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Predicting Present-Day Rates of Glacial Isostatic Adjustment Using a Smoothed GPS-Based Velocity Field for the Reconciliation of NAD83 Reference Frames in Canada

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ABSTRACT

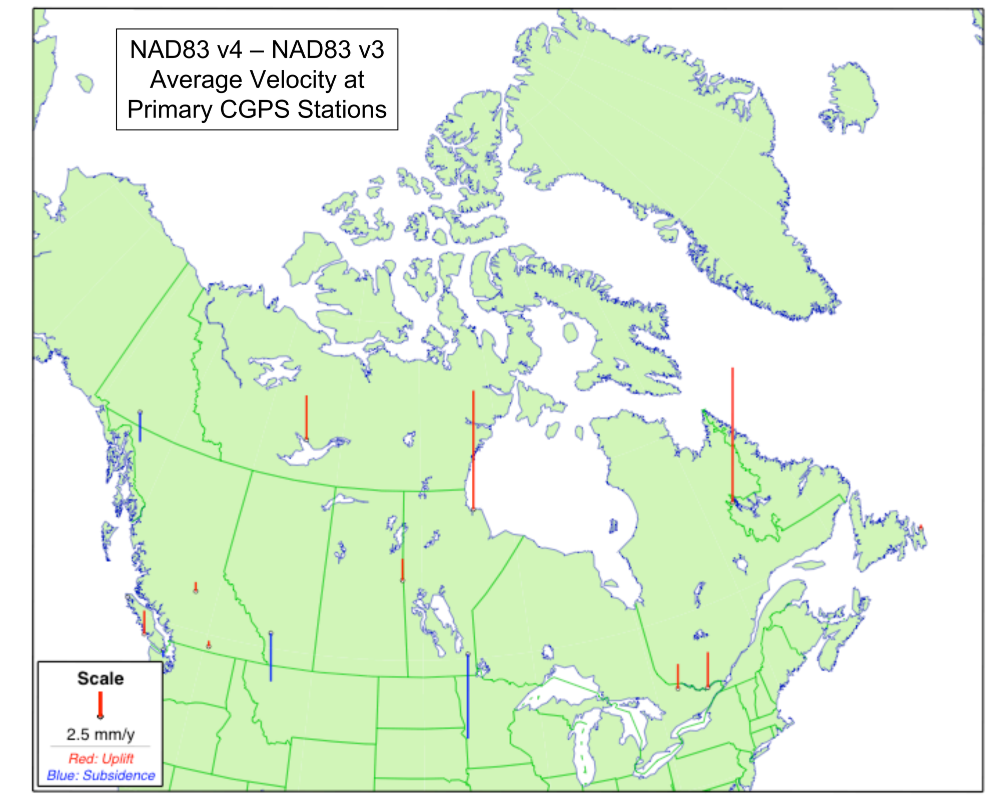
Glacial isostatic adjustment following the last glacial period is the dominant source of crustal deformation in Canada east of the Rocky Mountains. The present-day vertical component of motion associated with this process may exceed 1 cm/y and is being directly measured with the Global Positioning System (GPS). A consequence of this steady deformation is that high accuracy coordinates at one epoch may not be compatible with those at another epoch. For example, modern precise point positioning (PPP) methods provide coordinates at the epoch of observation while NAD83, the officially adopted reference frame in Canada and the U.S., is expressed at some past reference epoch. The PPP positions are therefore incompatible with coordinates in such a realization of the reference frame and need to be propagated back to the frame's reference epoch. Moreover, the realizations of NAD83 adopted by the provincial geodetic agencies in Canada are referenced to different coordinate epochs; either 1997.0 or 2002.0. Proper comparison of coordinates between provinces therefore requires propagating them from one reference epoch to another. In an effort to reconcile PPP results and different realizations of NAD83, we empirically represent crustal deformation throughout Canada using a velocity field based solely on high accuracy continuous and episodic GPS observations. The continuous observations from 2001 to 2007 were obtained from nearly 100 permanent GPS stations, predominately operated by Natural Resources Canada (NRCan) and provincial geodetic agencies. Many of these sites are part of the International GNSS Service (IGS) global network. Episodic observations from 1994 to 2006 were obtained from repeated occupations of the Canadian Base Network (CBN), which consists of approximately 160 stable pillar-type monuments across the entire country. The CBN enables a much denser spatial sampling of crustal motions although coverage in the far north is still rather sparse. NRCan solutions of the continuous GPS data were combined with those from other agencies as part of the North American Reference Frame (NAREF) effort to improve the reliability of the results. This NAREF solution has then been combined with our CBN results to obtain a denser velocity sampling for fitting different types of surfaces in a first attempt to determine a continuous GPS velocity field for the entire country. Expressing this velocity field as a grid enables users to interpolate to any location in Canada, allowing for the propagation of coordinates to any desired reference epoch. We examine the accuracy and limitations of this GPS velocity field by comparing it to other published GPS velocity solutions (which are all based on less data) as well as to GIA models, including versions of ICE-3G, ICE-5G and the recent Stable North America Reference Frame (SNARF) model. Of course, the accuracy of the GPS velocity field depends directly on the density of the GPS coverage. Consequently, the GPS velocity field is unable to fully represent the actual GIA motion in the far north but does a reasonable job in the south.

