Supporting Information for "Monitoring terrestrial water storage, drought and seasonal changes in central Oklahoma with ambient seismic noise"

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Introduction

In this supporting document, we provide additional details on data processing and analysis to support discussions in the main text. Section S1 illustrates the dominant frequency ranges of raw data and the corresponding depth sensitivity kernels; Section S2 shows the decomposition of dv/v into long-term trends, seasonal cycling, and short-term perturbations; Section S3 examines the uncertainty of dv/v with respect to different azimuthal angles and frequency ranges; Section S4 compares observed dv/v with simulated soil moisture near the Earth's surface in Oklahoma.

Text S1. Frequency spectrum and depth sensitivity kernels

Investigating the probability power density function of raw data, we find the dominant frequencies of ambient noise in central Oklahoma range from 1 to 100s (Figure S1), which are similar to the general survey in North America (McNamara & Buland, 2004). Considering the depth sensitivity kernels of fundamental mode Rayleigh wave (Figure S2), we filter the raw data from 1 to 10s in order to investigate groundwater distribution at depths shallower than $1 - 2km$.

Text S2. Postprocessing of dv/v

The time series of dv/v can be decomposed into three components: long-term trend, seasonal cycling, and short-term perturbations (Figure S4). Applying a Gaussian filter, the high-frequency perturbations are removed from the raw dv/v. Based on the least-square regression, the long-term trend of dv/v can be expressed by a 20th-order polynomial. Finally, the seasonal cycling of the dv/v is the subtraction of the long-term trend from the smoothed dv/v.

Text S3. Uncertainty of dv/v

Daily CCFs have different behaviors within different frequency ranges (Figure S5). Except for 0.1-1.0 Hz, we filter the raw data with different frequency bands (0.5-2.0 Hz, 0.2-0.8 Hz, 0.4-1.6 Hz) and then to compute dv/v (Figure S6). In spite of local disagreements, the similarity among time series with different frequency bands suggests acceptable uncertainties of our measurements.

Although we assume a homogeneous velocity perturbation, the changes in ambient noise cross-correlation functions could also be generated by heterogeneous noise source distributions, such as periodic ocean tides (Ardhuin et al., 2011) and wind speeds (Young et al., 1994). Hence, we re-group the station pairs based on different azimuthal directions, i.e., 0 to 90°, 90 to 180°, 180 to 270°, 270 to 360°, respectively, in order to evaluate the changes of dv/v with respect to azimuthal angles (Figure S7). The similar patterns of long-term and seasonal cycling among these four groups suggest that our measured changes mainly result from subsurface velocity changes in Oklahoma, rather than the consequence of noise source variations.

Text S4. Soil Moisture Simulation

In order to further understand the seasonal cycling pattern, we also compare dv/v with modeled soil moisture storage (SMS) in central Oklahoma, collected from the North American Land Data Assimilation System (NLDAS-LSM) (Cosgrove et al., 2003; Mitchell et al., 2004). The spatial resolution of the SMS models is 0.125° in longitude and latitude, and their temporal sampling is one month. Three LSMs models (NOAH, MOSAIC, and VIC) are the simulations of water balance near the Earth's surface based on the accumulation of precipitation, surface/subsurface runoff, evapotranspiration, etc (Rui & Mocko, 2022). The MOSAIC model accounts for subgrid vegetation variability with a tile approach. Each tile has a predominant soil type and three discontinuities at $10cm$, $40cm$, and $200cm$ depths respectively. The first two layers are in the root zone. In the NOAH model, four soil layers are set with thicknesses of $10cm$, $30cm$, $60cm$, and $100cm$. The first three layers are from the root zone in non-forested region with the fourth in forested regions. The thicknesses of three layers in the VIC model are spatially variable. Therefore, the root zone in the model is determined by local vegetation types. The first two layers contain the energy-balanced snow model.

