Wavelet methods for the analysis of GPS recordings of slow earthquakes

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November 23, 2022

Abstract

Slow-slip events were discovered in many subduction zones during the last two decades thanks to recordings of the displacement of Earth's surface by dense GPS networks. They can last from a few days to several years, and have a relatively short recurrence time (months to years), compared to the recurrence time of regular earthquakes (up to several hundreds of years), allowing scientists to observe and study many complete event cycles. Moreover, whereas regular earthquakes occur along the shallow part of the dipping plate boundary (in the seismogenic / locked zone), slow-slip events often occur on the plate boundary downdip of the locked zone. Slow-slip events could potentially trigger large earthquakes. This phenomenon provides a potential opportunity to further our understanding of subduction zone processes, and evaluate the time-varying seismic hazard. Wavelets methods such as the Discrete Wavelet Transform (DWT) and the Maximal Overlap Discrete Wavelet Transform (MODWT) are mathematical tools for analyzing time series simultaneously in the time and the frequency domain by observing how weighted averages of a time series vary from one averaging period to the next. In this study, we use wavelet methods to analyze GPS recordings of slow-slip events in New Zealand. An important application of the DWT and the MODWT is the estimation of a signal hidden by noise within an observed time series. We used synthetic time series with slow slip events of different durations, to which a Gaussian noise has been added, and denoised the signal using a wavelet-based method, and a low-pass filter. Although the signal was barely visible behind the noise, we could see a unique ramp-like signal in the data denoised with the wavelet-based method, whereas the low-pass filtered signal showed several ramp-like features which were not present in the original synthetic data. Eventually, we aim to be able to detect possible smaller (magnitude 5) slow-slip events that may be currently undetected with standard methods, detect longer (months to years) slow-slip events that are more difficult to detect than slow-slip events with a short duration (days to weeks), and determine the vertical displacement of the ground surface during a slow-slip event.

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Slow slip events

- Duration: Several days to several years.
- Generate much weaker seismic waves than ordinary earthquakes.
- Observed in many subduction zones, such as Cascadia, Nankai, Alaska, Costa Rica, Mexico, and New Zealand (Beroza and Ide, 2011 [3] ; Audet and Kim, 2016 [2]).

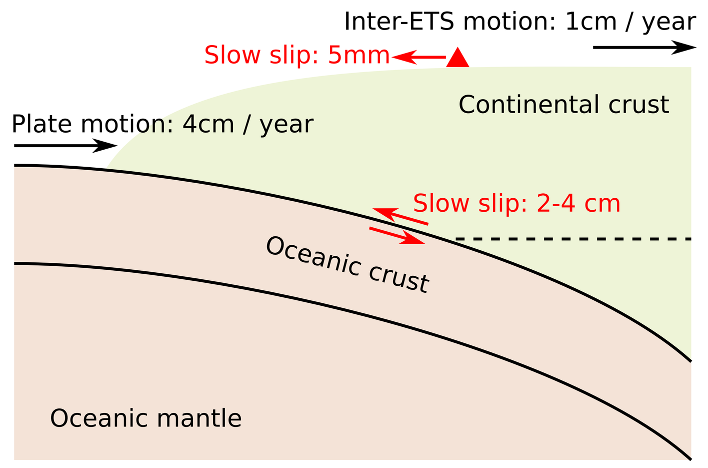

Figure 1: Slow slip event in northern Cascadia.

Wavelet decomposition

Maximal Overlap Discrete Wavelet Transform (MODWT):

X_t (length N) $\rightarrow$ J wavelet vectors $W_j \, (j = 1, ..., J)$ of length N $\rightarrow$ J details $D_j \, (j = 1, ..., J)$ of length N and one smooth S_J of length$N$.
$J =$ Level of the wavelet decomposition (Percival and Walden, 2000 [6]).
Detail D_j associated with changes on scale $\tau_j = dt2^{j-1}$, smooth S_J associated with averages in scale $\lambda_J = dt2^J$.

Multiresolution analysis (MRA): $X = \sum_{j=1}^{J} D_j + S_J$.