1. REALIZATIONS OF THE NAD83 REFERENCE FRAME

- NAD83 is the official civil reference frame in Canada and the US.
- Defined as a time-dependent 7 parameter transformation from ITRF.
- Different realizations based on different ITRF's at different epochs.

Version	Based on	Epoch
NAD83 v1	ITRF93	Unknown
NAD83 v2	ITRF96	1997.0
NAD83 v3	ITRF97	1997.0
NAD83 v4	ITRF2000	2002.0
NAD83 v5	ITRF2005	2006.0

- Significant differences between realizations at different epochs primarily due to effects of crustal motion – in particular GIA (see figure).
- Need to reconcile discrepancies using a model (grid) of crustal motion based on GPS measurements (velocity field) to propagate positions to specific epochs



2. GPS VELOCITY FIELD

Continuous GPS (NAREF)

- Using results from the North American Reference Frame (NAREF) Working Group of IAG Sub-Commission 1.3c for North America.
- Consolidating regional solutions into a continental one aligned to IGS realization of ITRF a weekly basis.
- Using following regional weekly solutions up to GPS week 1399:

Solution	# Sites Used	From
NRCan/GSD Bernese (GSB)	~112	2001.0
NRCan/GSD GIPSY (GSG)	~ 43	2001.0
NRCan/PGC Bernese (PGC)	~55	2001.0
NGS/CORS PAGES (NGS)	~870 (~570 used)	2002.0
SIO GIPSY (PBO)	~700 (~140 used)	2001.0
MIT PBO (MIT)	~670 (~185 used)	2006.0

