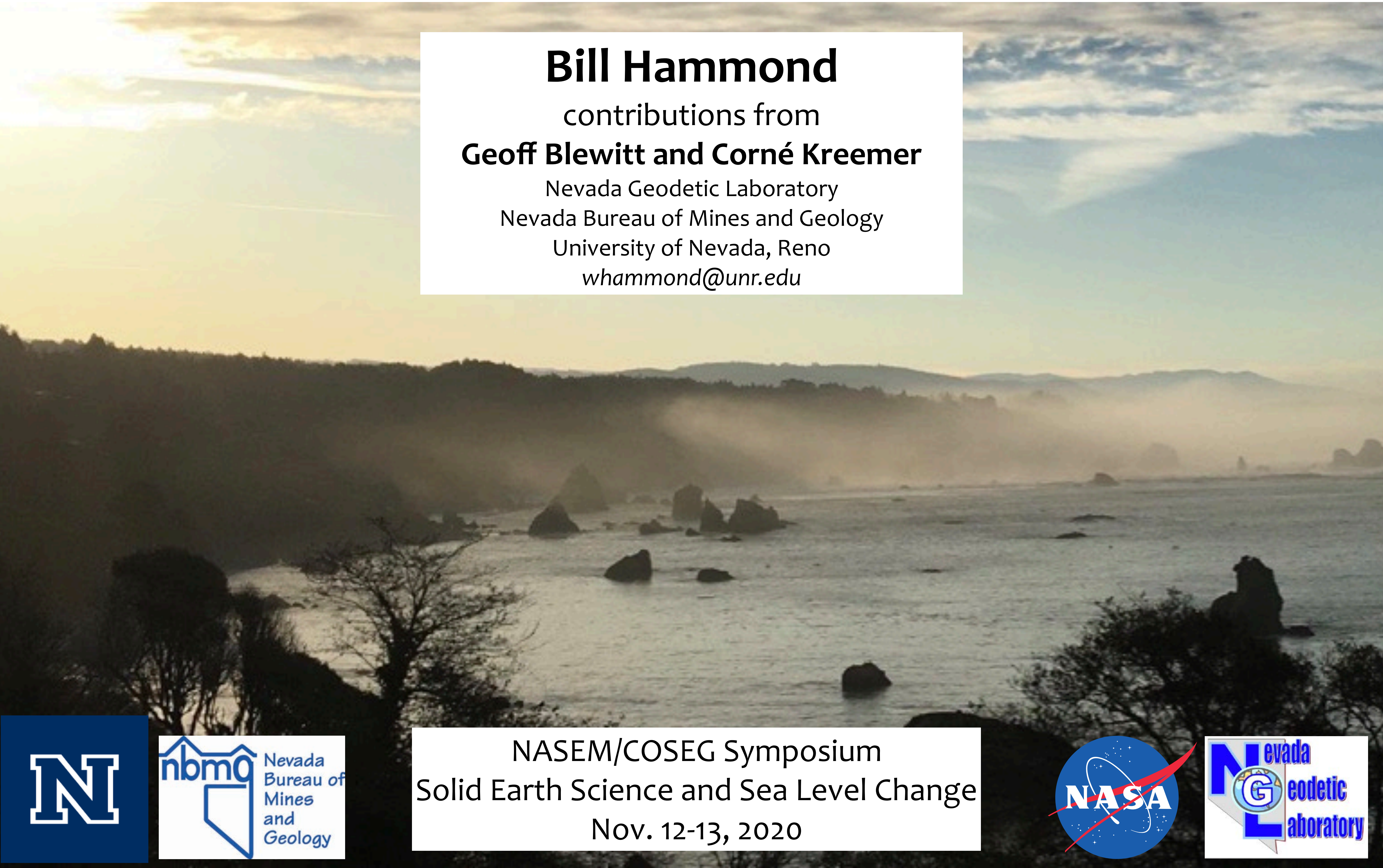
Using GPS Networks to Measure Global Vertical Land Motion and its Impact on Sea Level Rise



Bill Hammond

contributions from

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Solid Earth Science and Sea Level Change
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Nevada Bureau of Mines and Geology

Nevada Geodetic Laboratory

Vertical Land Motion: Why do we need to know it?

- **Impacts** of Sea Level Rise are driven by relative motion of the sea with respect to land. So we need to know the Vertical Land Motion (VLM), which directly influences impact.

- VLM is one of the fundamental observables, and is important for both global, regional and local studies.

- Help close the loop between geocentric measures of sea surface rise (e.g., altimetry) and near shore data such as tide gauges.

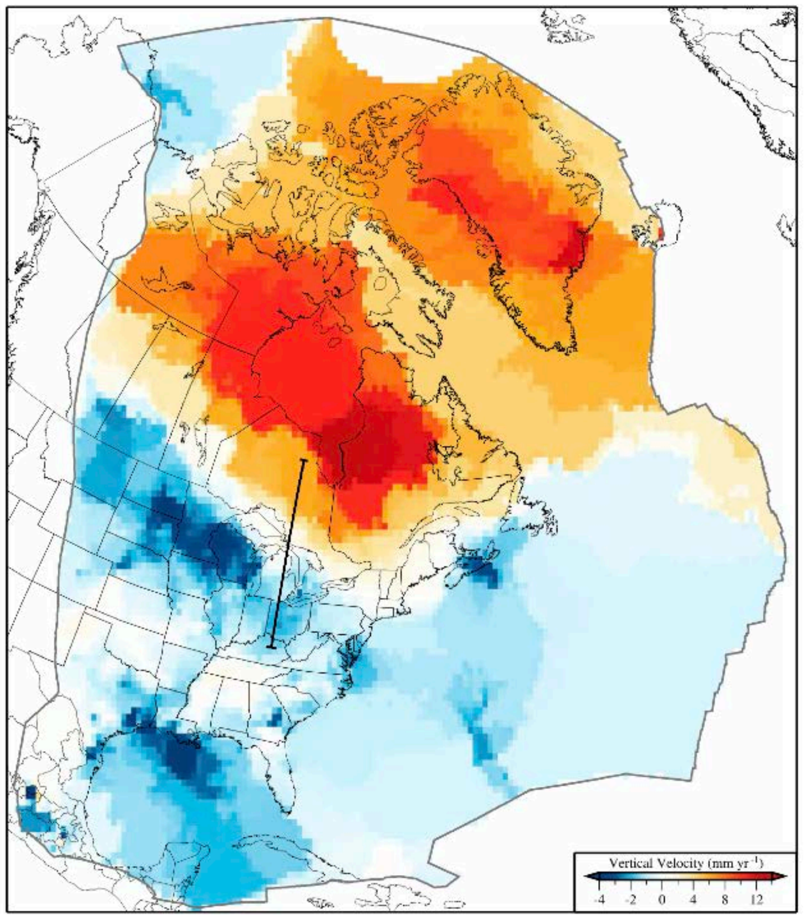
- GPS data constrain VLM near coast and inland. Important for process recognition. Where SLR is attributable to VLM, solid Earth dynamics can be the root cause.

- Solid (and partially solid) Earth VLM exhibits highly variable spatial and temporal scales

- Diversity of processes contribute to VLM.

