Comparison of GRACE Monthly Estimates with Surface Gravity Variations at North American Sites

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OVERVIEW

GRACE monthly gravity estimates have been compared with surface gravity variations to examine similarities and differences in observed trends and seasonal variations. The ultimate aim is to detect changes in water storage at different spatial scales.

Two types of comparison are made:

1) Comparison of GRACE trends with trends from annual absolute gravity measurements at mid-continent North American sites where postglacial rebound dominates (Figure 1), and
2) Comparison of GRACE seasonal variations with superconducting gravimeter data and bi-monthly absolute gravity data at selected sites in western and eastern Canada (Figure 2).

Monthly GRACE gravity values were derived from the CSR-RL04 spherical harmonic monthly models for the period of April 2002 to June 2007 (Lower left panel).

Surface gravity observations for estimating long-term postglacial rebound trends have been carried out annually at mid-continent sites for well over a decade. The surface gravity values reported here are based on at least 24 hours of gravity observations using free-fall absolute gravimeters. Seasonal surface gravity variations are observed continuously by a superconducting gravimeter at the Canadian Absolute Gravity Site, Cantley, Quebec and by absolute gravity observations several times a year on southern Vancouver Island since 1995 (Lower middle panel).

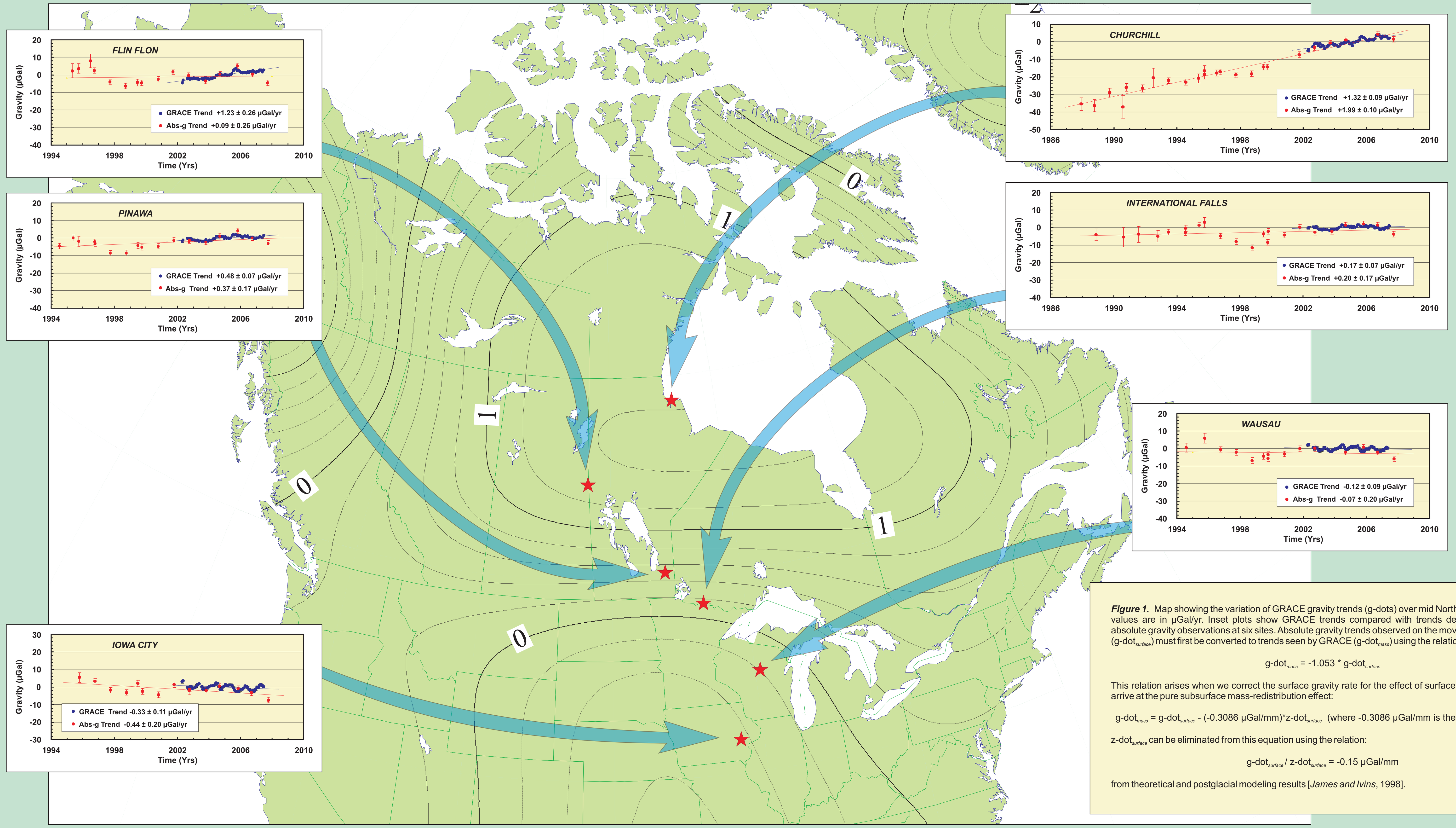


Figure 1. Map showing the variation of GRACE gravity trends (g-dots) over mid North America. Contour values are in µGal/yr. Inset plots show GRACE trends compared with trends derived from annual absolute gravity observations at six sites. Absolute gravity trends observed on the moving Earth's surface ($\text{g-dot}_{surface}$) must first be converted to trends seen by GRACE (g-dot_{mass}) using the relation:

$$\text{g-dot}_{mass} = -1.053 * \text{g-dot}_{surface}$$

This relation arises when we correct the surface gravity rate for the effect of surface vertical velocity to arrive at the pure subsurface mass-redistribution effect:

$$\text{g-dot}_{mass} = \text{g-dot}_{surface} - (-0.3086\ \mu\text{Gal/mm})*\text{z-dot}_{surface} \quad \text{(where } -0.3086\ \mu\text{Gal/mm is the free-air gradient)}$$

$\text{z-dot}_{surface}$ can be eliminated from this equation using the relation:

$$\text{g-dot}_{surface} / \text{z-dot}_{surface} = -0.15\ \mu\text{Gal/mm}$$

from theoretical and postglacial modeling results [*James and Ivins*, 1998].