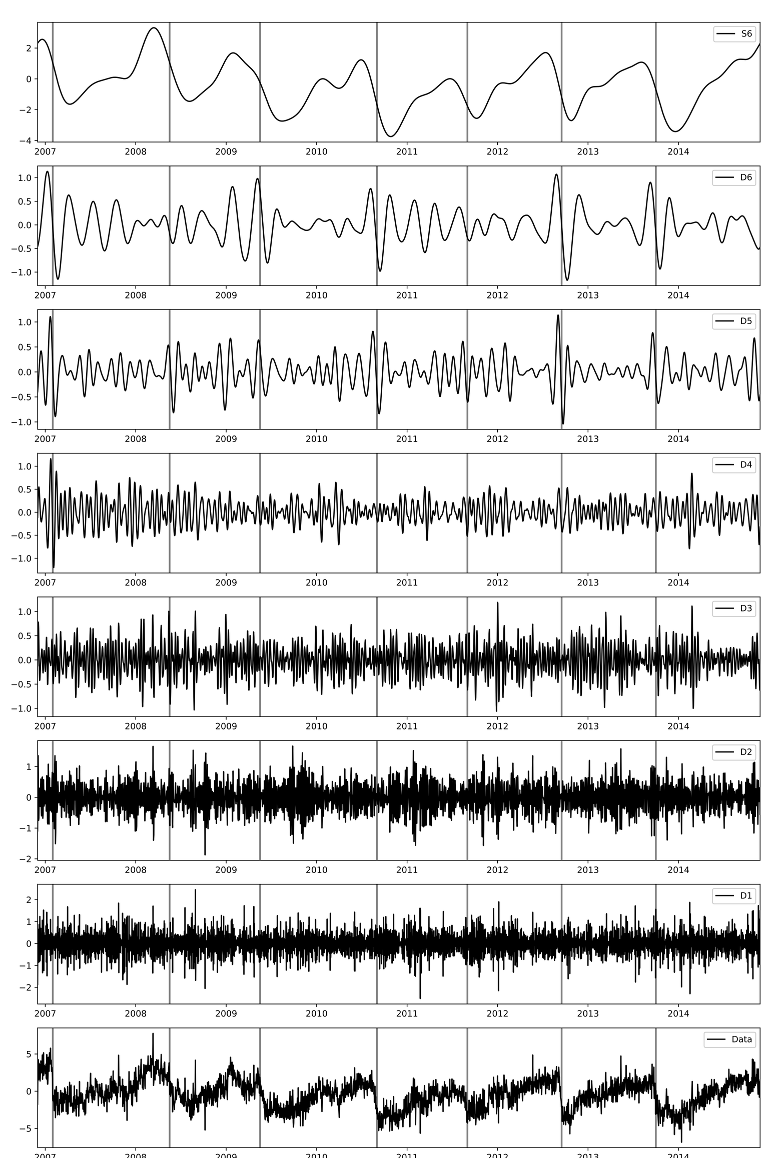

Figure 2: Example of wavelet decomposition. The bottom panel is the longitudinal component of the displacement recorded at GPS station PGC5, located on southern Vancouver Island, Canada. The data has been linearly detrended, and steps due to earthquakes or hardware upgrades, and annual and semi-annual sinusoids signals simultaneously have been estimated and removed following Szeliga *et al.* (2004 [8]). The middle six panels show the details of the decomposition at level 1 to 6 (corresponding to a time scale of 2, 4, 8, 16, 32, and 64 days). The top panel shows the 6th level smooth. Peaks corresponding to the August 2010, September 2012 and September 2013 Episodic Tremor and Slip (ETS) events can clearly be seen in both the 5th and the 6th level details.