Since the NLDAS-LSM models give us results at different depths, in this study, we extract their temporal evolutions at depths ranging from 0 to 100 cm (Figure S8A). All SMS models show inter-annual cycling, which matches our dv/v measurements. Taking the NOAH model as an example, we also check its behavior at different depths (Figure S8B). Results from all depths have a similar intra-annual pattern with dv/v observations.

Other than groundwater storage, these comparisons suggest the sensitivity of dv/v with respect to soil moisture, especially for the inter-annual trend. However, these SMS simulations can only predict the distribution of soil moisture within hundreds of centimeters, while surface and coda waves used in this study might not sensitive to such shallow parts of the crust (Figure S2). More investigations are needed to better clarify the impact of soil moisture on near-surface seismic velocity.

References

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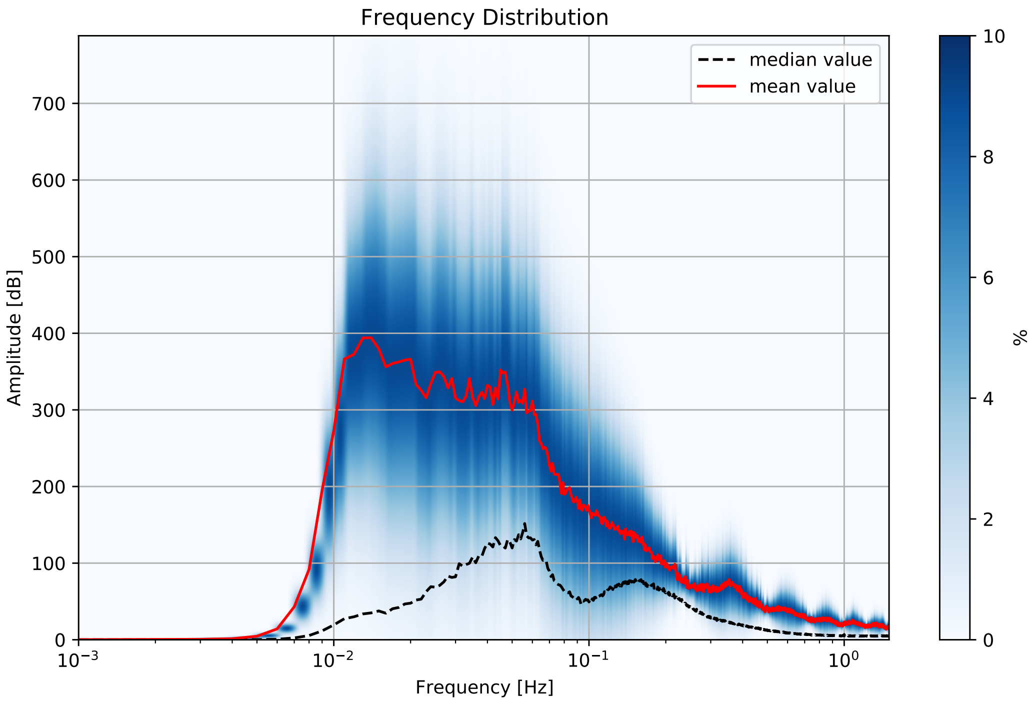

Figure S1. Probability distribution function (PDF) of the frequency spectra of all available seismic recordings in this study. The dominant period of ambient seismic noise ranges from 1 to 100s in central Oklahoma. Regarding the penetrating depths of surface waves, we filter the raw data into 1 to 10s.

