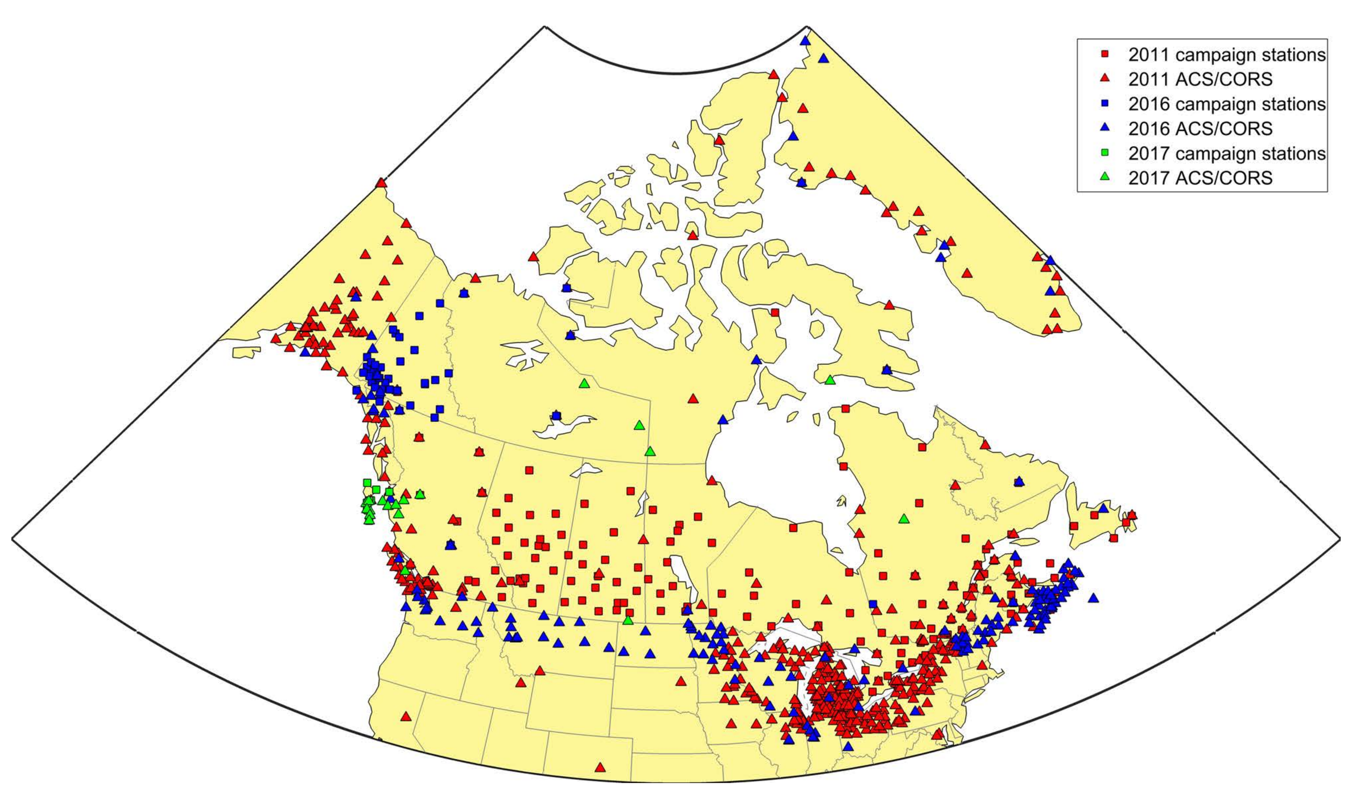
- Network of stable pillar monuments
- Forced centering antenna mounts
- 58 survey campaigns from 1994 to 2016

Regional Campaigns

- Pacific Geoscience Center Yukon: 22 campaigns (1999-2011)
- Eastern Canada Deformation Array: 20 campaigns (2005-2016)
- Haida Gwaii: 8 campaigns (1998-2013)