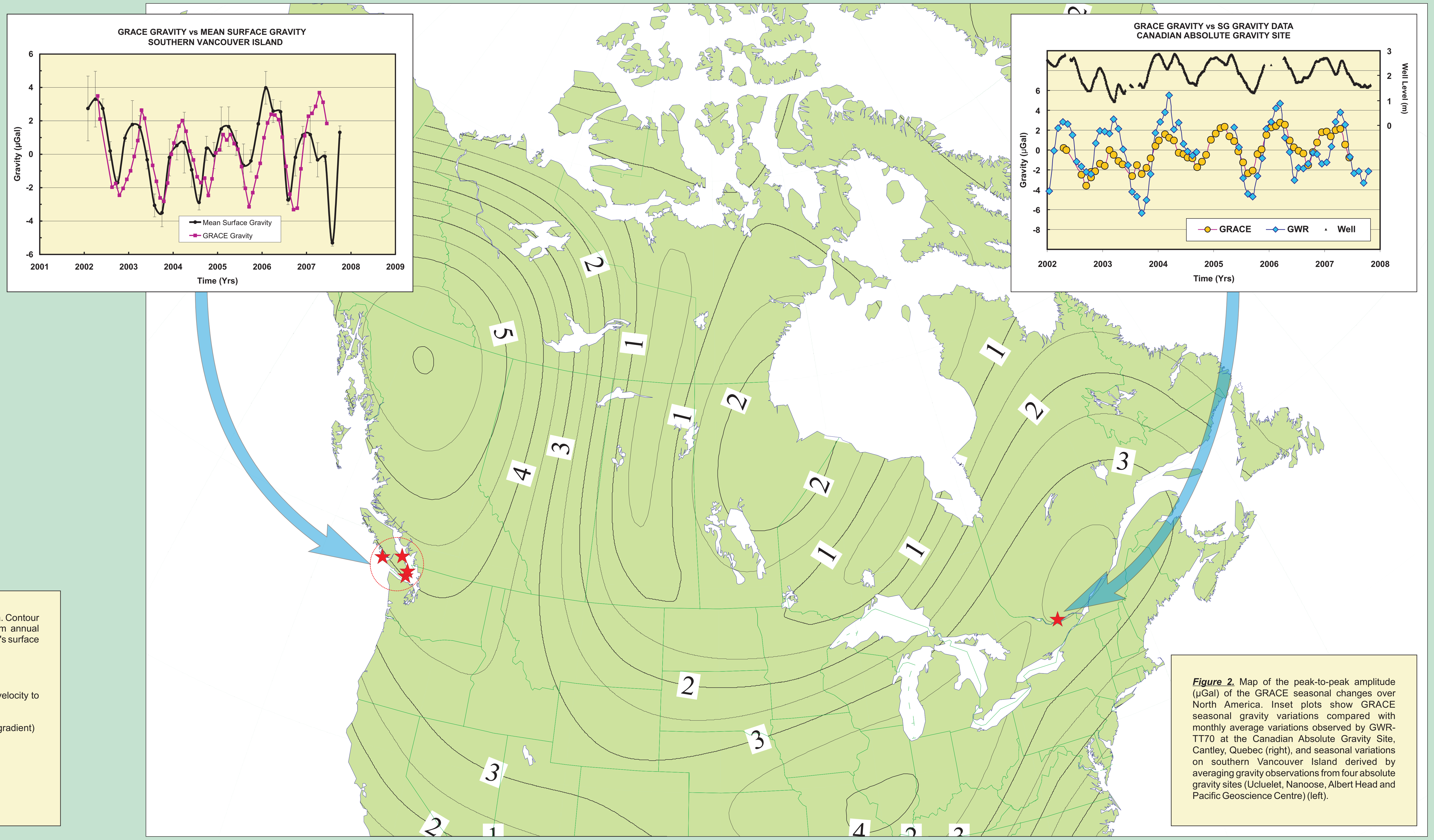


Figure 2. Map of the peak-to-peak amplitude (µGal) of the GRACE seasonal changes over North America. Inset plots show GRACE seasonal gravity variations compared with monthly average variations observed by GWR-TT70 at the Canadian Absolute Gravity Site, Cantley, Quebec (right), and seasonal variations on southern Vancouver Island derived by averaging gravity observations from