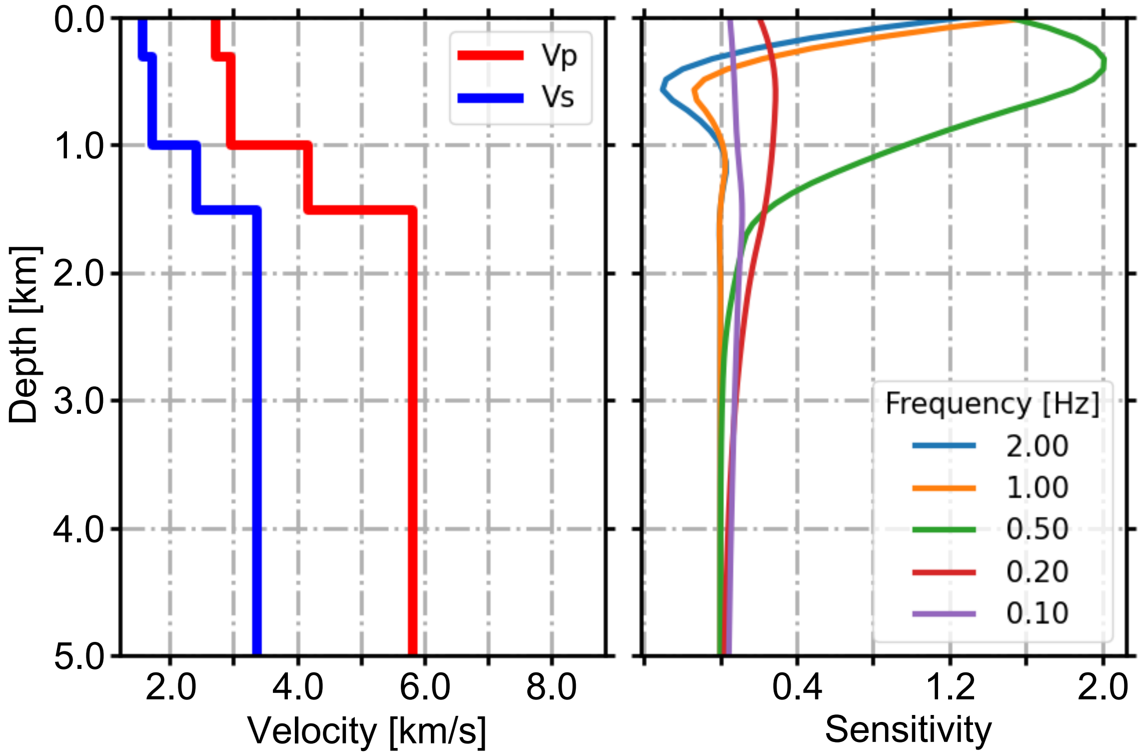

Figure S2. Depth sensitivity kernels of fundamental mode Rayleigh wave (right) based on the 1-D velocity model (left) provided by the Oklahoma Geological Survey. The Vp/Vs ratio is set as 1.732.