Vertical Land Motion: Example Processes

GIA
(long term >10^4 yrs)

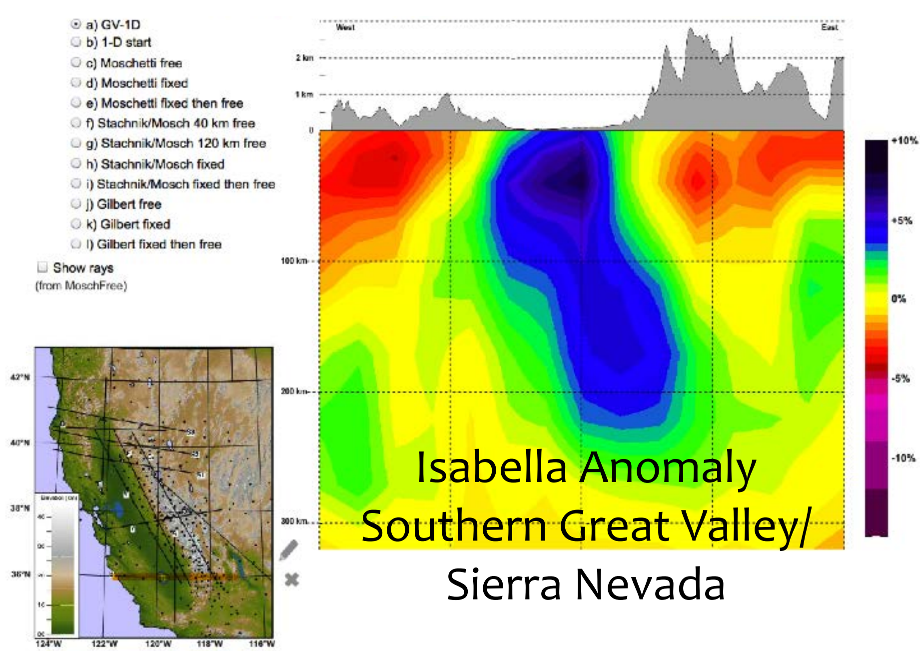


Kreemer et al, 2018 *JGR*

Mantle Flow/ Dynamic Topography
(long term >10^6 yrs)

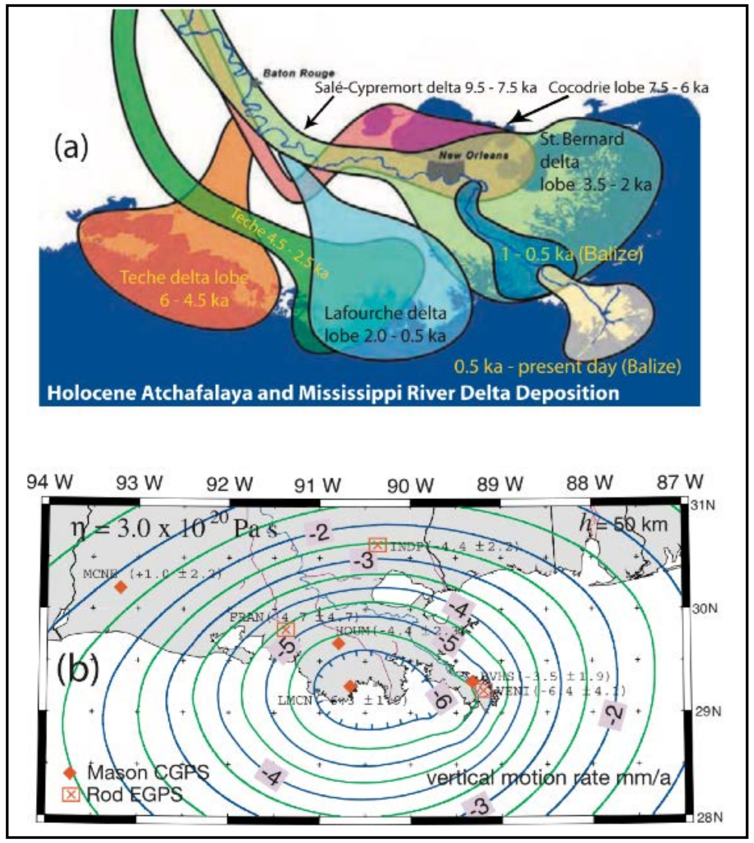
e.g. slabs, drips, delaminations, plumes, super plumes, rolls, channel flow

Not static, but *changing* part



Jones et al., 2014 *Geosphere*

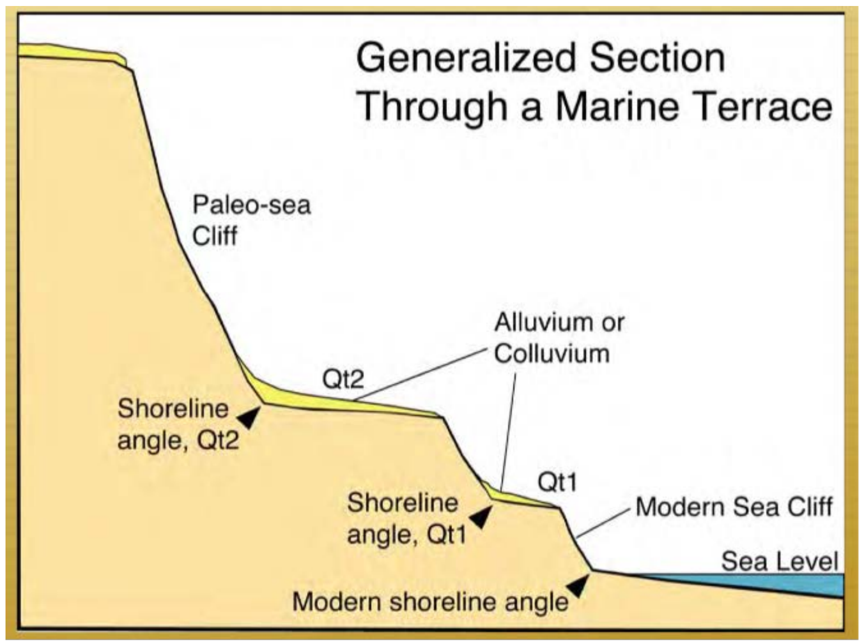
Sediment Loading
(long term >10^{4+} yrs)

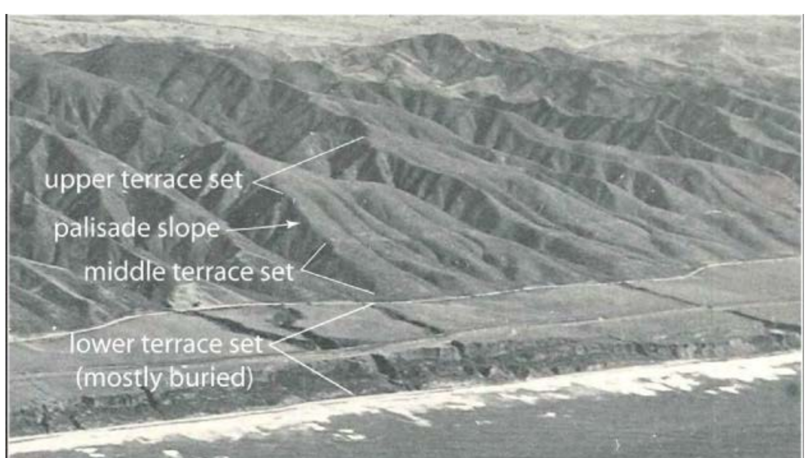


Ivins et al, 2007 *GRL*

Vertical Land Motion: Example Processes

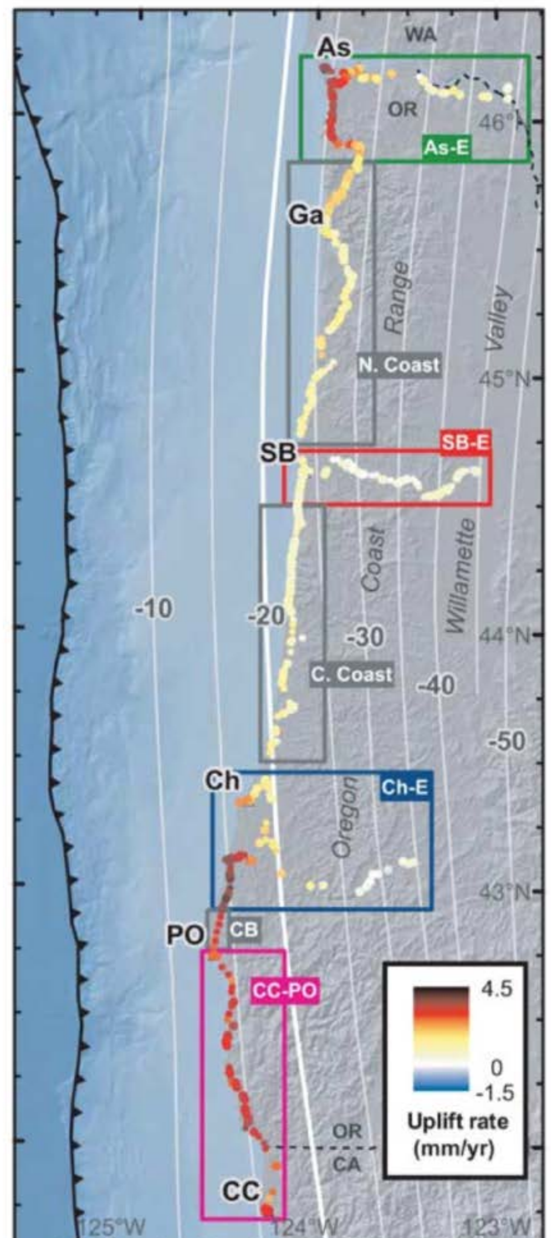
Tectonics Long Term
(longest term >10^6 yrs)