Application: Denoising of GPS time series

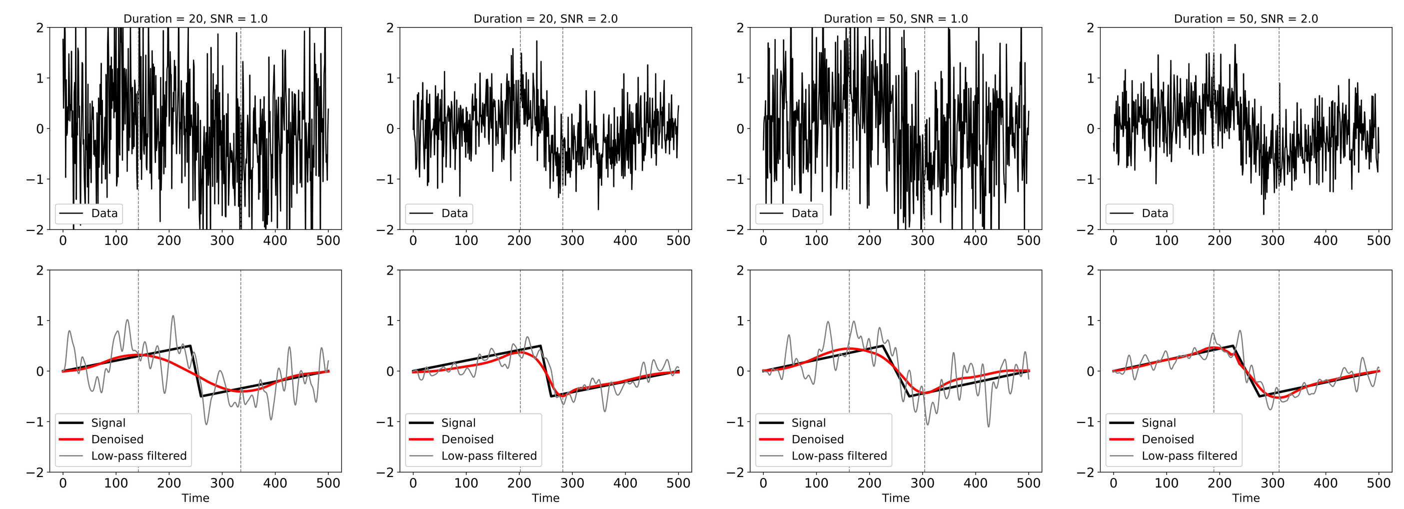

Figure 3: Denoising of synthetic time series using wavelets for two durations of the slow slip and two signal-to-noise ratios. The black line on the bottom panels is the signal. The black line on the top panels is the signal to which a Gaussian noise has been added. The red line on the bottom panels is the denoised signal obtained using thresholding of the wavelet vectors. The two vertical dashed lines show the time of the maxima and minima of the denoised signal. The grey line on the bottom panels is the signal obtained with a low-pass filter.

- **Application of MODWT:** Estimation of a signal hidden by noise within an observed time series.
- Main idea:
  - Compute wavelet coefficients W_j.
  - Thresholding, scaling, or shrinkage of the W_j $\rightarrow$ New wavelet coefficients W_0 (Percival and Walden, 2000 [6]).
  - Inverse wavelet transform of W_0 $\rightarrow$ Denoised signal.
- Example with synthetics (top figure).
- Example with GPS data (bottom figure).

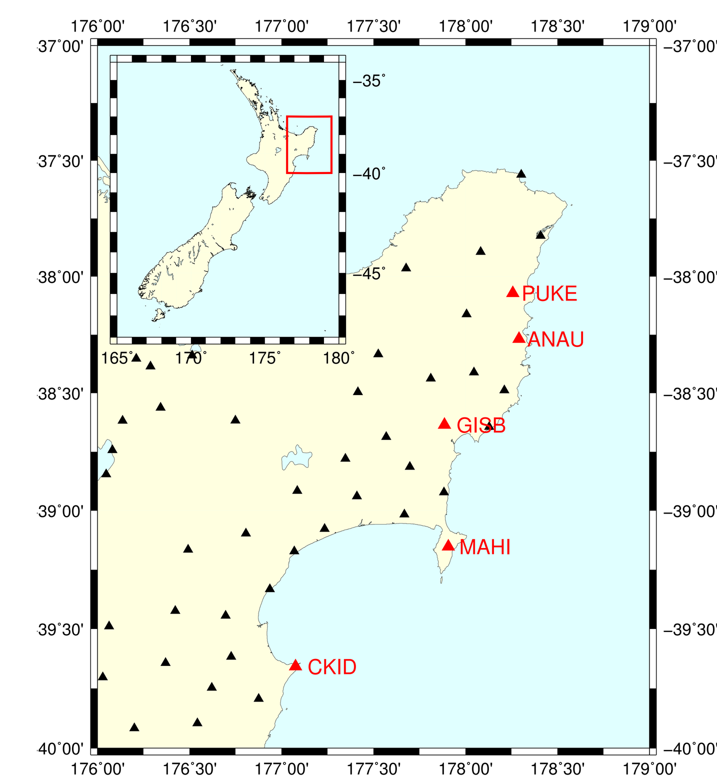

Figure 4: Map of GPS stations in northern New Zealand.