four absolute gravity sites (Ucluelet, Nanoose, Albert Head and Pacific Geoscience Centre) (left).

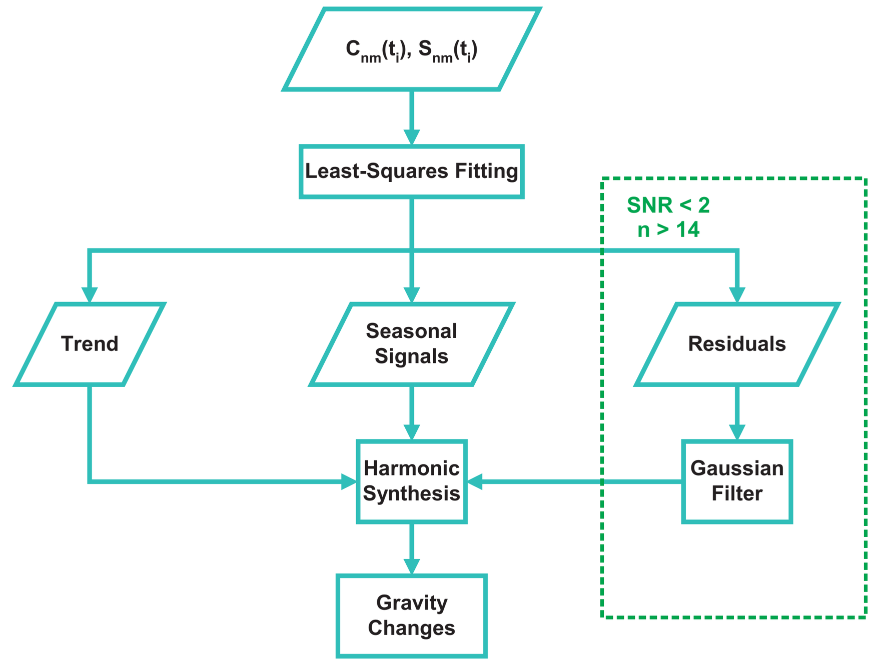
GRACE DATA PROCESSING

Fitting Model (7 unknowns):

$$\bar{C}_{nm}(t_i) = \bar{C}_{nm}(t_0) + v^C_{nm}(t_0)(t_i - t_0) + \frac{1}{2}a^C_{nm}(t_i - t_0)^2 + A^C_{nm}\cos(2\pi(t_i - t_0) + \phi^C_A) + B^C_{nm}\cos(4\pi(t_i - t_0) + \phi^C_S) + r^C_{nm} \qquad i = 1,2,\ldots n$$