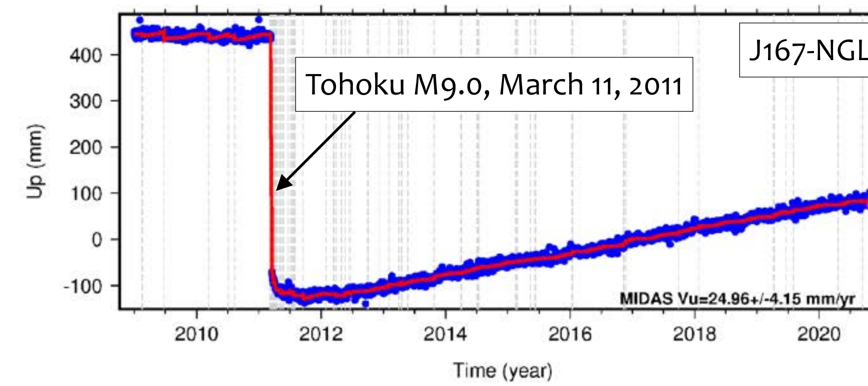
Rockwell 2013 *SONGS SSHAC Talk*

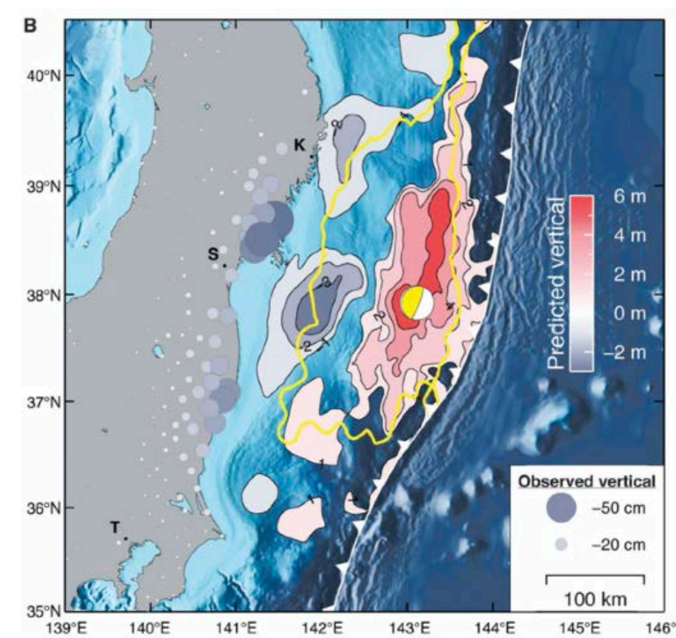
Tectonics Interseismic
(medium term 10^2-10^4 yrs)



Burgette et al, 2009 *JGR*

Tectonics Coseismic
(very short term 1s to 10 min.)



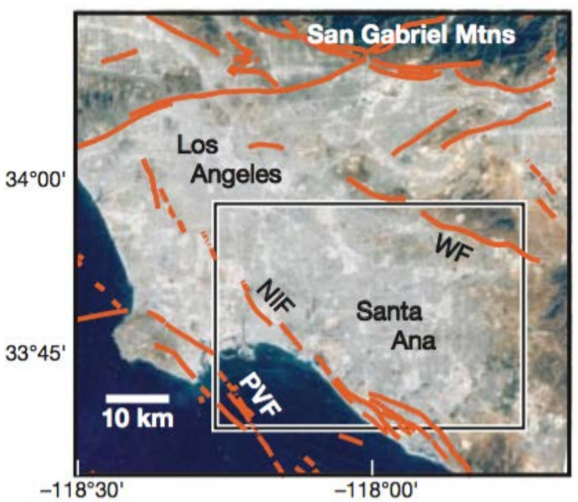


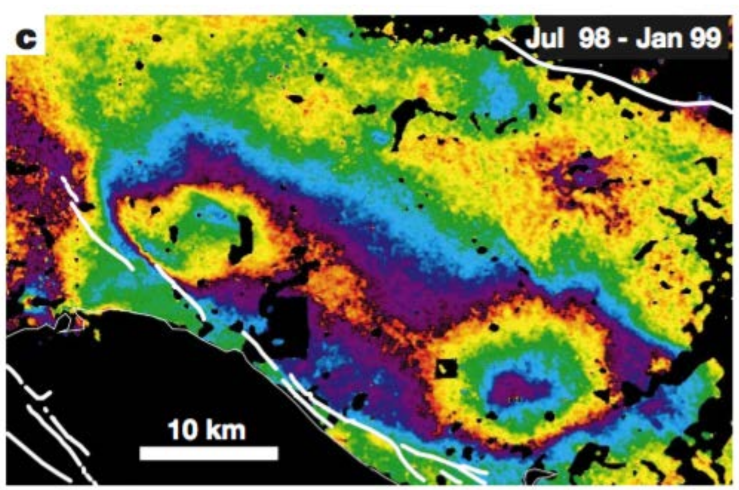
Simons et al, 2011 *Science*

Vertical Land Motion: Example Processes

Groundwater Pumping/Recharge

(often anthropogenic)
(short term 0.1-10 yrs)

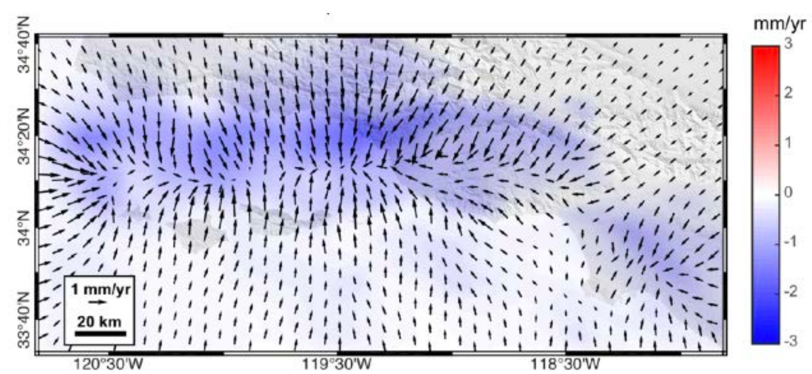


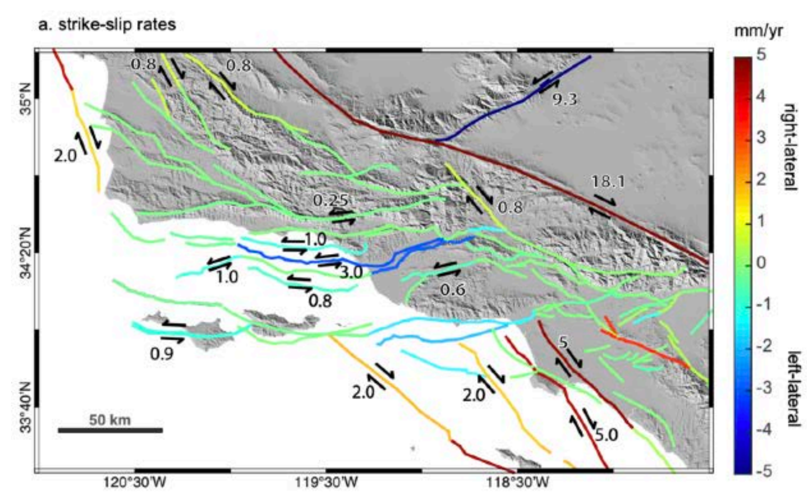


Bawden et al, 2001 *Nature*

Sediment Compaction

(sometimes anthropogenic)
(short to long term)