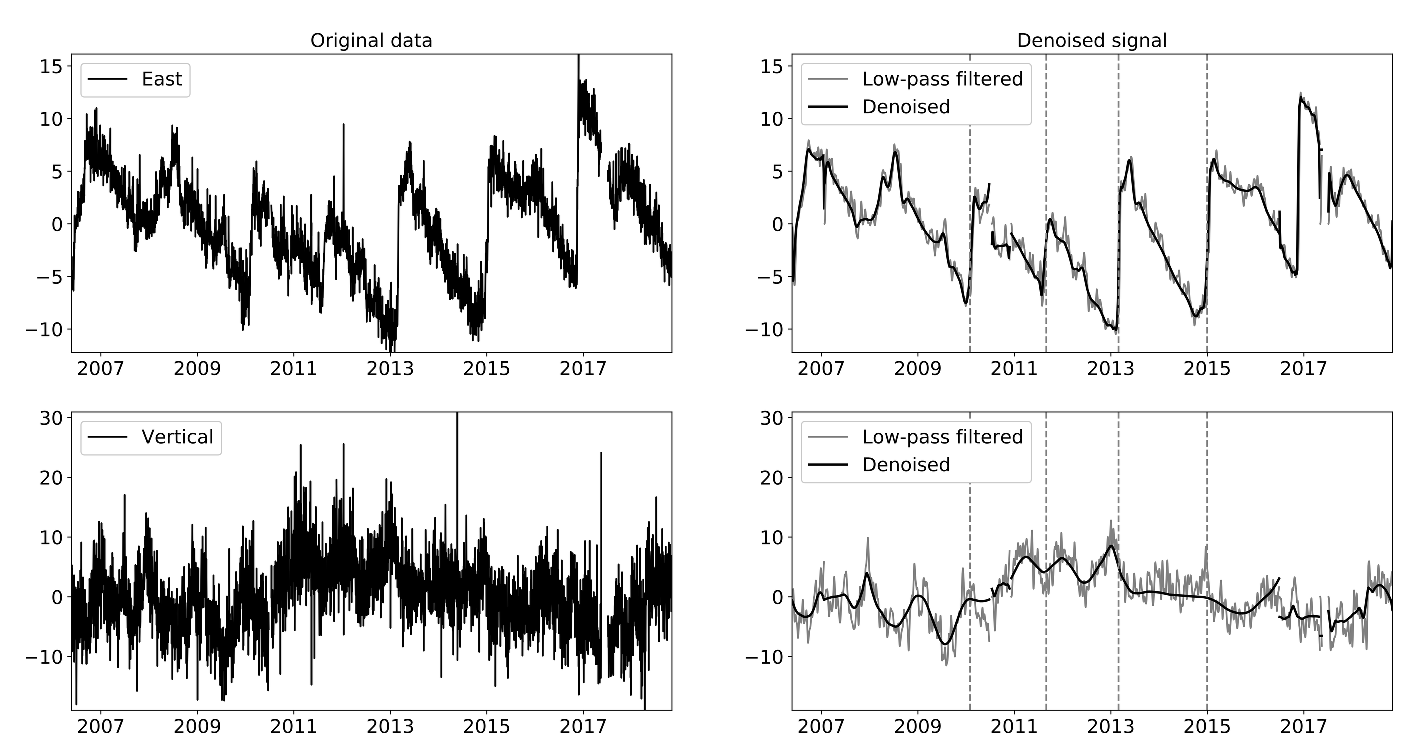

Figure 5: Original (left) and denoised (right) displacement observed at GPS station CKID for the eastern (top) and vertical (bottom) components. The black line on the right panels is the denoised signal obtained using thresholding of the wavelet vectors. The grey line on the right panels is the signal obtained with a low-pass filter. The vertical dashed lines indicate the timing of the slow slip events identified by Todd and Schwartz (2016 [10]).