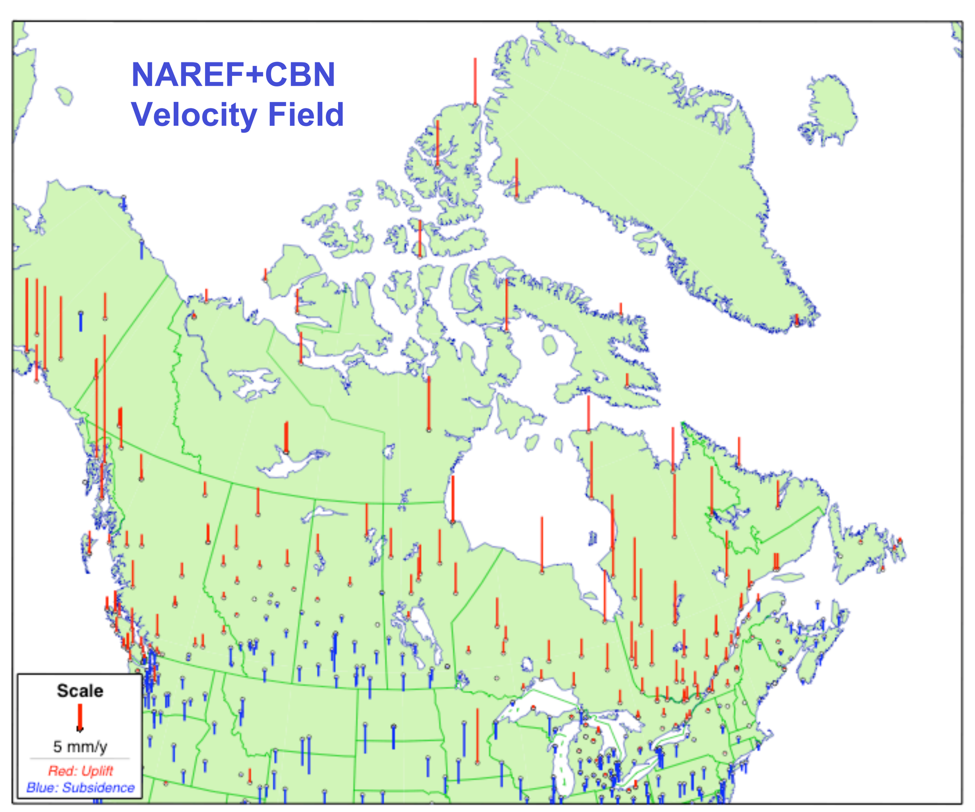
- Combined weekly NAREF solutions into a "cumulative" solution with velocity estimation.
  - All regional solutions using relative phase centers
  - ⇒ Using solutions only up to GPS week 1399
- 328 sites rejected due to:
  - Short time span (less than 2 years) ~206 sites
  - Collocated/redundant sites ~50 sites
  - Poor time series (gaps, noisy, offsets) ~20 sites

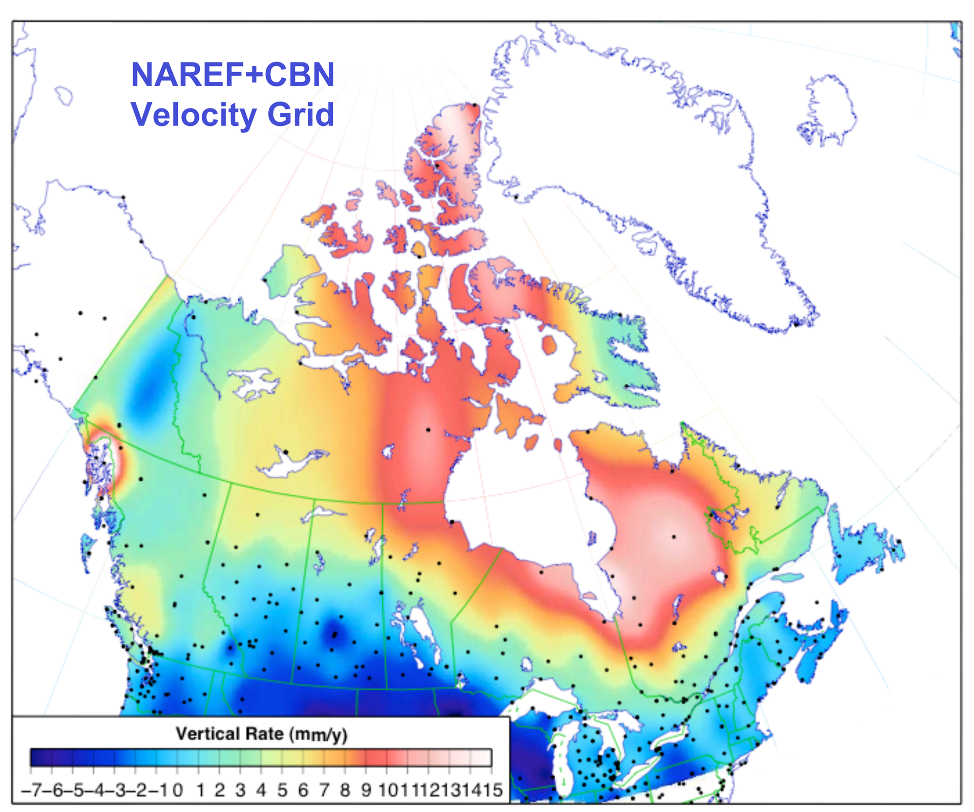
Episodic GPS (CBN)