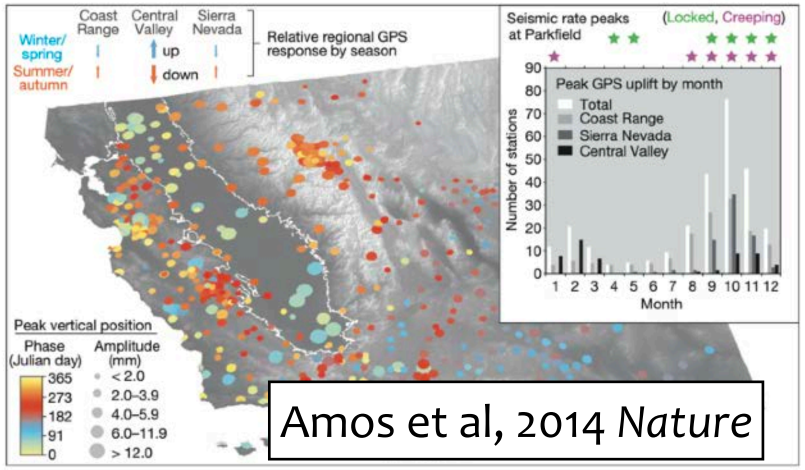




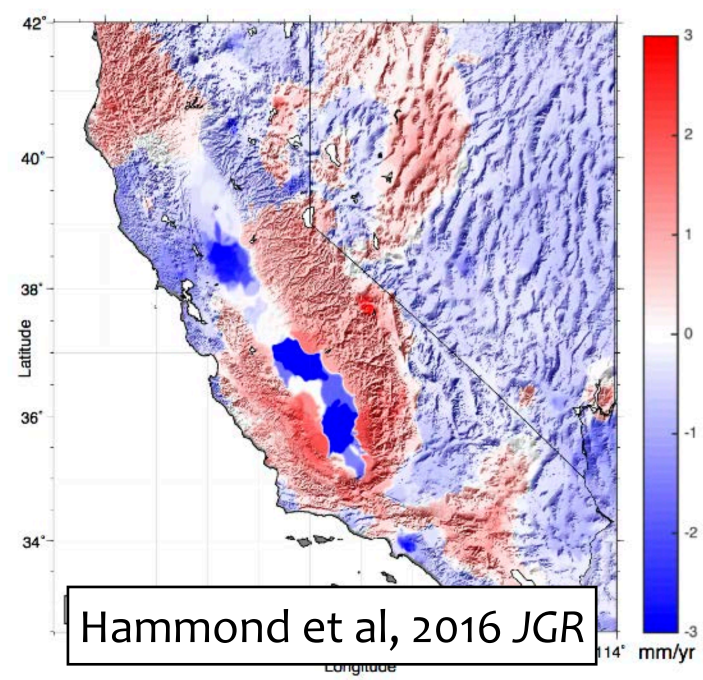
Johnson et al, 2020 *JGR*

Climate Change/ Hydrological Loading

(sometimes anthropogenic)
(short term, storm - 10 yrs)



Amos et al, 2014 *Nature*



Hammond et al, 2016 *JGR*

Vertical Land Motion: GNSS Data

- Regardless of the process we can measure VLM with GNSS
- Very high positioning accuracy and precision in global reference frame (<1 mm each day)
- ITRF2014 reference frame has origin aligned to Earth center of mass with drift within ~0.2 mm/yr (Altamimi et al., 2016)
- But requires a permanent ground station to collect data
- And that stations is preferably in a place whose movement is representative of a large volume of Earth's crust.

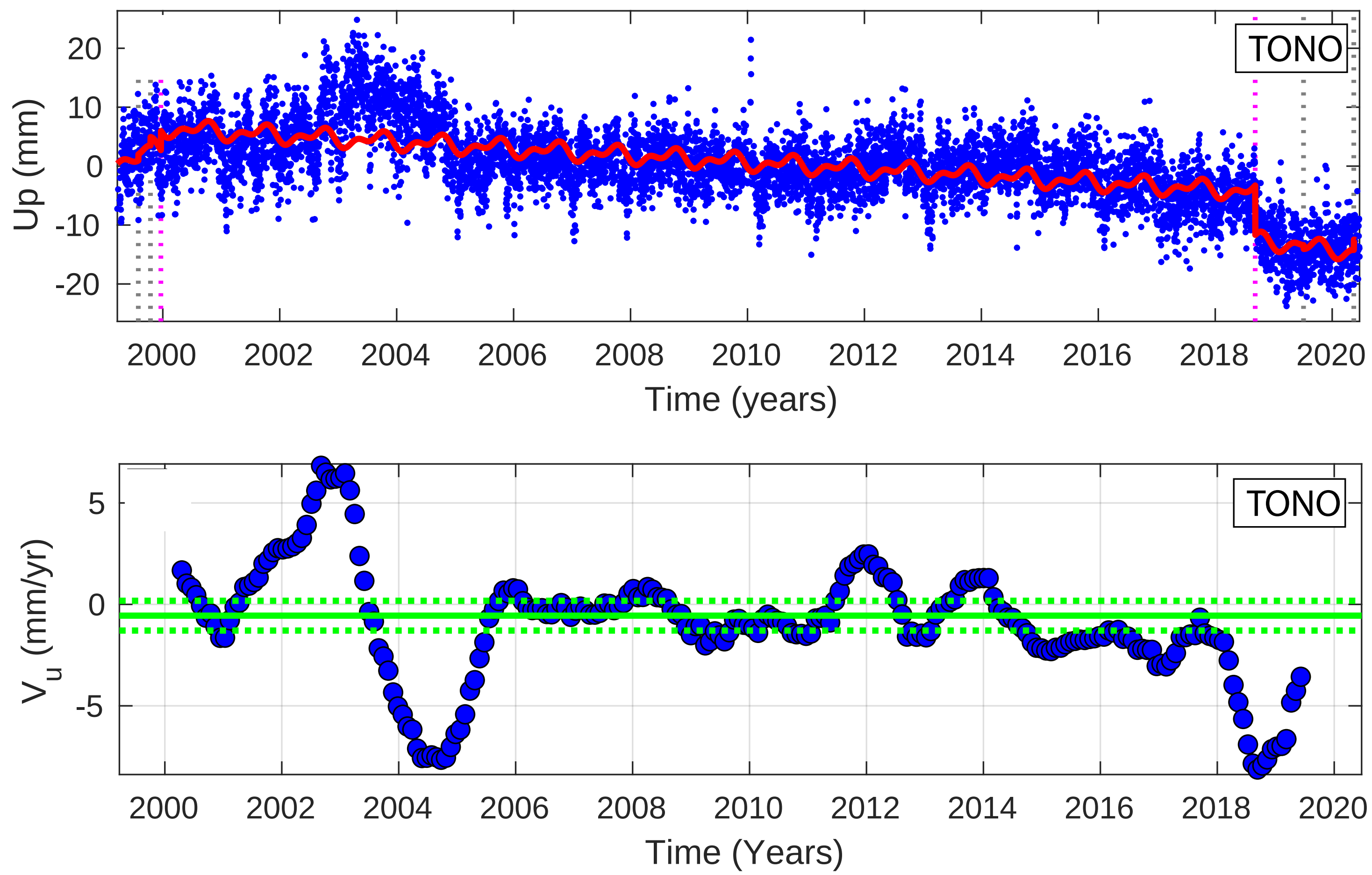
P534 - NSF NOTA station north of Santa Cruz, CA
Pacific Ocean in background