The flowchart on the right side describes the procedure used to determine gravity change estimates from the monthly GRACE gravity models [*Tapley et al.*, 2004]. A least-squares model has been used to solve for linear and quadratic terms, and to solve for annual and semi-annual seasonal variation amplitudes and their respective phases. The standard deviations of the spherical harmonic coefficients are used to form initial diagonal covariance matrices for each coefficient time series. The estimated trend (linear & quadratic) and seasonal terms with *posteriori* signal-to-noise ratios greater than 2 and below spherical harmonic degree 15 are directly used to compute more robust gravity changes without further filtering. The omitted coefficients and the residuals are then used to compute the remaining gravity changes through the Gaussian filter [*Wahr et al.*, 1998] with a 450 km radius.

Analysis shows that the well-known GRACE striping pattern starts contaminating results above degree 14 without any filtering, even when the signal-to-noise ratio is greater than two. This observation corresponds to an RMS error-jump detected after degree 14. Of all terms, annual term is the strongest representing 58% of the total signal while the semi-annual term only accounts for 1%. The trend (linear & quadratic terms) constitutes about 10% of the total GRACE variation. Unmodeled residuals make up about 31% of the signal that needs to be further analysed and modeled.



SURFACE GRAVITY INSTRUMENTATION & DATA PROCESSING

Mid-continent gravity measurements

Absolute gravimeters:
- JILA2, JILA4 (1987-1992);
- FG5-102, FG5-111 (1993-2002)
- FG5-106 (1995-present) [*Faller et al.*, 1983; *Niebauer et al.*, 1995]

Seasonal gravity measurements

Canadian Absolute Gravity Site, Cantley, Quebec
- Absolute gravimeters: JILA2 and FG5-236
- Superconducting Gravimeter: GWR-TT70 [*Goodkind*, 1999; *Bower et al.*, 1991]

Vancouver Island
- Absolute gravimeter: FG5-106

Data processing

Absolute gravity and superconducting gravimeter (SG) data processing

Data corrections:
- solid earth tides
- ocean loading
- polar motion
- local atmospheric attraction and loading
- drift correction to the SG data based on absolute gravimeter calibrations

SUMMARY OF RESULTS

- GRACE and surface gravity trends at mid-continent North American sites are in good agreement except for Churchill and Flin Flon. The trend from surface measurements at Churchill is expected to be higher than the GRACE trend as a result of Hudson Bay outflow, which should reduce the GRACE trend and increase the surface gravity trend. Flin Flon is located in an area of high spatial variation in postglacial rebound [*Pagiatakis and Salib*, 2003]. Our GRACE processing may not yet have the spatial resolution required to resolve the trend at this site.

- Absolute gravity measurements at the mid-continent sites suggest the presence of inter-annual variations that have not yet been detected by GRACE. Future comparisons using a longer data set should indicate the spatial scale of the associated mass anomaly and the possible relationship to groundwater.

- Seasonal gravity variations observed by surface gravity measurements on southern Vancouver Island and by GRACE have similar amplitudes. The surface gravity, being more representative of the west coast rainforest climate, tends to rise sooner at the beginning of the wet season than the GRACE gravity which includes part of the drier continental interior.

- Seasonal variations observed at the Canadian Absolute Gravity Site (CAGS), Cantley, Quebec are similar in phase but significantly larger than those observed by GRACE. Both the surface gravimeter and GRACE broadly follow the variations in a collocated well. The correlation is not perfect as both gravity systems respond to snow in the winter which is not reflected in the well levels until it melts. A higher seasonal range in water mass than average might be expected for a hilltop site such as CAGS.

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