Application: Detection of small slow slip events

- **Application of MODWT:** Detection of small slow slip events.
- Main idea:
  - Compute details D_j for 10 GPS stations.
  - Apply a time shift $t = s * latitude$ for different values of the slowness s.
  - Stack over the 10 GPS stations.
  - Plot amplitude of detail in function of time and slowness.
- Stacked 4th level detail.
- Sum of the stacked 4th, 5th and 6th level details.
- Tremor recorded in the vicinity of GPS stations.

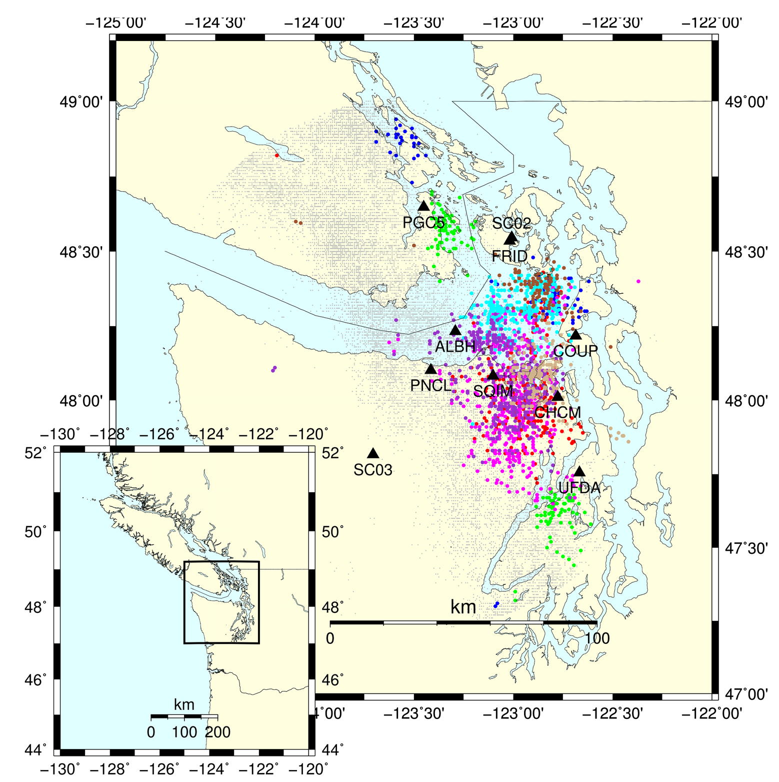

Figure 6: Map of GPS stations in northern Cascadia (black triangles). The dots are the tremor recorded around the stations during the period 2007-2012. The colored dots correspond to the eight tremor episodes emphasized in Figure 7.