Station operated by UNAVCO

Vertical Land Motion: GNSS Data

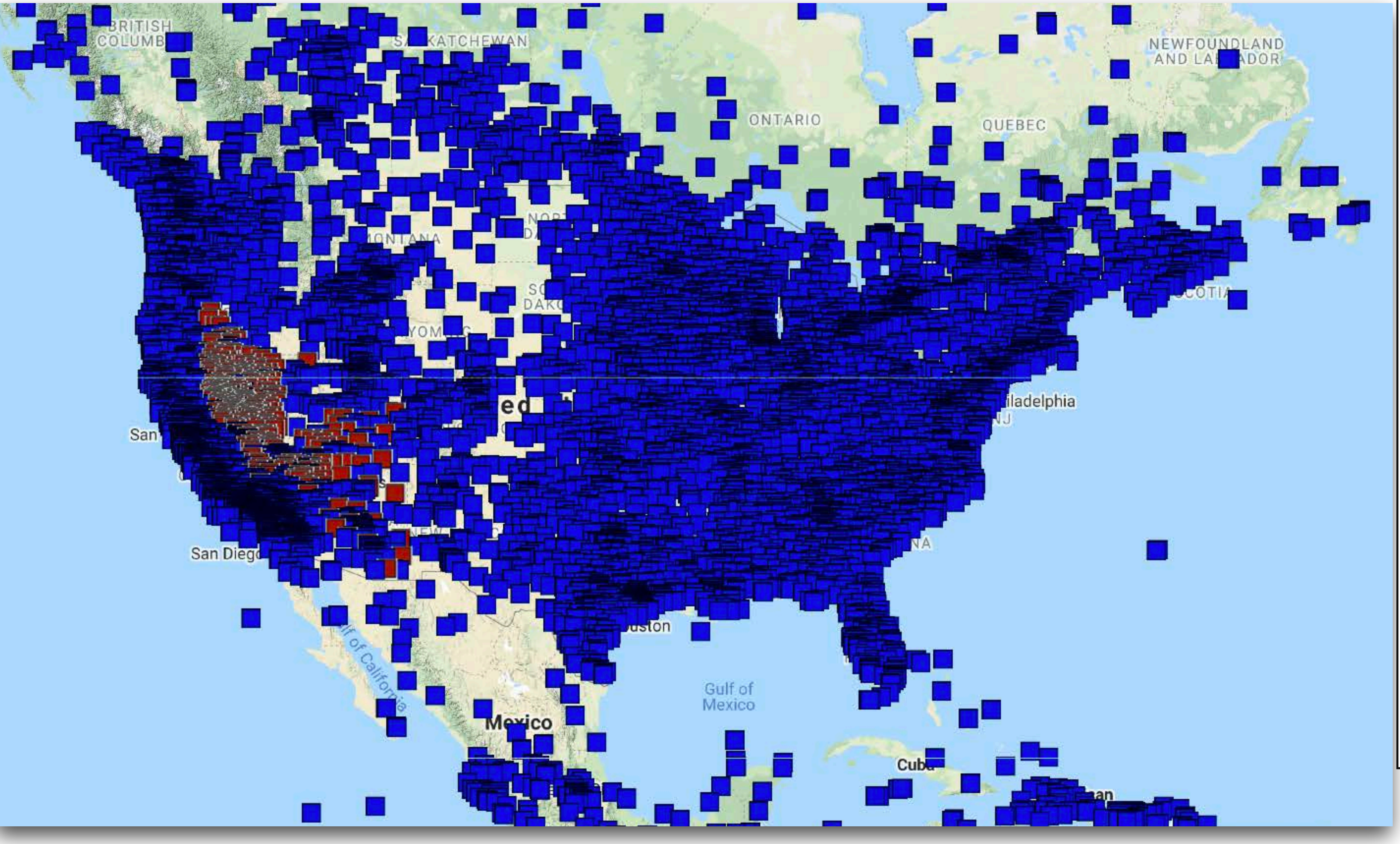
- Data reveal ***trends*** with some variability
- Example on right shows station with a rate of subsidence 0.56 mm/yr
- Trend is small but convincing because of the 20 year duration of the time series
- Though some digressions from constant rate are apparent
- Station had transient movement an order of magnitude faster
- But the trend seems representative of long term movement
- As have been found in many studies of tectonics and crustal deformation, e.g., by comparing geodesy to geologic rates

A Example GNSS Vertical Position Time Series



Distribution of GPS: The Mega-Network

Global Map of NGL GPS Data Holdings



- ~19,000 stations
- Hundreds of different network operators providing open data
- Processed at NGL with latest version of GIPSY and products from JPL
- Durations up to ~27 years
- Latency >= 2 hours (~2000 stations)
- Geographic density of network highly variable
- And so is the quality of constraint on VLM
- Need to sort through it all!

All solutions available at http://geodesy.unr.edu

Nevada Geodetic Laboratory

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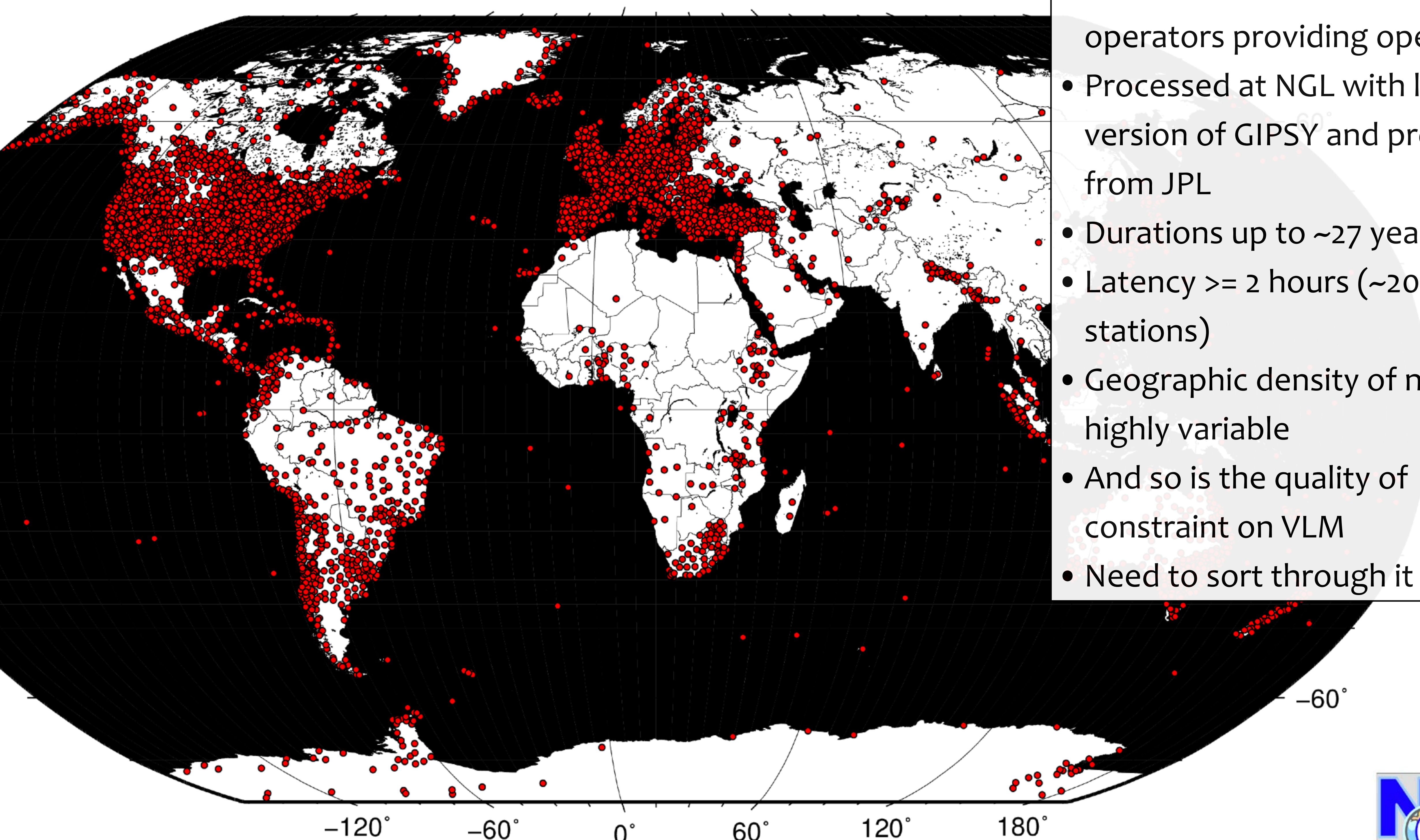

