Climate modulated water storage, the deformation, and California earthquakes

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Seasonal Displacements
Vertical GPS Time Series

Seasonal modulation

Groundwater Extraction

Vertical rate map from Hammond et al., JGR-Solid Earth 2016
Periodicity in Seismicity Records

Evidence for Stress Modulation

Central Coast Ranges Seismicity
$M \geq 2.5$ Declustered and Detrended

Dutilleul, Johnson, Bürgmann, et al., JGR, 2015
Seasonal Loading and Coulomb Failure

Stress on faults 1-100 MPa (range of stress drop)

Tectonic Loading
5-50 kPa/yr loading rate

Seasonal Modulation
100 mm water load ≈ 1kPa
Evidence of Water/Snow Loading and Seismicity

Snow Loading in Japan

<10kPa Stress Change

Heki, 2003

Average Water Thickness in California

Argus et al., 2014
Elastic Load Model

- Effective Water Storage estimated from vertical GPS displacement
- GPS Stations in the Central Valley omitted
- Invert displacement for mass on surface and estimate water storage

Inversion following Argus et al., GRL, 2014 and Fu et al., JGR, 2015
Terrestrial Water Storage

Inverted using vertical GPS displacement following Argus et al. GRL 2014 & Fu et al. JGR 2015

Observed

Modeled

Residual

Johnson, Fu, and Bürgmann, Science, 2017
GRACE / GLDAS Comparison
- Gravity Measurements to Infer Water Storage
- Composite models
Deformation Modeling

• Linear Elastic
• Stress at 8 km Depth
• Rotate to Failure Plane
• Shear ($\sigma_S$) and Normal ($\sigma_N$)
• $\Delta$Coulomb = $\Delta\sigma_S + \mu \Delta\sigma_N$
• Seasonal stress on focal plane

2006-2015 declustered focal mechanisms
Percent excess $M \geq 2.0$ seismicity
Shear Stress Amplitude and Rate

Johnson, Fu, and Bürgmann, Science 2017
Are Other Loading Sources Contributing to Earthquake Modulation?

- Surface Water
- Atmosphere
- Temperature
- Ocean
- Non tidal Ocean
- Earth Body Tides
- Earth Pole Tides

Johnson, Fu, and Bürgmann, JGR 2017
What is the Largest Annual Load?

Table 1: Average Seasonal Peak-to-Peak Stress (Pa) With 1-Standard Error for Each Loading Source

<table>
<thead>
<tr>
<th>Loading source</th>
<th>Normal</th>
<th>Shear</th>
<th>Coulomb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere (annual)</td>
<td>760 ± 225</td>
<td>171 ± 144</td>
<td>371 ± 240</td>
</tr>
<tr>
<td>Earth body tide (annual)</td>
<td>2 ± 1</td>
<td>3 ± 1</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>Earth body tide (semiannual)</td>
<td>14 ± 12</td>
<td>16 ± 11</td>
<td>14 ± 10</td>
</tr>
<tr>
<td>Earth pole tide</td>
<td>125 ± 25</td>
<td>25 ± 10</td>
<td>53 ± 31</td>
</tr>
<tr>
<td>Nontidal ocean</td>
<td>44 ± 95</td>
<td>28 ± 58</td>
<td>22 ± 60</td>
</tr>
<tr>
<td>Ocean tide</td>
<td>4 ± 3</td>
<td>3 ± 2</td>
<td>4 ± 3</td>
</tr>
<tr>
<td>Temperature (annual)</td>
<td>474 ± 204</td>
<td>101 ± 69</td>
<td>133 ± 122</td>
</tr>
<tr>
<td>Hydrosphere</td>
<td>2,654 ± 2,764</td>
<td>1,052 ± 1,091</td>
<td>1,477 ± 1,370</td>
</tr>
</tbody>
</table>

Johnson, Fu, and Bürgmann, JGR, 2017
**Background Stress Orientation**

Invert using high quality focal mechanisms

No amplitude information

$S_{H\text{max}}$ Azimuth shown

Colored by Tensor Shape

Describes the Rupture Style

Project Seasonal Stress into Principal Orientations

Test for Excess Seismicity
Percent Excess Seismicity

2006-2014 declustered hypocentral seismicity
Principal components derived from focal mechanism inversion
Loading time series projected into ambient stress field
Earthquakes at each inversion point used in calculation
Fault unclamping indicates a correlation

Johnson, Fu, and Bürgmann, JGR 2017
Failure Mechanism

• Change in mean normal stress
  – Possible fluid interaction
1/ Is Seasonal Hydrological Loading Modulating Seismicity?

Are faults responding to stress perturbations with annual periods? Hydrological loading is a large contributing factor in the modulation of earthquakes from the annual stress cycles.

Is the crust critically stressed?
Excess seismicity from a 1-5 kPa

What is the failure mechanism for earthquake nucleation?
Positive correlation with peak stress amplitude suggests an instantaneous threshold failure stress. Positive correlation with peak stressing rate agrees with lab and model results.

2/ Are Other Natural Deformation Sources Contributing?

All natural loading cycles should be considered when analyzing seasonal stress cycles. Water is the largest.

Seismicity indicates more events when loading align with ambient background stress orientation.
Thank You

Questions?