Determining Sea Level Rise and Coastal Subsidence in the Canadian Arctic Using a Dense GPS Velocity Field for North America

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ABSTRACT

With observed climate warming in the western Canadian Arctic and potential increases in regional sea level, we anticipate expansion of the coastal region subject to rising relative sea level and increased flooding risk. This is a concern for coastal communities such as Holman NWT and Kugluktuk NU and for the design and safety of hydrocarbon production facilities on the Mackenzie Delta. To provide a framework in which to monitor these changes, a consistent velocity field has been determined from GPS observations throughout North America, including the Canadian Arctic Archipelago and the Mackenzie Delta region. An expanded network of continuous GPS sites and multi-epoch (episodic) sites has enabled an increased density that enhances the application to geophysical studies including the discrimination of crustal motion, other components of coastal subsidence, and sea-level rise. To obtain a dense velocity field consistent at all scales, we have combined weekly solutions of continuous GPS sites from different agencies in Canada and the USA, together with the global reference frame under the North American Reference Frame initiative. Although there is already a high density of continuous GPS sites in the conterminous United States, there are many fewer such sites in Canada. To make up for this lack of density, we have incorporated high-accuracy episodic GPS observations on stable monuments distributed throughout Canada. By combining up to ten years of repeated, episodic GPS observations at such sites, together with weekly solutions from the continuous sites, we have obtained a highly consistent velocity field with a significantly increased spatial sampling of crustal deformation throughout Canada. This exhibits a spatially coherent pattern of uplift and subsidence that is consistent with the expected rates of glacial isostatic adjustment. To determine the contribution of vertical motion to sea-level rise under climate warming in the Canadian Arctic, we have established co-located tide gauges and continuous GPS at a number of sites across the Canadian Arctic.

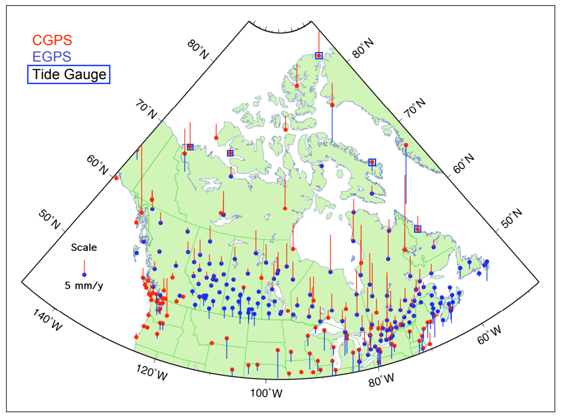
MEASURING VERTICAL MOTION

Continuous GPS (CGPS) sites (red symbols at right) are part of the continent-wide North American Reference Frame (see naref.org) and provide the backbone for estimating velocities that are consistent across the entire Arctic region. Requires several years of observations to reliably estimate and remove the effect of significant seasonal variations. Continuous data provide a more detailed picture of higher frequency variations due to loading and other effects such as snow/ice build up on antennas.

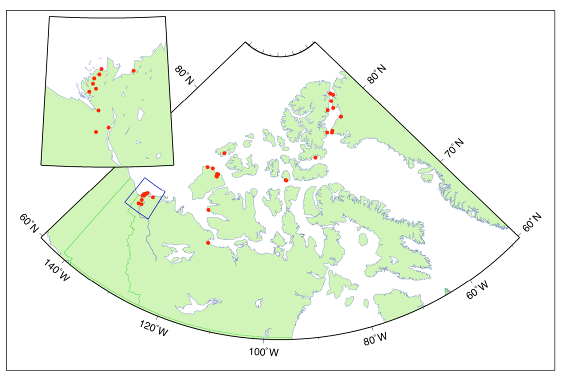
Multi-epoch GPS (EGPS) (blue symbols at right), using several days of high accuracy GPS occupations, is used to densify the CGPS network to provide greater spatial sampling of crustal motion and to enable easier RTK operations for georeferencing geological data. This requires periodic observations over several years or more to reliably resolve the small vertical motions. Observations need to be made at same time of year to avoid effect of seasonal biases. Many EGPS sites have been established in the Arctic over the last several years, including a significant number in the Mackenzie Delta (inset at bottom right).

Tide gauges (blue rectangles at right) co-located with some CGPS sites enable determination of sea level trends after compensating for crustal motion in a consistent manner across the entire Arctic region.