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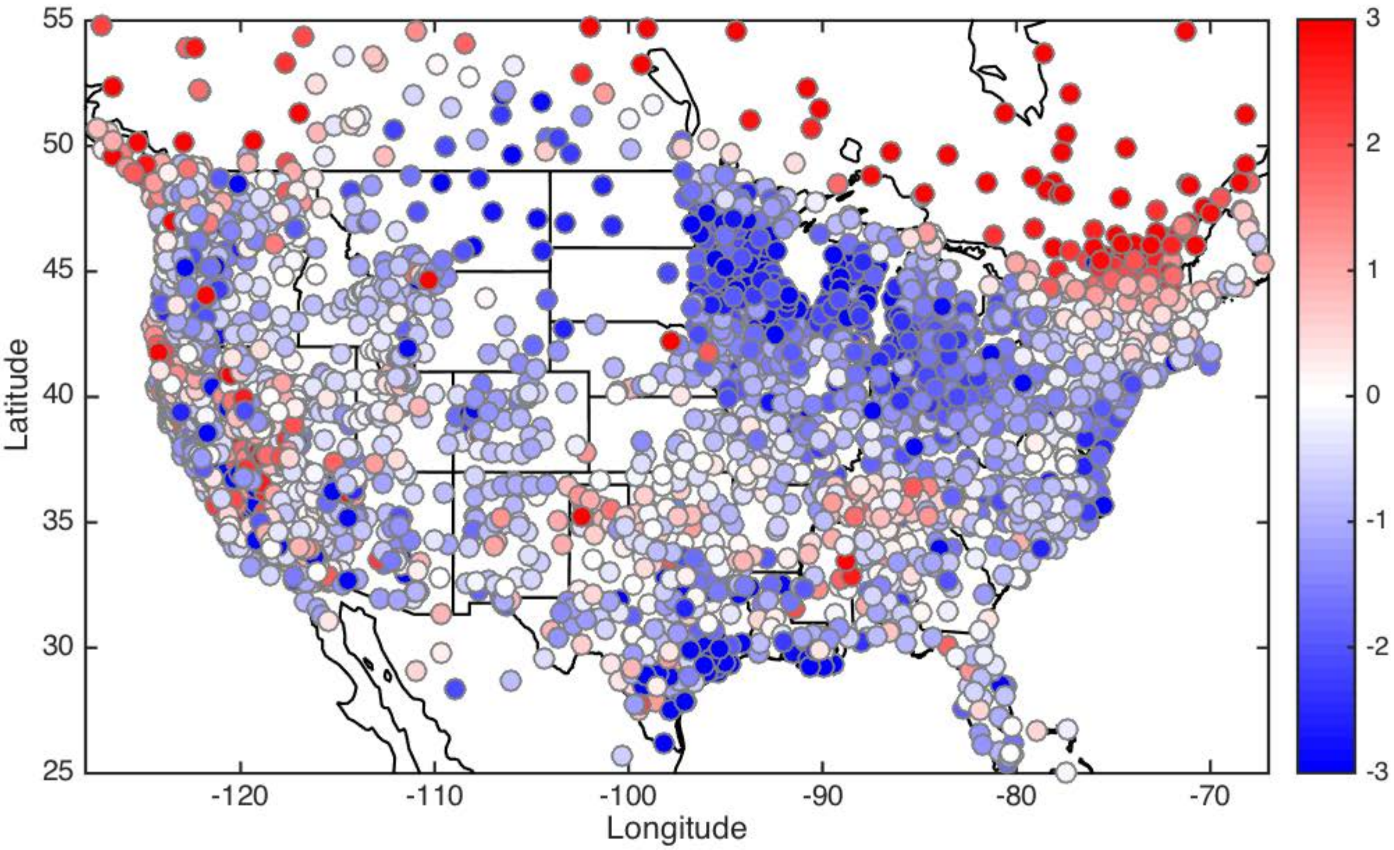
Vertical Land Motion: Imaging



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  - Unbiased nonparametric trend estimator that is insensitive to outlier positions, seasonality, steps

- Robust derivation of vertical rate field with **GPS Imaging**
- Field estimated with weighted median filtering of GPS rates
- Method resolves small signals that are supported by multiple stations

Hammond et al., 2016,GPS Imaging of vertical land motion in California and Nevada: Implications for Sierra Nevada uplift, *J. Geophys Res.*, **121,** doi: 10.1002/2016JB013458

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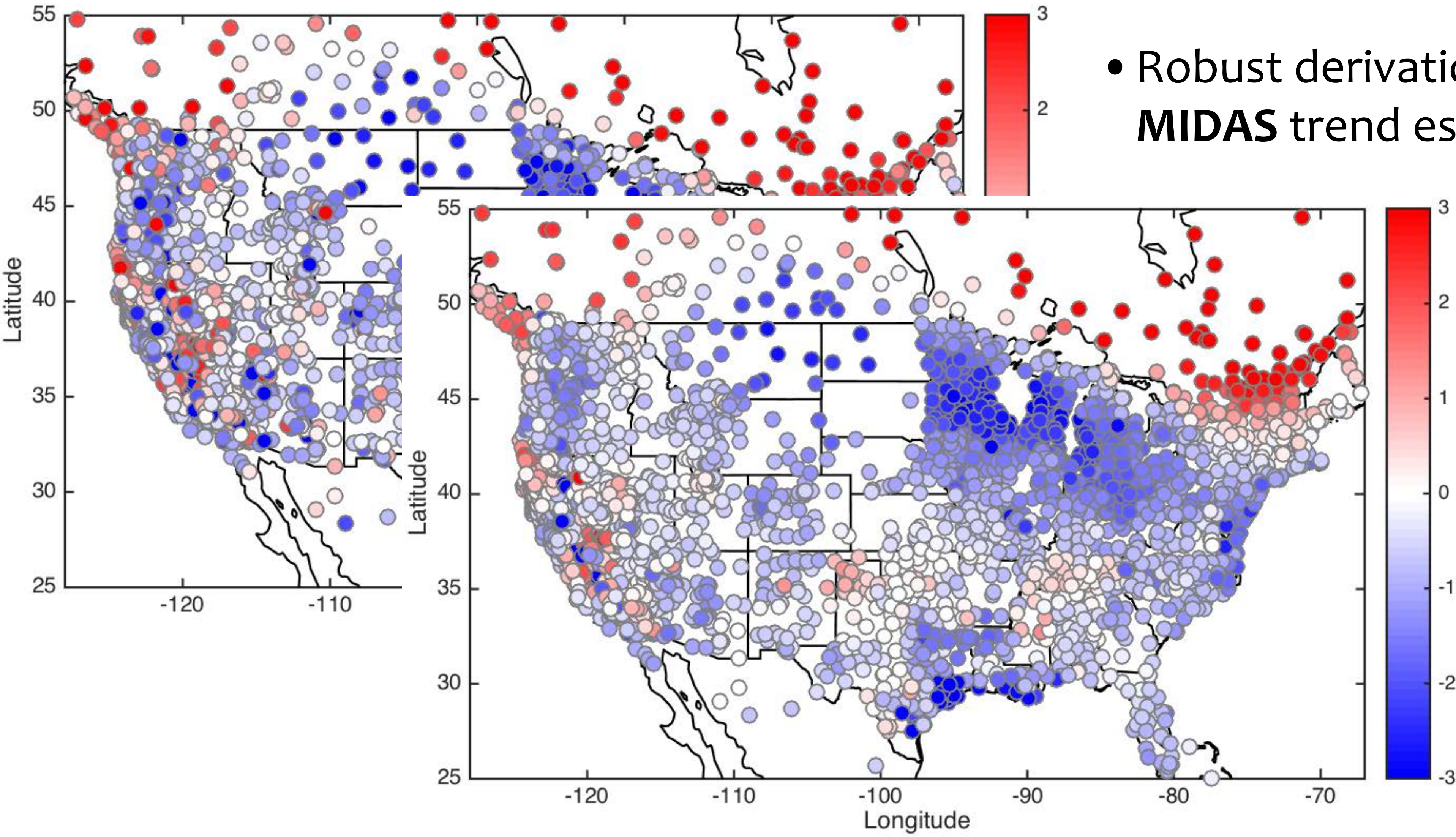
Vertical Land Motion: Imaging