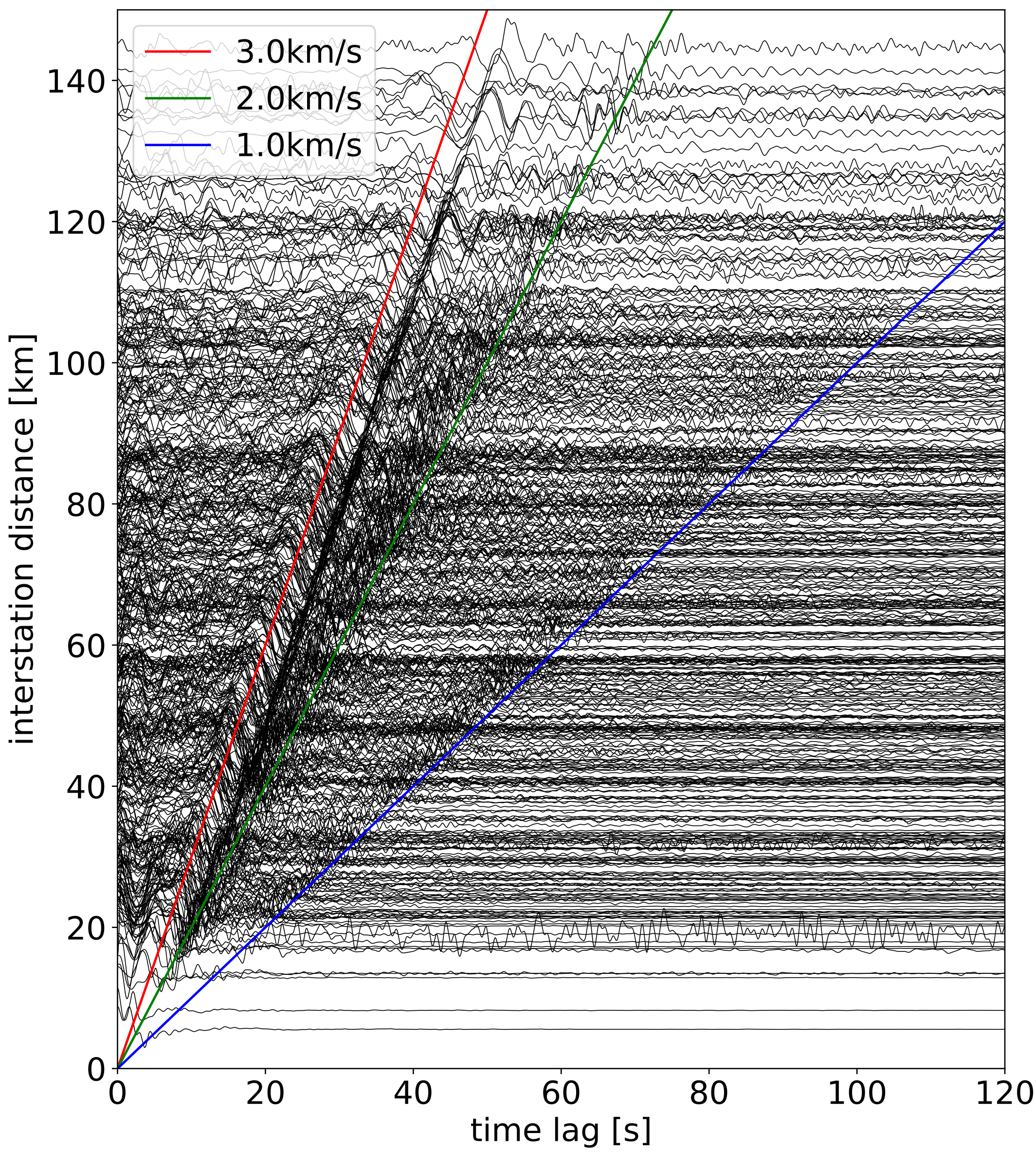

Figure S3. Reference cross-correlation functions of all station pairs, aligned as the function of inter-station distance. Contributions from surface and coda waves can be isolated by apparent velocities, $3.0km/s$ and $2.0km/s$, respectively