Multi-Year Combination

- 959 network solutions with full covariance information using new SINEX software
- All station positions & velocities rigorously and simultaneously determined
- Translation, rotation & scale (and rates of change) with an alignment condition for the combined cumulative solutions
- Variance factor for each solution was estimated and applied to each weekly covariance matrix
- Input station coordinate residuals > 20 mm (5σ) rejected; residuals between cumulative solutions and ITRF2008/IGb08 > 20 mm (5σ) (position) or 10 mm/yr (5σ) (velocity) also rejected

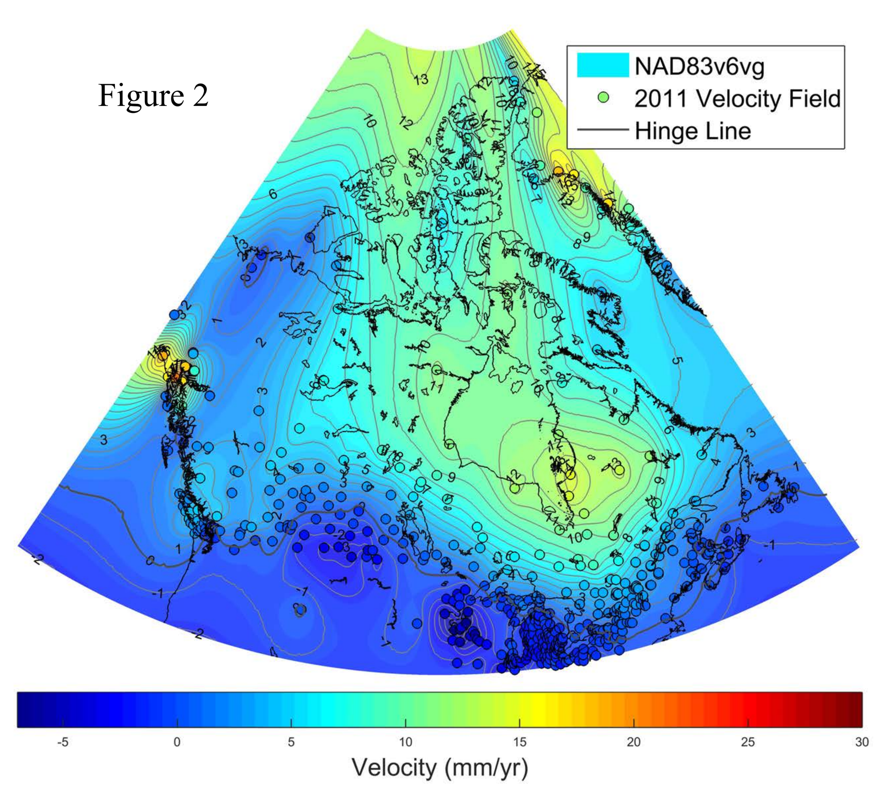


- Stations whose velocities were used in the current velocity grid (NAD83v6vg) are plotted in red. Squares represent campaign stations, and triangles represent permanently operating stations (ACS in Canada & CORS in the US). Some CBN's have been converted to ACS's since 2011 (not identified on this map).
- Methods for integrating geophysical models with GPS velocities were tested on the 2011 dataset (Section 3).
- 2016 & 2017 velocity fields include updated velocities at the 2011 stations as well as new stations (plotted blue and green).
- Stations marked in green will be included in the official velocity grid which will be available by February 2017. Data from Cape Dorset (Hudson Straight) will not be available due to communication issues.

2. NAD83v6vg

- The current vertical velocity grid (Figure 2) was calculated in 2011 by interpolating velocities at stations shown in red in Figure 1, using block mean mode in the Generic Mapping Toolbox.
- Velocity solutions were analyzed to remove outliers and ensure coherence on a regional scale.
- Most outliers have short observation periods.