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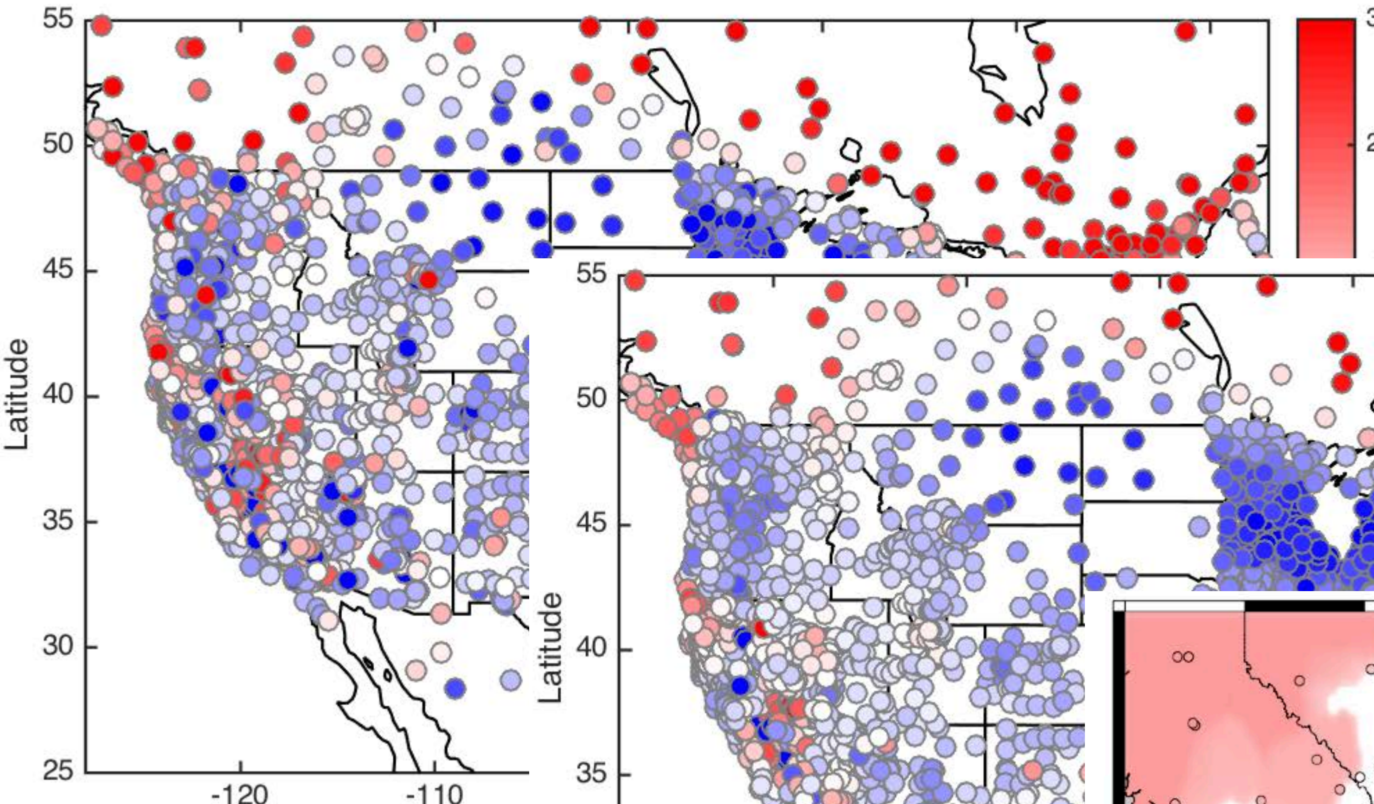

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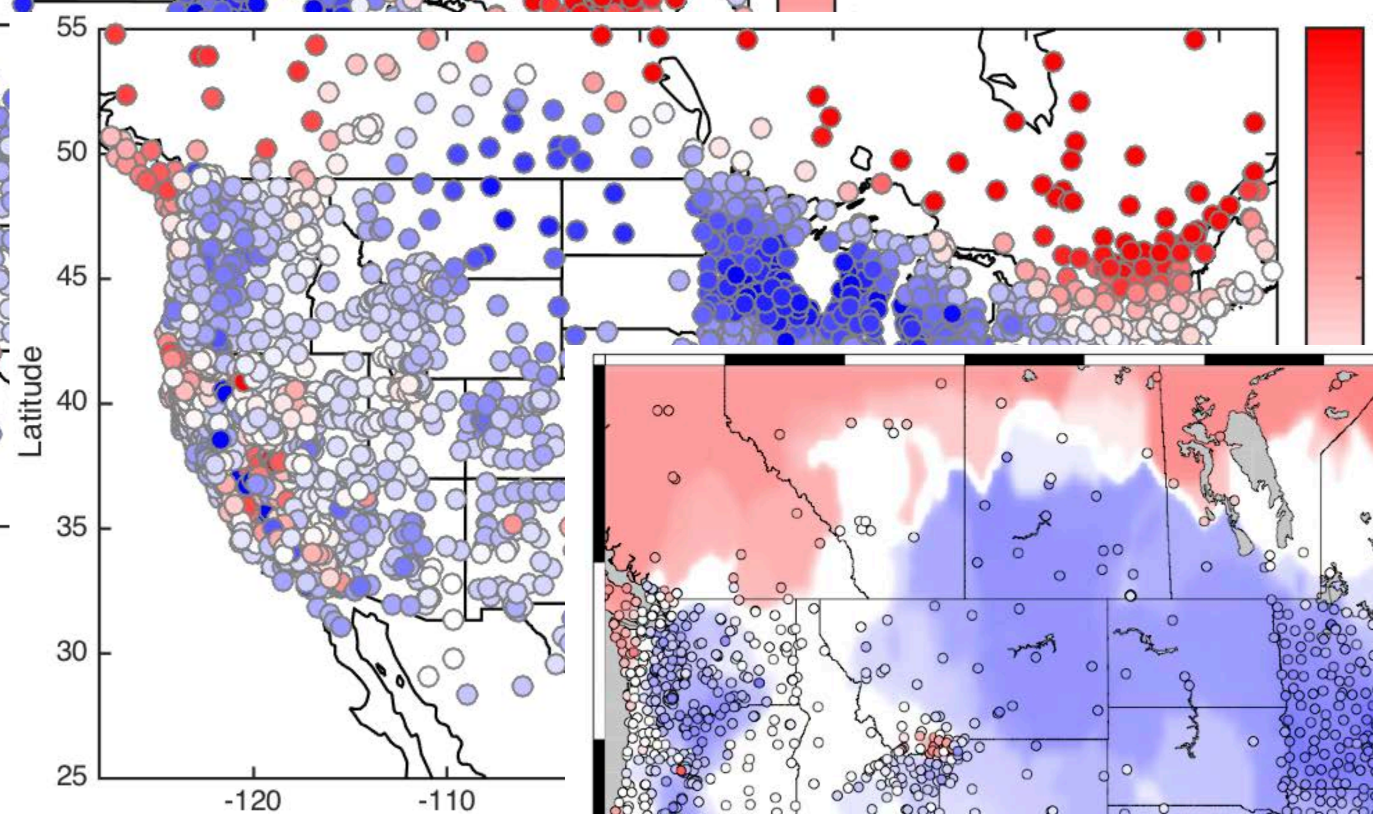