The combined CGPS/EGPS velocity field is shown at upper right. Typical CGPS time series (top right) are shown for a few sites. Note the offset in the series for Inuvik (INVK), due to the addition of an antenna dome, and the significant seasonal variations in all the series. These estimates of vertical motion are broadly consistent with the ICE-5G model of glacial isostatic adjustment. Sites in Holman (HOLM) and Alert (ALRT) are co-located with tide gauges, as are others in Tuktoyaktuk, Qikiqtarjuaq, and Nain.

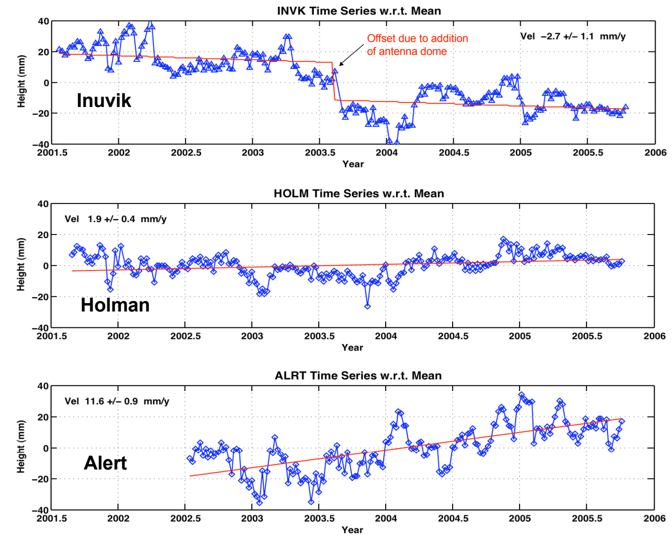


Preliminary velocity field for combined CGPS & EGPS network in Canada

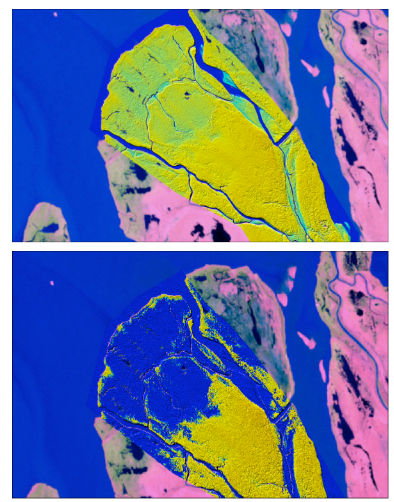


Additional EGPS Densification Sites

GPS TIME SERIES

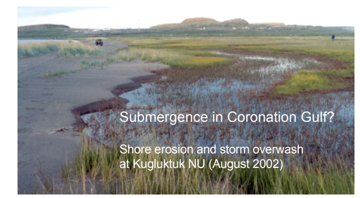


LiDAR SURVEYS OF MACKENZIE DELTA



LiDAR survey to simulate effects of subsidence in the outer delta.
Lower panel shows flooding to 1 m above MSL (upper panel). This could become the mean topography through a combination of regional and local subsidence.

COASTAL IMPACTS



In the western Arctic, geomorphic evidence of recent submergence is widespread. Diagnostic features include submerged ice-wedge polygon terrain, river-mouth estuarine embayments, prograded beach-ridge sequences rising seaward, and transgressive beach and barrier systems, among others. Combined with the geodetic data, these observations provide an opportunity to test model estimates of relative sea-level trends in the context of climate warming and regional sea-level rise over coming decades. Of particular interest is the transition zone between present submergence and emergence (as at Kugluktuk shown above), where accelerated sea-level rise may lead to expansion of the zone of submergence to include communities where relative sea level is stable or falling at present.

We are investigating additional sources of subsidence in the Mackenzie Delta, including sediment loading, compaction of unfrozen and discontinuously ice-bonded sediments, and anticipated subsidence resulting from future natural gas production. Further densification of the velocity field, including the addition of new sites in the delta (inset in lower map at left), and regular reoccupation of episodic sites will assist in determining local rates of motion. Strategies for discriminating the various components of subsidence in this large delta include GPS observations on monuments and borehole casing penetrating to various depths and supporting InSAR analysis and geological data. Coastal flooding hazards will be evaluated using digital elevation models derived from real-time kinematic GPS and airborne LiDAR surveys (digital elevation model at left).

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