Figure 2



3. HYBRID VELOCITY GRID

- Vertical velocities were predicted over large areas by glacial isostatic adjustment (GIA) models using ice histories constrained by historic shoreline reconstructions and sea level records. Recent GIA models have also been optimized to fit GPS velocities.
- The hybrid velocity grid was created by integrating a GIA model with GPS data over the entire grid.
- GPS velocities were quality controlled using a combination of automated solution selection and manual inspection of flagged outliers.
- Three GIA models[1,2,3] were tested against GPS velocities, in particular against two subsets of the velocity field (18 and 123 stations each) in areas of sparse coverage where the GIA model has the most influence. Laur16Innu[1] was the best fit for both subsets.
- A model of elastic rebound in response to recent ice melt in Greenland and northern Canada (provided by K. Simon) was added.
- Differences between velocities at all GPS stations and those predicted by the combined GIA + elastic models were interpolated to the grid. A number of interpolation methods were tested using 3 cross-validation techniques (Figure 3).
- Weighted kriging provided a good compromise between best predicted residuals for the cross-validation and smoothness of the surface. Each data point was weighted by the uncertainty provided by the SINEX combination.
- The interpolated differences were added to the combined GIA & elastic models to create the hybrid grid.
- The same interpolation methods have been tested for the horizontal velocity grids, with no model currently incorporated.

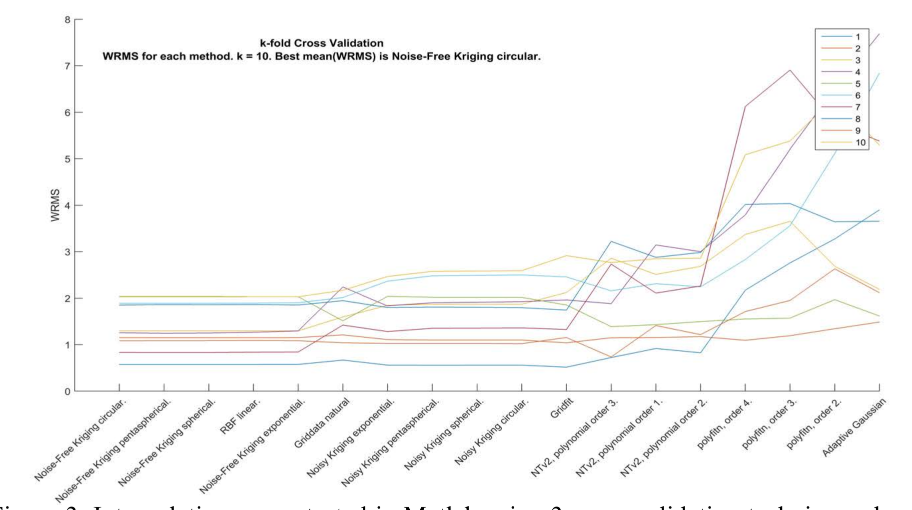


Figure 3. Interpolations were tested in Matlab using 3 cross-validation techniques, based on removing members of a set of 120 of the northern stations and comparing the RMS of the predicted residuals (velocity at the removed stations minus the interpolated velocities). Cross-validation techniques used were (1) Monte Carlo type (10% of the testing stations randomly removed), (2) k-fold (5% and 8% of stations systematically removed until all stations have been tested), and (3) leave one out (LOO) where each station is removed individually. Testing statistics were RMS, weighted RMS (shown here) and R^2.