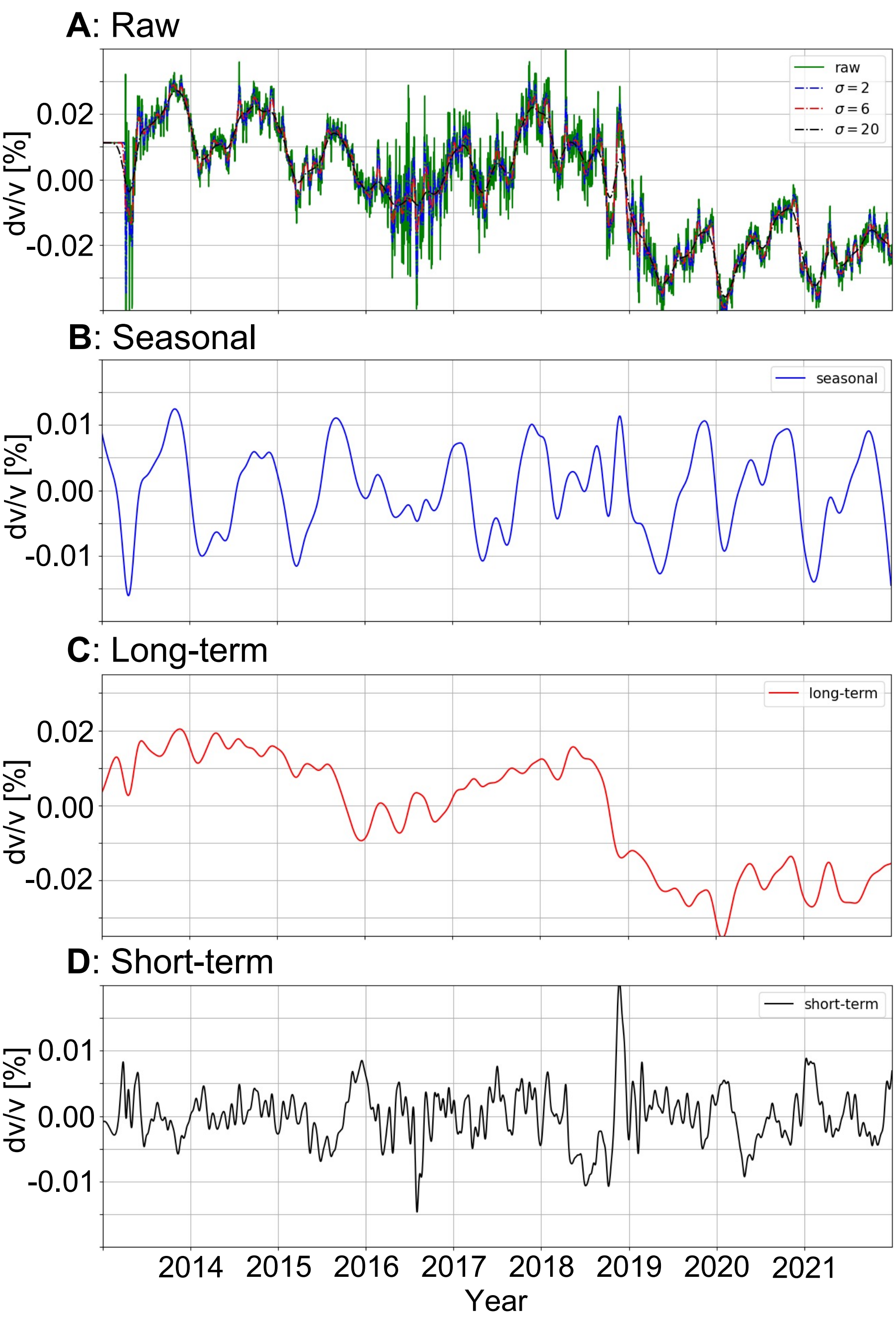

Figure S4. Decomposition of raw dv/v in central Oklahoma. The long-term trend (C) is fitted by a 20th-order polynomial by a least-square regression. Seasonal cycling (B) is the subtraction of the long-term trend (C) from the smoothed dv/v (A). Removing both long-term trends and seasonal cycling, the residual dv/v represents short-term perturbations (D).