- Repeated survey campaigns of the Canadian Base Network
  - Network of stable pillar monuments
  - Forced centering antenna mounts
  - Covers all of Canada (sparser in the north)
  - Multiple (3-4) 24 hr occupations of each site
- Using 27 repeated survey campaigns from 1994 to 2006.
  - 1st campaign 1994-1999 (no 1998)
  - 2nd campaign 2001(east)-2002(west)
  - 3rd campaign 2005(east)-2006(west)
  - Several other smaller campaigns
- Each epoch
  - Processed with Bernese GPS Software
  - Using relative phase centers
  - Aligned to IGS realization of ITRF2005
- Combined all epochs into a "cumulative" solution with velocity estimation.

NAREF+CBN Velocity Field

- Individually re-aligned NAREF & CBN solutions to ITRF2005
- Combined together with weighted ITRF2005 constraints (see plot below left)

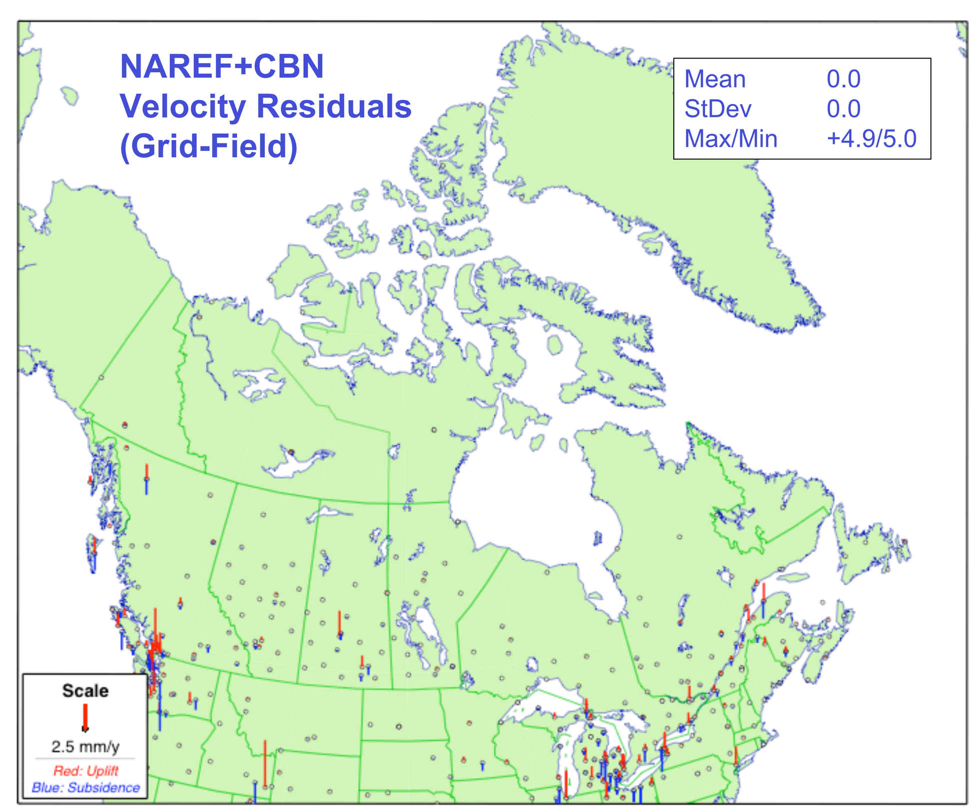




3. VELOCITY GRID GENERATION

- Using GMT (Wessel & Smith, EOS Trans. AGU, 72, 441, 1991).
  - "blockmean" with 1 deg x 1 deg block size
  - "surface" with 0.25 deg grid & tension 0 (min curvature; smoothest for GIA signal)
  - Above parameters minimized effect of anomalous velocities for given station spacing
- Residual fit of velocity field to grid (see plots below)