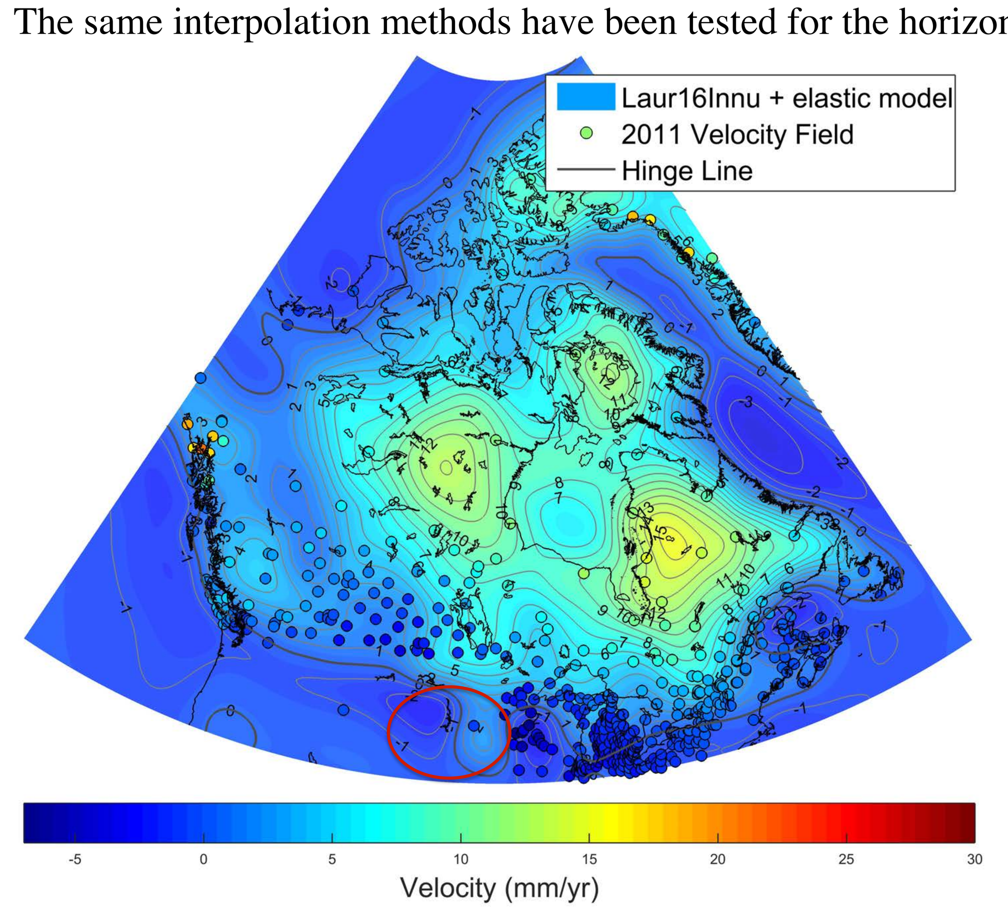


Figure 4. Combination of the Laur16Innu GIA model[1] and the elastic model. Laur16Innu is derived from the ICE-5G ice history model, adjusted to optimize the fit in 4 regions of northern Canada. The feature circled in red is from the Ice-5G model, and does not appear in ICE-6G[2]. We also tested NAICE[3].