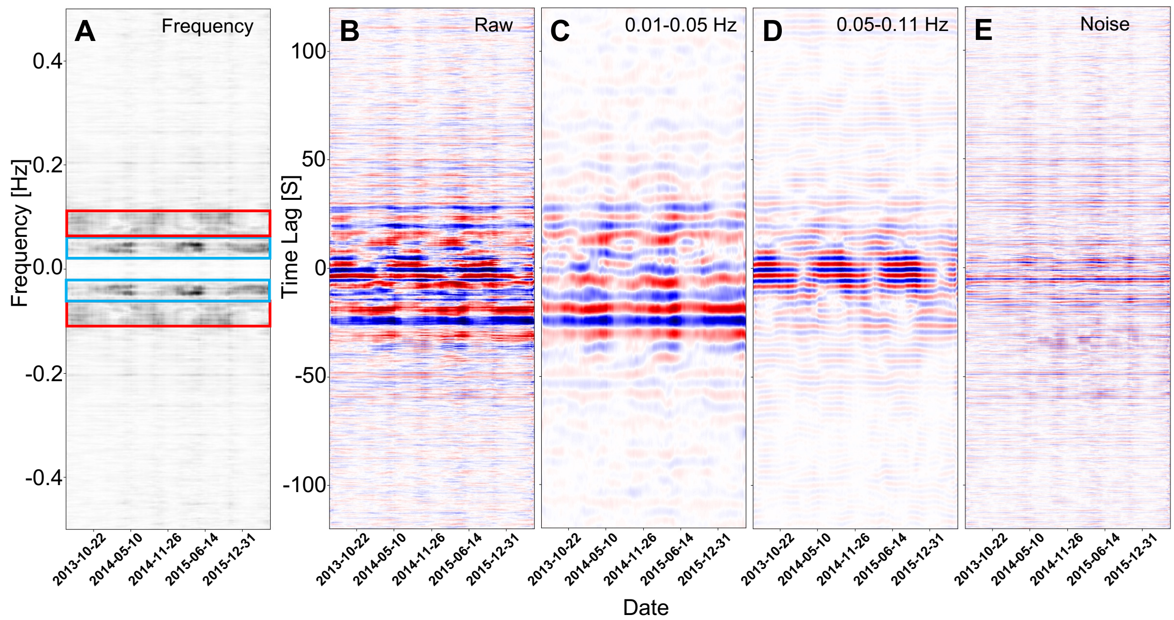

Figure S5. Taking station pair NX.STN03 and NX.STN32 as an example, different frequency ranges in daily cross-correlations give us different patterns.

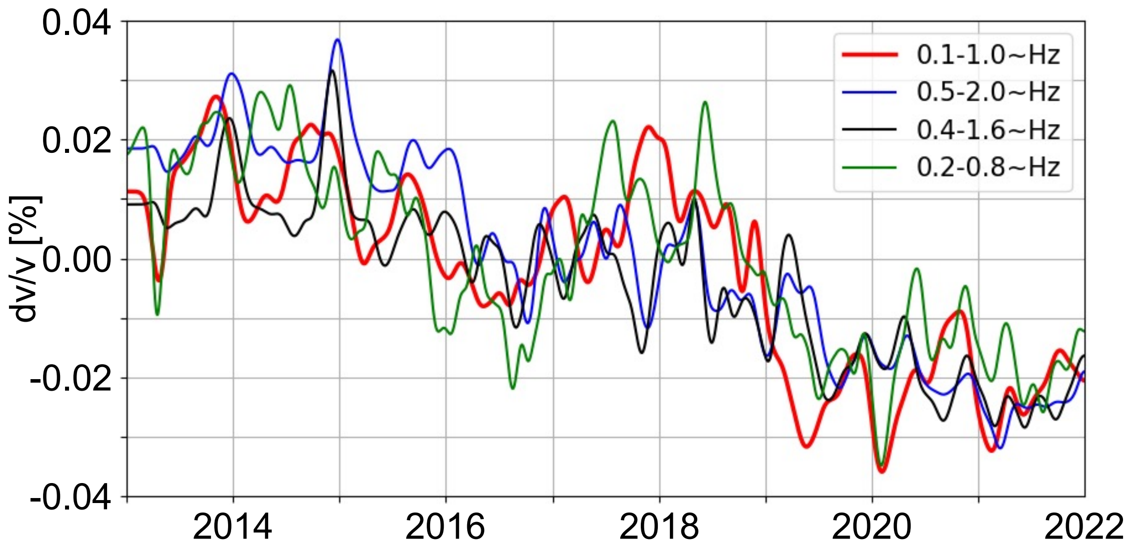

Figure S6. The similarity of dv/v with different frequency bands suggests acceptable uncertainty of seismic velocity with respect to the frequency band. As a comparison, the thick red line is the one used in the main text for discussion.