Mean	0.0 mm/y
StDev	0.9 mm/y
Max/Min	+4.7/-5.0 mm/y



4. COMPARISON WITH ICE-4G & ICE-5G

ICE-4G VM1/2

- VM1 better fit than VM2
- Misfit of VM1 wrt GPS:

Mean	-0.2 mm/y
StDev	2.4
Max/Min	+6/-23

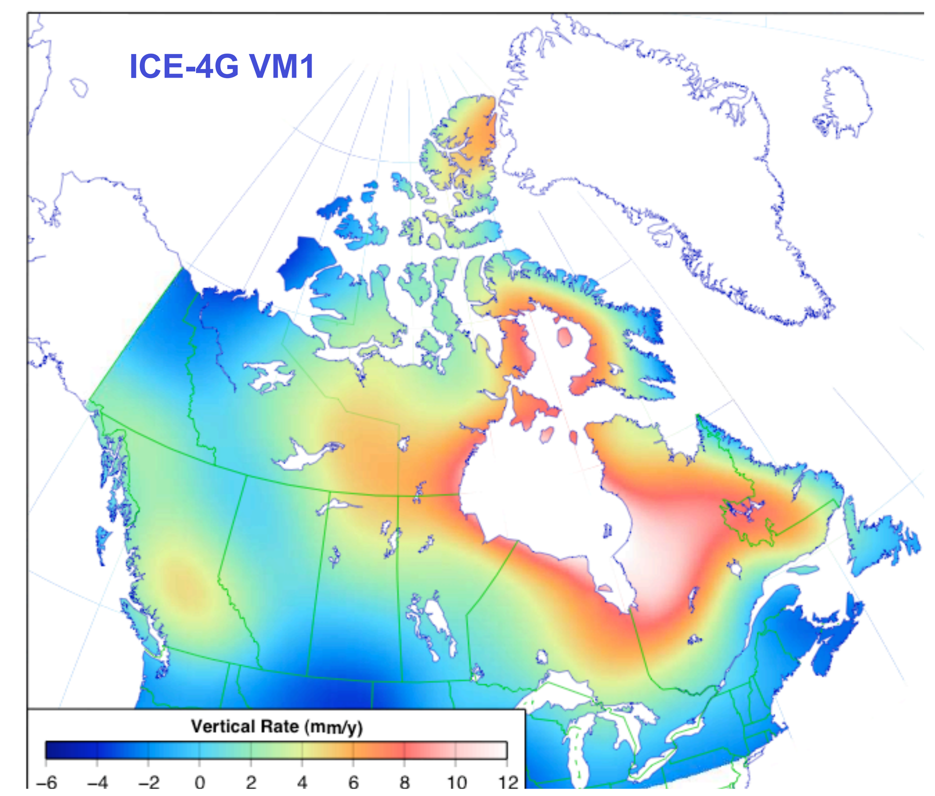
- Better fit in the south than the north