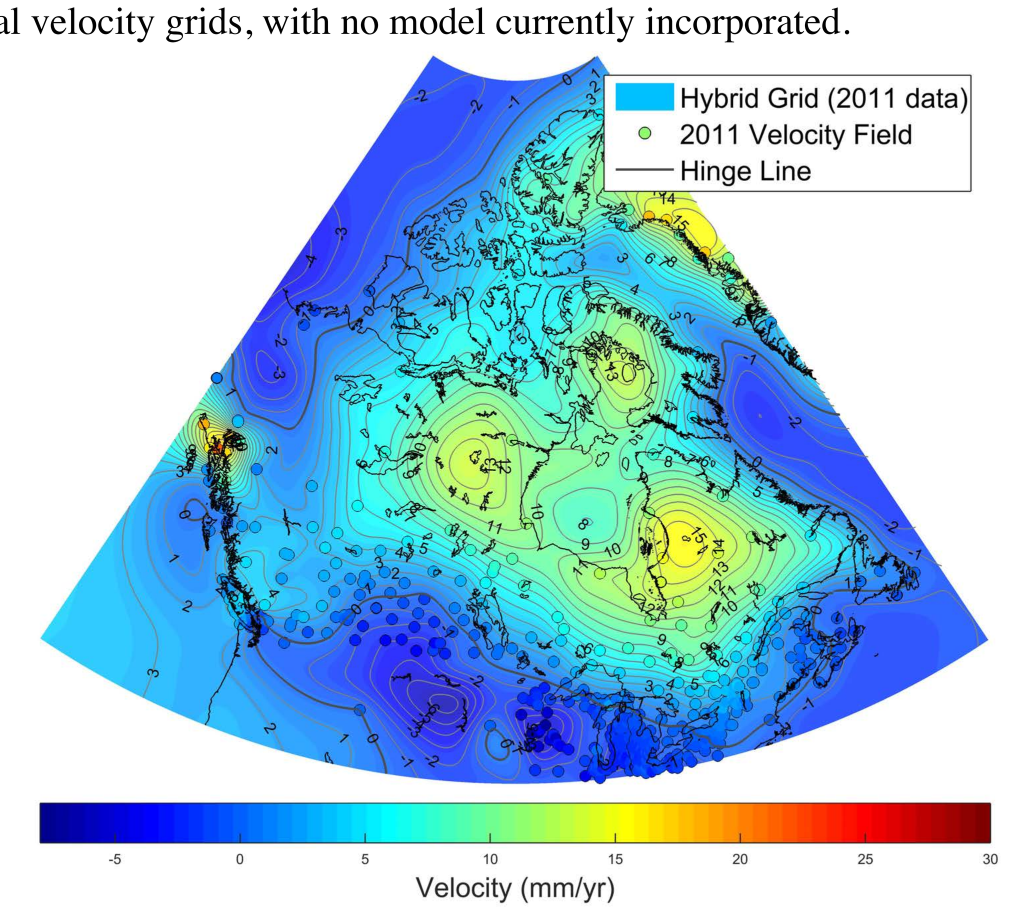


Figure 5. Hybrid grid calculated using the procedure described in Section 3, using the 2011 data used for NAD83v6vg, and the Laur16Innu+elastic combined models. Comparison with Figure 2 highlights the effect of changing the interpolation method and including the geophysical models.

