

Time-Variable Satellite Gravity Constraints on Snow-to-Groundwater Hydrological Memory Across Northern Hemisphere Basins.

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Seasonal snow represents a major temporary component of terrestrial water storage, yet the large-scale propagation of snow-mass anomalies into subsurface water storage remains poorly constrained. Here, we use monthly GRACE and GRACE Follow-On observations from 2003–2024 to investigate snow-water variability and its subsequent relationship with groundwater storage across ten major Northern Hemisphere basins. A mass-conserving disaggregation framework is applied to terrestrial water storage anomalies to derive GRACE-constrained snow water equivalent (SWE), supported by auxiliary hydrological and reanalysis datasets. Interannual SWE variability is examined using area-weighted empirical orthogonal function analysis and lagged correlation techniques. The first three modes explain approximately 45–60% of total interannual SWE variance. ENSO is significantly associated with the secondary SWE modes, with correlations of approximately $r = 0.4$ – 0.6 in selected regions and contributions of about 10–25% to regional SWE variance across western North America and parts of Central Asia. In contrast, NAO-related variability is more prominent across northern Europe, where it explains up to approximately 30% of regional variance. The analysis further examines the propagation of SWE anomalies into groundwater storage. Basin-dependent lag relationships reveal substantial regional differences in snow-to-groundwater memory, ranging from relatively rapid coupling to delayed responses over several months. Eurasian basins generally exhibit clearer delayed responses, whereas several high-latitude and permafrost-influenced basins show weaker or more complex coupling, suggesting a greater role of surface runoff and restricted subsurface transfer. These results demonstrate how time-variable satellite gravity, combined with complementary hydrological information, can provide a mass-based framework for tracing water-storage redistribution from seasonal snow accumulation to subsequent groundwater response. The approach highlights the potential of GRACE and GRACE-FO for investigating hydrological mass transport and large-scale terrestrial water-storage memory.

Keywords: GRACE/GRACE-FO; time-variable gravity; snow water equivalent; groundwater storage; hydrological memory; mass transport.

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