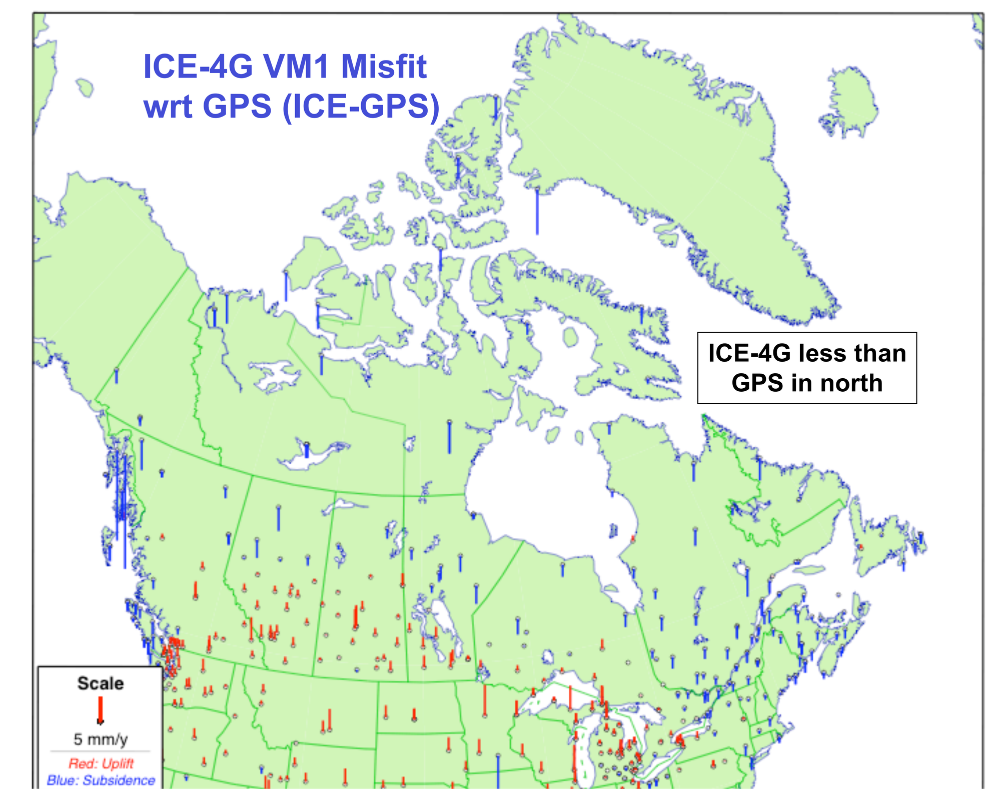
ICE-5G VM2/4

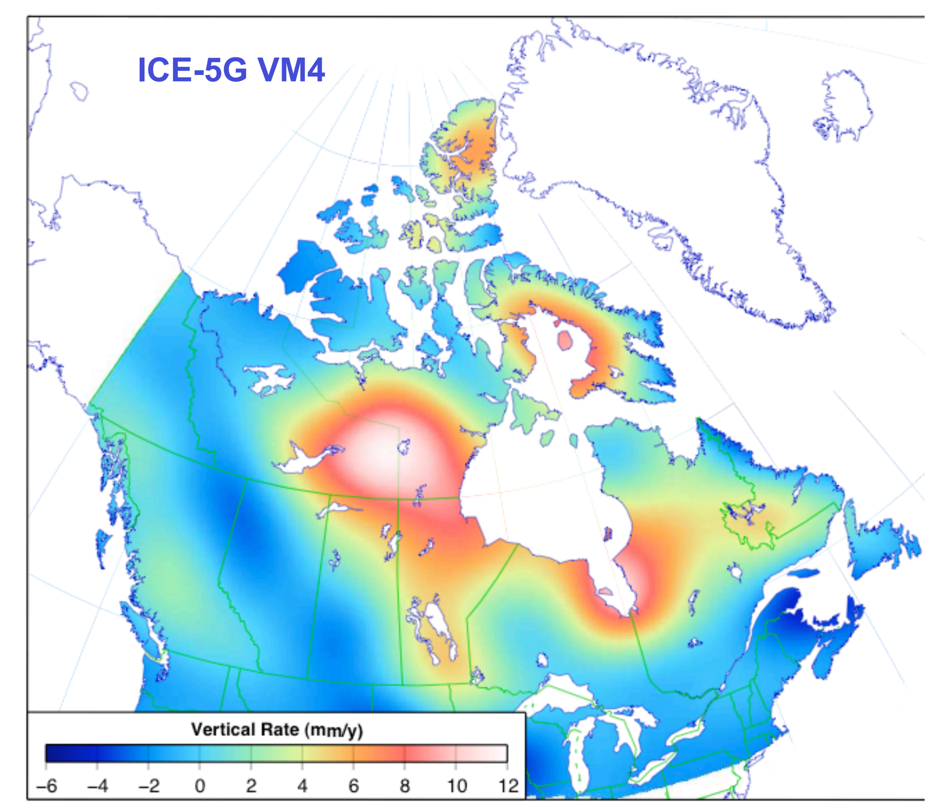
- VM4 better fit than VM2
- Misfit of VM4 wrt GPS