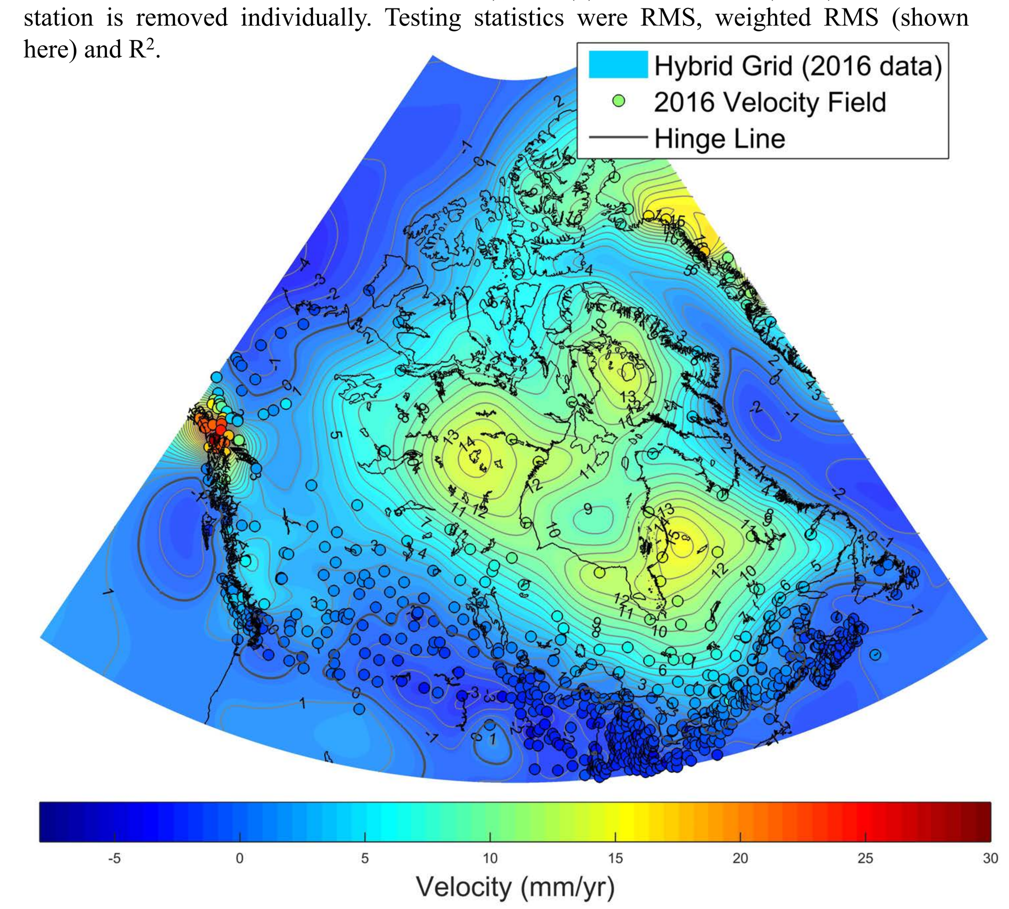


Figure 6. Hybrid grid calculated as in Fig. 5 but including the 2016 data. Differences between the two grids are due to denser data in northern BC and Alaska (defining the Little Ice Age uplift), and new data from the north central states. New 2017 data in Nunavut is likely to adjust the uplift dome west of Hudson's Bay. The 2016 GPS solutions have not yet been manually quality controlled.

4. UNCERTAINTY GRID

- GIA model uncertainty is defined as the standard deviation of the differences between hybrid grids calculated with each of 3 GIA models[1,2,3]. Thus the GIA model uncertainty is smallest where the GPS network is dense, and is almost 0 at the GPS stations.
- Data & interpolation uncertainty is calculated from the kriging variance. This part of the uncertainty increases with distance from stations, and is generally slightly larger than the GPS velocity uncertainties (except for stations with large uncertainties which are weighted much less in the interpolation).
- The GIA & GPS uncertainties are added in quadrature.
- 2016 GPS uncertainties appear overly optimistic and will be reviewed.
- Figure 7 is the uncertainty grid for the model in Figure 5; Figure 8 is the uncertainty grid for the model in Figure 6. The red circle in Figs. 7, and 8 highlights the correction to the GIA model provided by the additional data in the northwest USA.

