Spatial variation in Earth structure inferred by GNSS seasonal deformations due to snow loads

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Seasonal variations are observed in GNSS site coordinate time series (e.g., Murakami and Miyazaki, 2001; Munekane et al., 2004). Heki (2001) showed that snow loads cause seasonal subsidence in winter in the Tohoku region, northeast Japan from the Geospatial Information Authority of Japan's (GSI) GEONET GNSS daily site coordinates during the period 1999.0-2001.0. It becomes worth reevaluating this issue because the observed GNSS data are accumulated over 10 years and the amplitude of apparent seasonal components can be reduced with revised analysis strategies (e.g., Nakagawa et al., 2009). Here we show that the correlation between a seasonal variation and snow depth over 10 years is good in some areas with the largest snow depths among the study areas, the ratio of seasonal subsidence to snow depth shows spatial variation, and the variation can be explained by spatial variation of underground structure.
We obtain daily coordinate time series at GEONET sites in the Tohoku region by applying GIPSY-OASIS II software (version 6.3) (Zumberge et al., 1997) to observed phase data provided by GSI. A seasonal signal in vertical component for each year is estimated for each site. These seasonal signals are compared with daily snow depth measurements at AMeDAS sites. We use data at 135 GEONET sites and 102 AMeDAS sites in the Tohoku region during the period 1999.5-2009.5.
The Tohoku region is divided into a number of areas as large as 0.5 degree in latitude and 0.5 degree in longitude in order to find spatial variation in the correlation between the seasonal signal and the snow depth. We calculate an averaged seasonal signal for each area from the seasonal signals of individual GEONET sites in the area. Similarly, an averaged snow depths are calculated for each area. These averages are converted to time series of monthly values. We find a correlation coefficient larger than 0.6 on most areas with the maximum averaged snow depth > 150 cm. We estimate the ratio of seasonal subsidence to snow depth (defined as "the ratio b") from the monthly values on these areas. The ratio b of the range 0.021-0.053 mm/cm is obtained from five areas among eight areas where maximum snow depths are higher than 150 cm (three areas are eliminated because subsidence due to pumping of groundwater in winter is suggested).
For comparison with the observed ratio b, we compute the expected ratio b assuming the Gutenberg-Bullen A Earth model (Sato et al., 1968) with snow density of the range 0.2-0.5 g/cm^3 (Kawashima et al., 2007) using SPOTL (Agnew, 1996). In this case, the ratio b of the range 0.0083-0.021 mm/cm (defined as "b_basement") is expected. b_basement is smaller than the observed ratio b, indicating that the observed subsidence is larger than the calculated one assuming a global Earth model without a softer sediment layer.
Next we estimate the ratio b for a sedimentary basin because the study area includes Niigata basin where one of the thickest sediment layer is observed in Japan. Assuming averaged values of Vp, Vs, and for the Niigata sediment layer (Koketsu, 2008), Young's modulus of 7.2 GPa, and then the strain of 2.7-6.8e-7 are obtained under the same snow load as b_basement.. Assuming that deformation caused by snow load occurs in the sedimentary layer with the thickness of 8 km (J-SHIS, http://www.j-shis.bosai.go.jp), subsidence of 2.2-5.4 mm and the ratio b (b_sediment) of 0.022-0.054 mm/cm is expected. Although this estimation is very rough, the ratio b_sediment can explain the observed ratio b, which is larger than b_basement. Therefore, the spatial variation of the ratio b observed by GNSS can not be explained by the variation in snow density only, and an

additional amplifying factor, possibly an effect of softer sedimentary layer, must be required.
This study shows a possibility to be able to probe the spatial variation of the elastic response to snow loads with GNSS.

Keywords: Deformation by surface load, Seasonal variation in crustal deformation, Sedimentary layer