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Analysis of the high-frequency noise field recorded by a vertical borehole array in Taiwan 2: Probing subsurface properties using the coda of ambient noise cross correlation

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We investigate changes of crustal properties by analyzing the coda of cross correlation functions of ambient seismic noise (C1) recorded by a vertical borehole array consisting of 7 sensors between 950 and 1280 m depth situated in the Chelungpu fault zone, Taiwan. It has become standard technique to exploit relative arrival times expressed in the coda of the C1 function; measuring changes using coda waveforms is superior compared to analyzing temporal changes of the direct arrivals due to the increased time delays accumulated by multiply scattered and hence longer travelling coda phases. We analyze noise in the frequency range between 1 and 5 Hz, which has been demonstrated to be of mainly anthropogenic origin. Standard processing (whitening, amplitude clipping) is applied to 2 years of daily segmented noise records, although the C1 functions are found to converge at sub-daily time scales. No errors due to malfunctioning clocks are detected, and no systematic differences have been observed by processing only day- or night-time data. We also find only a weak dependence of the spectral content of the C1 function on strong rainfall events. Hence, observed temporal changes in coda-phase travel times are unlikely to be artifacts associated with changes of the source or the corresponding spectral content. A stacked coherency function of all daily C1 functions reveals an overall linear decay with correlation lag time, with intermittent 'holes'; it suggests a time window between [-8 -3] and [3 8] seconds of the C1 coda suitable to be scrutinized for evidence of time delays. We analyze the coda of C1 functions obtained from all useful Z-Z, N-N, E-E correlation pairs to measure relative arrival time changes (dt/t), applying the stretching method and a time domain phase correlation technique. Both approaches are carried out using a constant and a moving reference stack, leading to 12 independent measures of temporal subsurface property changes; all stacks are improved by iteratively discarding traces with a low similarity to the resulting average. Two types of robust signals emerge in all measured dt/t functions. First, the low frequency component displays a distinguished seasonal variation over the course of the analysis period (2008-2009), with a stronger contrast during the first year. Time delays during the summer months are decreased with respect to winter months, i.e. relative wave speed is increased. Second, short-duration positive dt/t transients or decreased velocities are superimposed on the seasonal variations. All processing steps are repeated by analyzing the coda of the C3 function (correlation of C1 coda), which benefits from the sub-daily convergence of the C1 function, confirming the C1-obtained results. We assess physical mechanisms responsible for the observed signals considering meteorological and seismological explanations. Nearby measured atmospheric pressure and temperature profiles exhibit seasonal variations, whereas the short duration anomalies tend to coincide with rainfall events during monsoon season. No dataset explains a specific feature in every detail, which can partially be explained by the various smoothing operations applied before arriving at the final dt/t measures. Hence the resulting velocity changes are possibly caused by temperature induced thermal straining or differences in atmospheric pressure load modulated by variable subsurface fluid saturation and discharge properties. These hypotheses are tested using simple analytical models to obtain order-of-magnitude estimates associated with the individual contributions. Regional earthquake activity does not indicate a causative relation to the observed signals.