Figure 7

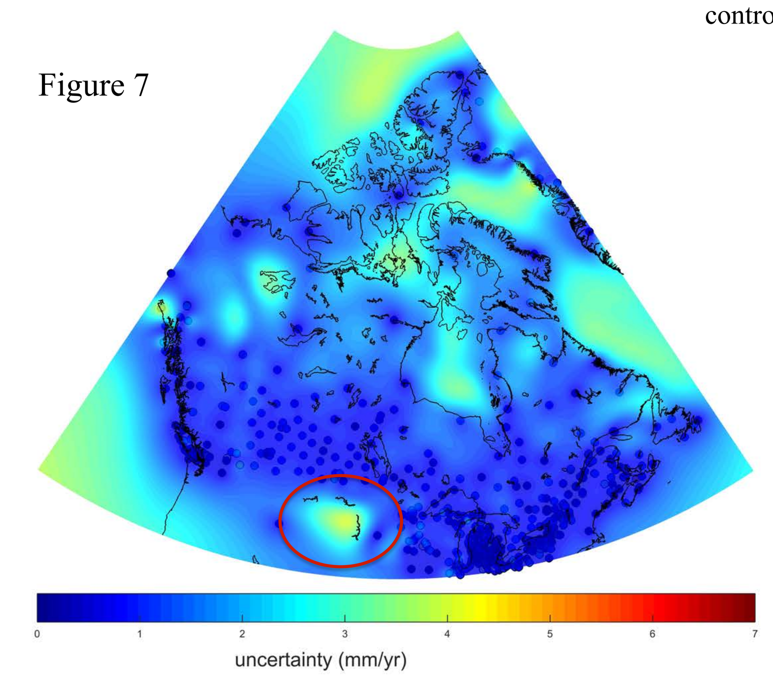
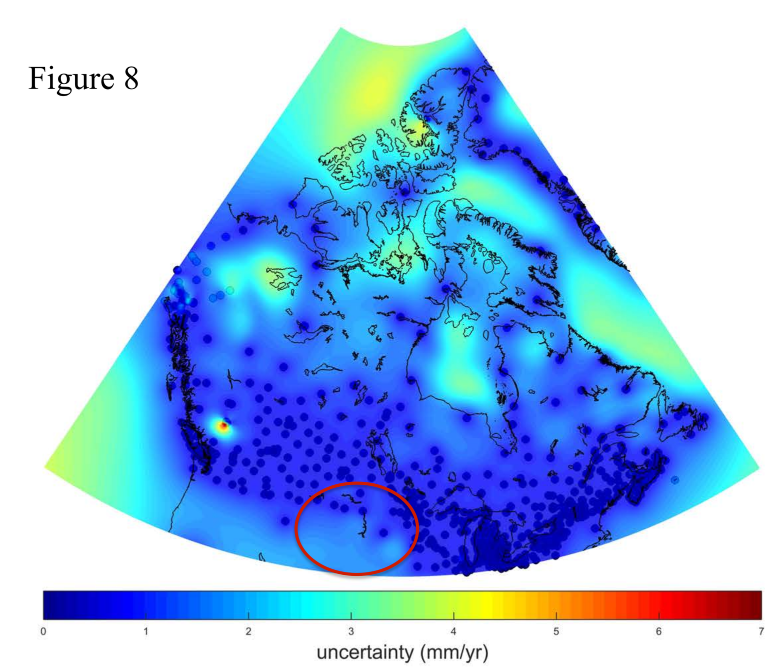


Figure 8



6. FURTHER WORK

- Review data uncertainties from SINEX processing.
- Quality control new 2016 & 2017 solutions for regional inconsistencies and outliers (mainly due to shorter time series).
- Test new solutions against 3 GIA models and interpolation methods.
- Integrate tectonic blocks in the west coast for the horizontal velocity grid.
- Include new permanent stations proposed in the Yukon and Nunavut.

7. ACKNOWLEDGEMENTS

- Karen Simon for supplying Lau16Innu and the elastic models on our grid nodes
- CGS and provincial geodetic agencies for installation of highly stable CBN monumentation
- CGS field survey personnel for consistently highly accurate GPS survey campaigns

8. REFERENCES

1. Simon, K.M., James, T.S., Henton, J.A. & Dyke, A.S. (2016) A glacial isostatic adjustment model for the central and northern Laurentide Ice Sheet based on relative sea level and GPS measurements. *Geophys. J. Int.* 205, 1618-1636

2. Peltier, W.R., Argus, D.R. & Drummond, R. (2015) Space geodesy constrains ice age terminal glaciation: The global ICE-6G_C (VM5a) model. *J. Geophys. Res. Solid Earth*, 120, 450-487

3. Gowan, E.J., Tregoning, P., Purcell, A., Montillet, J.-P. & McClusky, S. (2016) A model of the western Laurentide Ice Sheet, using observations of glacial isostatic adjustment. *Quat. Sci. Rev.*, 130, 1-16.