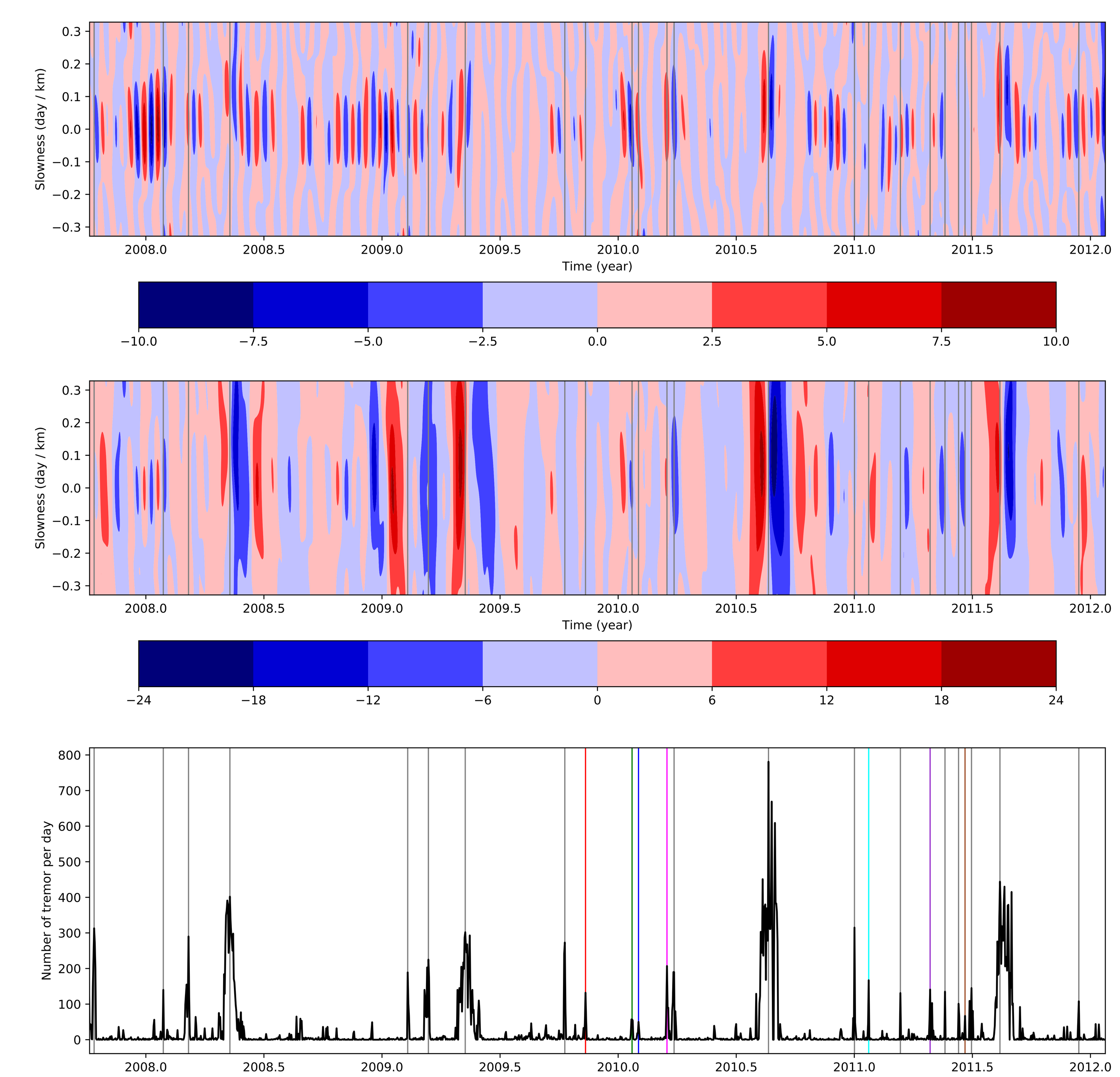

Figure 7: Stacking of the 4th level detail (top) and sum of the stacking of the 4th, 5th, and 6th level details (middle) of the wavelet decomposition of the longitudinal component of the displacement recorded at 10 GPS stations. A time shift corresponding to different values of the slowness of the propagation of the slow slip is applied before the stacking. The bottom panel represents the number of tremor recorded per day in the vicinity of the GPS stations. The colored vertical bars show the timing of the tremor from Figure 6. We can see an increase in amplitude of the 4th level detail corresponding to the tremor episodes recorded in January 21-23 2010, February 1-3 2010, and March 16-21 2010.

Summary

- Slow slip events can last from a few days to several years, and have a relatively short recurrence time (months to years), compared to the recurrence time of regular earthquakes.
- Wavelets methods are mathematical tools for analyzing time series simultaneously in the time and the frequency domain by observing how weighted averages of a time series vary from one averaging period to the next.
- Aim of the project: Use wavelet methods to analyze GPS recordings of slow slip events in New Zealand.
- Detect possible smaller (magnitude 5) slow slip events:
  - Nankai and Cascadia: Tectonic tremor observations spatially and temporally correlated with slow slip observations → Episodic Tremor and Slip (Obara, 2002 [5]; Rogers and Dragert, 2003 [7]).
  - Tremor can be used as a proxy to study slow slip events (Aguiar *et al.*, 2009 [1] ; Frank, 2016 [4]).
  - What can we do when there is no spatial / temporal correlation between tremor and slow slip?
- Determine the vertical displacement of the ground surface during a slow slip event:
  - Vertical component most useful in constraining the up-dip and down-dip extent of slip (Szeliga *et al.*, 2008 [9]).
  - Smaller than the horizontal displacement, and generally hard to resolve.

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Acknowledgements

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Paper number: S13F-0508

A.D. would like to thank Pr Donald Percival for introducing her to wavelet methods during his excellent class taught at University of Washington. This work was funded by the grant from the National Science Foundation EAR-1358512.