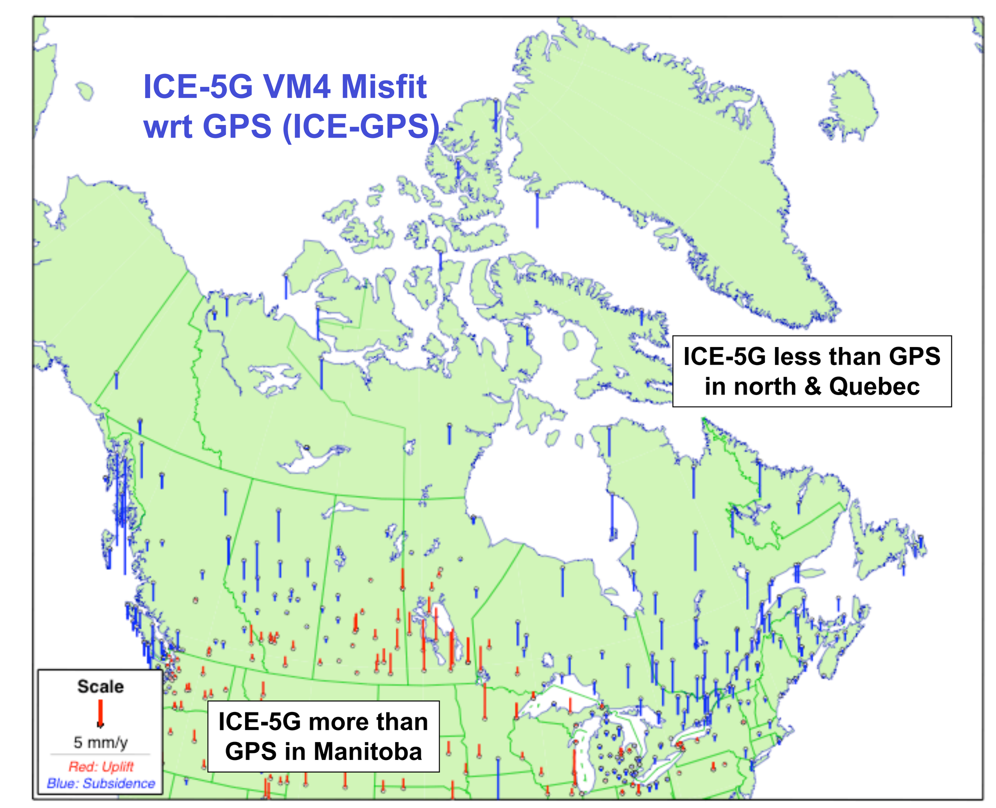
Mean	-0.9 mm/y
StDev	2.9
Max/Min	+8/-23

- GPS does not support uplift in S. Manitoba or subsidence in N. Alberta/BC









5. FURTHER WORK

- Test success of velocity grid to propagate NAD83 positions to difference epochs – must account for ITRF2005 origin drift with respect to previous ITRFs and NAD83.
- Further experimentation with GMT gridding options.
- Evaluate and possibly adopt SNARF v2 GIA model.
- Another complete or targeted CBN survey campaign to resolve anomalous velocities.

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  - SIO: Peng Fang
  - PGC: Herb Dragert
  - MIT: Tom Herring
- Combination software: Remi Ferland
- CBN survey campaigns: GSD field personnel
- ICE-4G: Richard Peltier