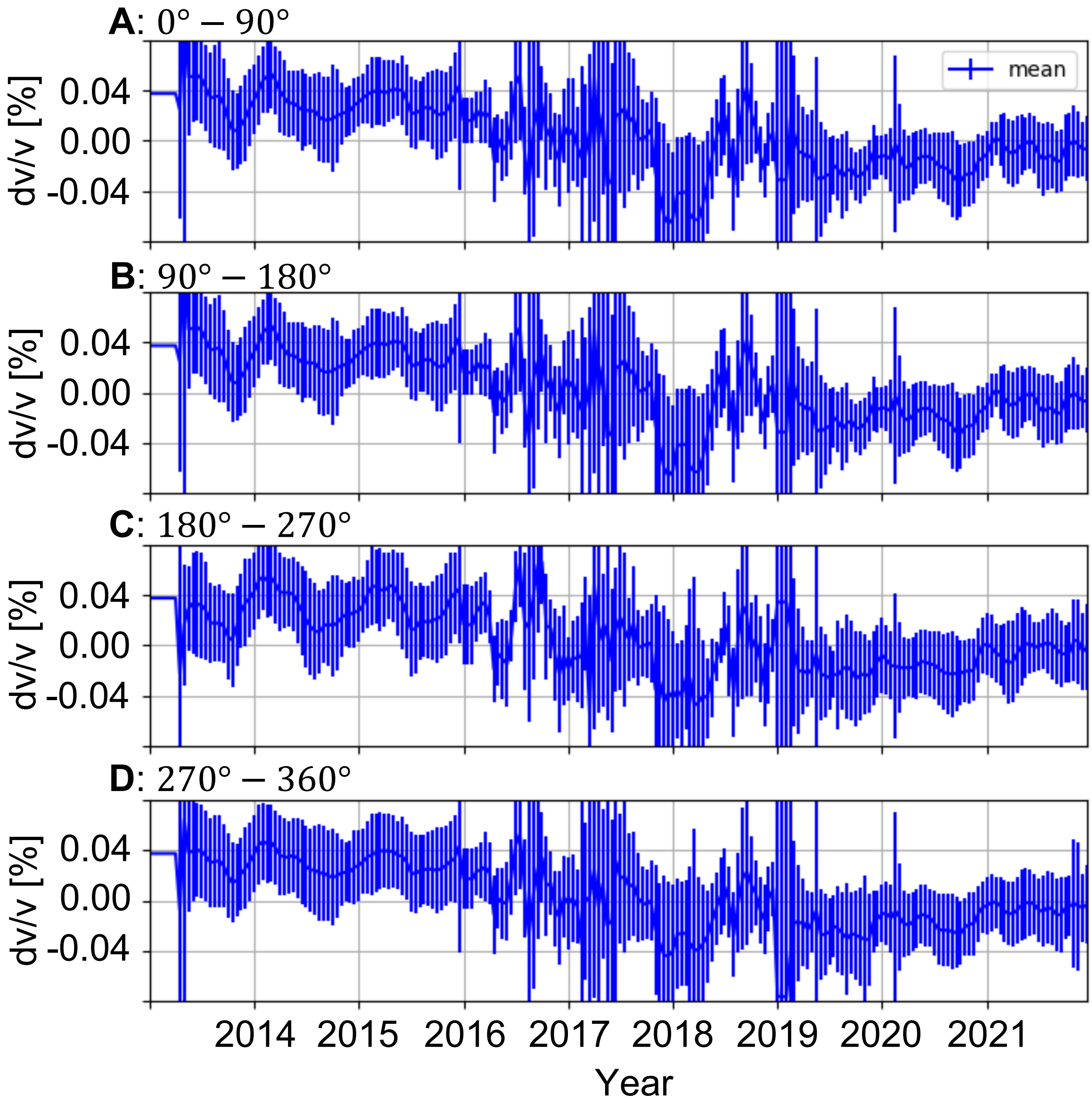

Figure S7. Uncertainty of dv/v with respect to different azimuthal angles. From top to bottom are the results with azimuthal angles of 0-90°, 90-180°, 180-270°, and 270-360°, respectively. Different azimuthal angles give us dv/v measurements with similar seasonal cycling and long-term trend.

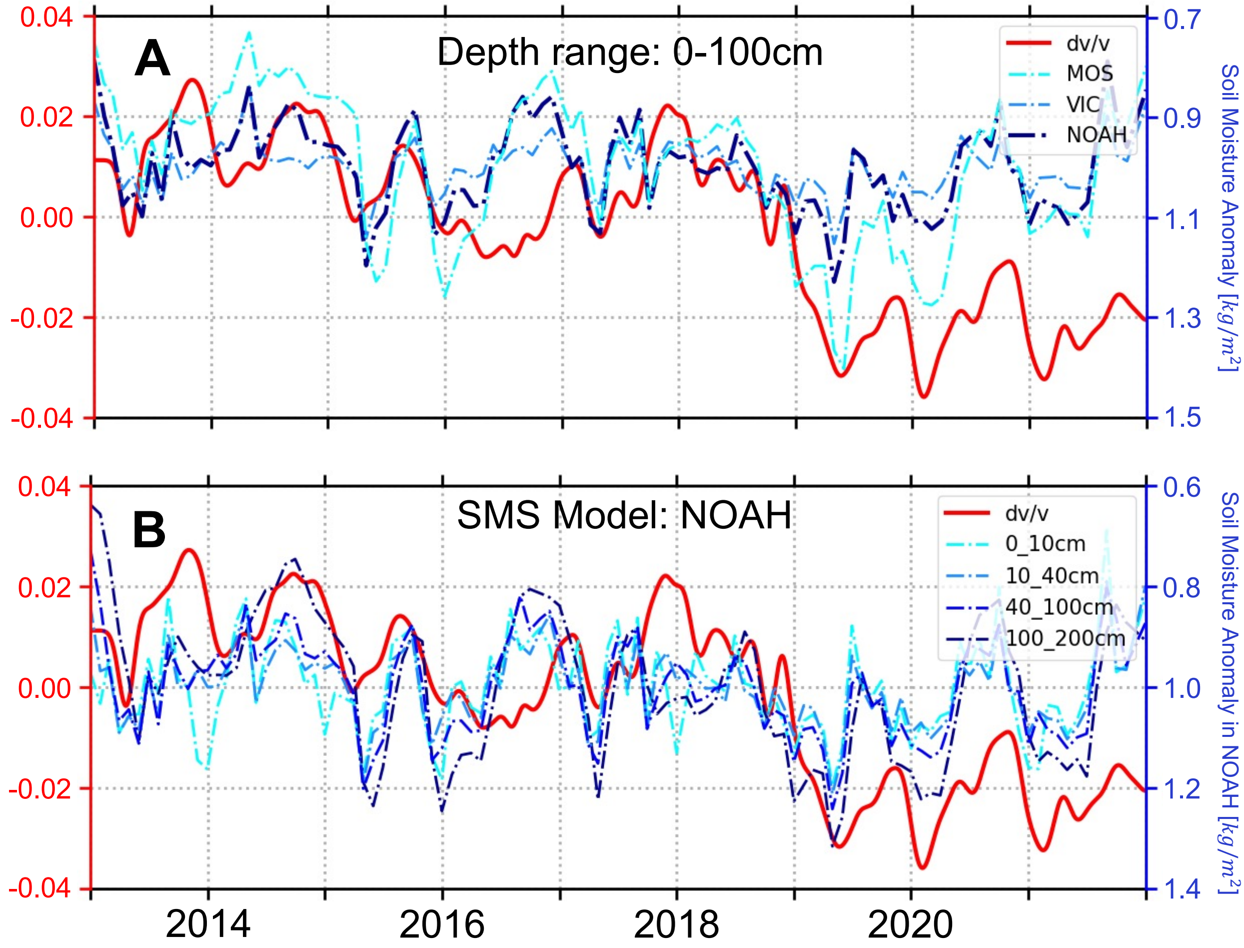

Figure S8. Comparison among dv/v and soil moisture simulations from different models. Panel A shows soil moisture simulations at $100cm$ depth from MOSAIC, VIC, and NOAH models. Panel B illustrates the results from model NOAH at different depths. All soil moisture simulations, with different depths and model settings, are consistent with the measured intra-annual cycling of dv/v.