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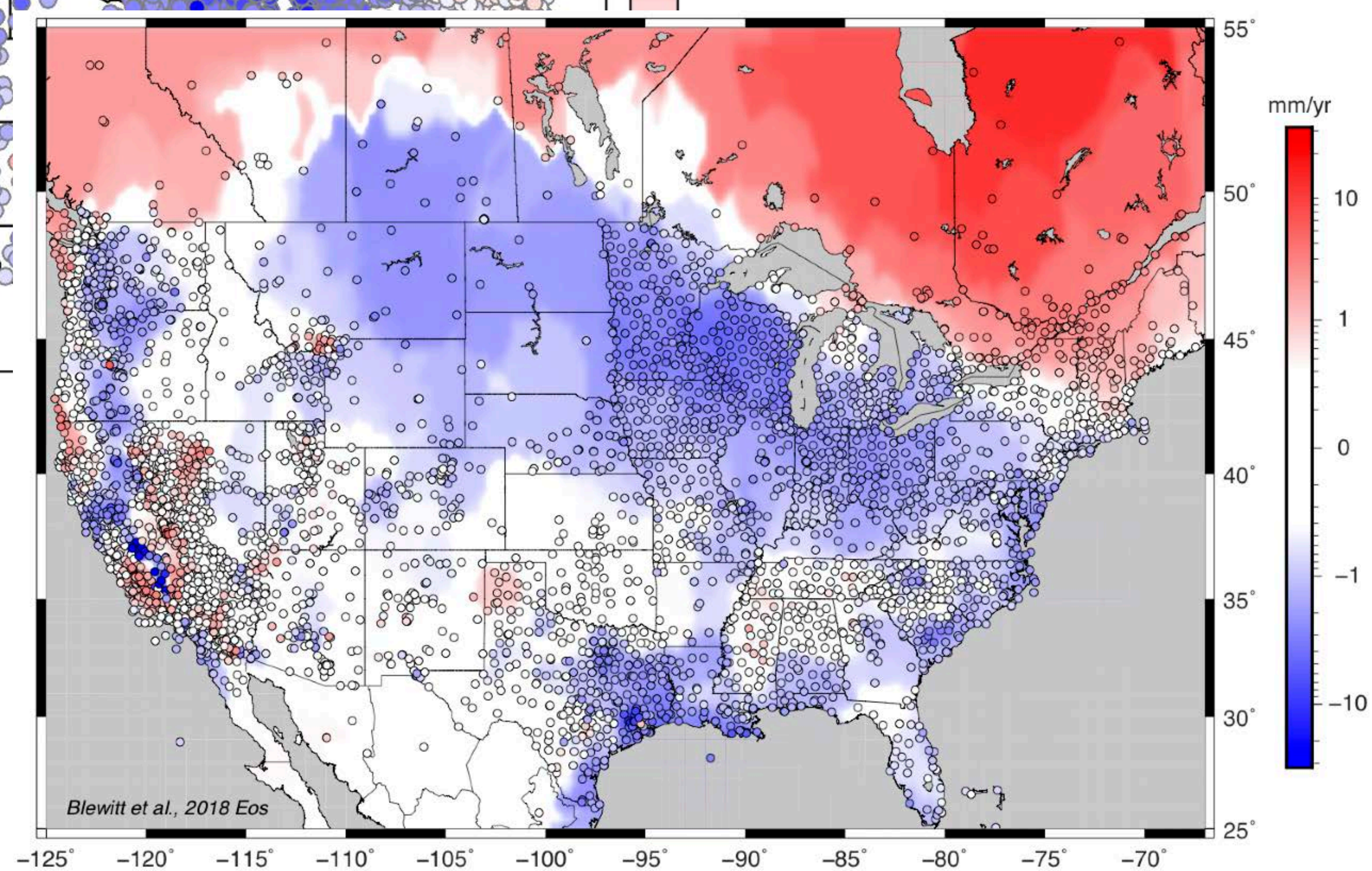

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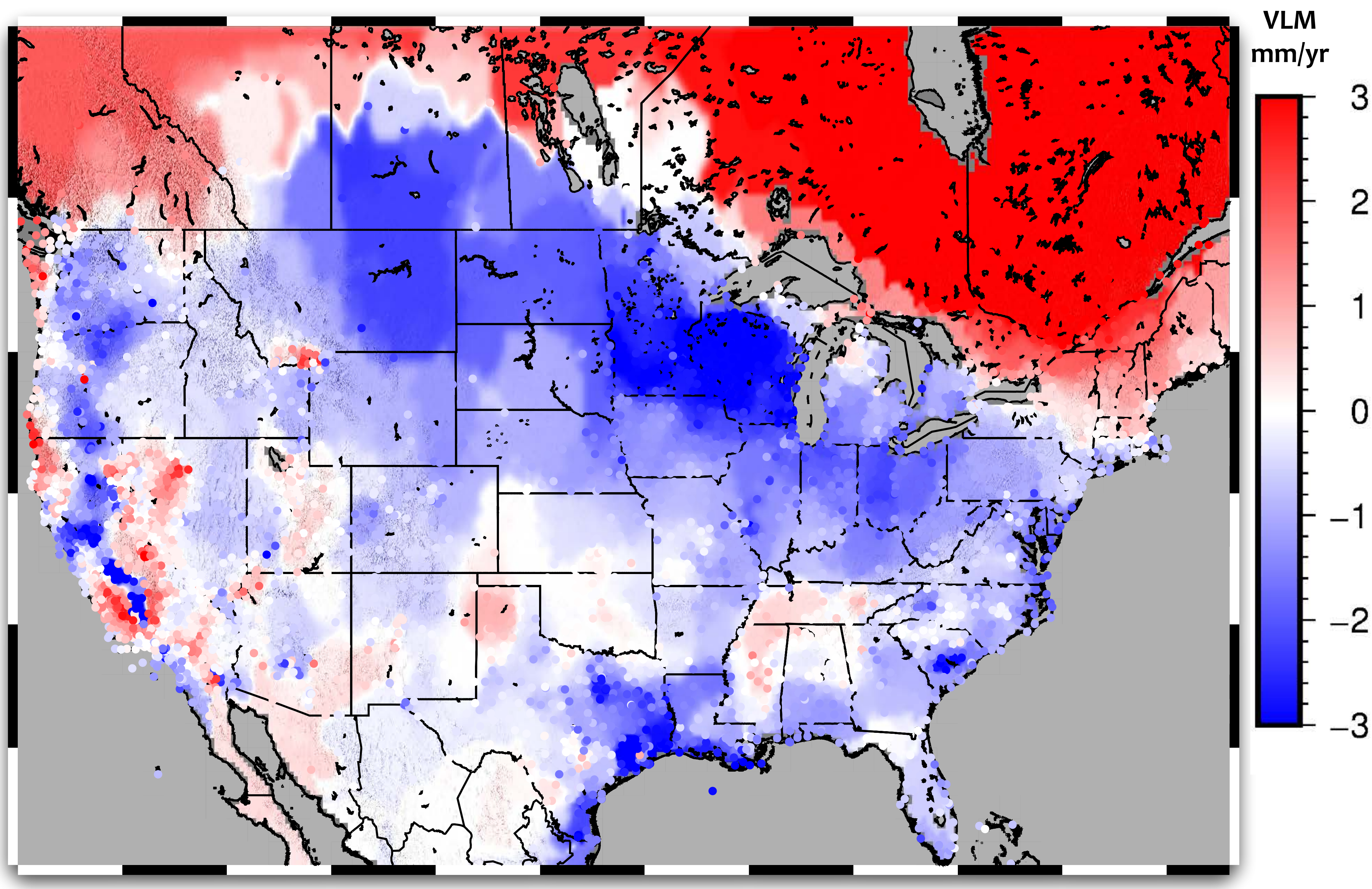
Vertical Land Motion: Imaging

Some things we see

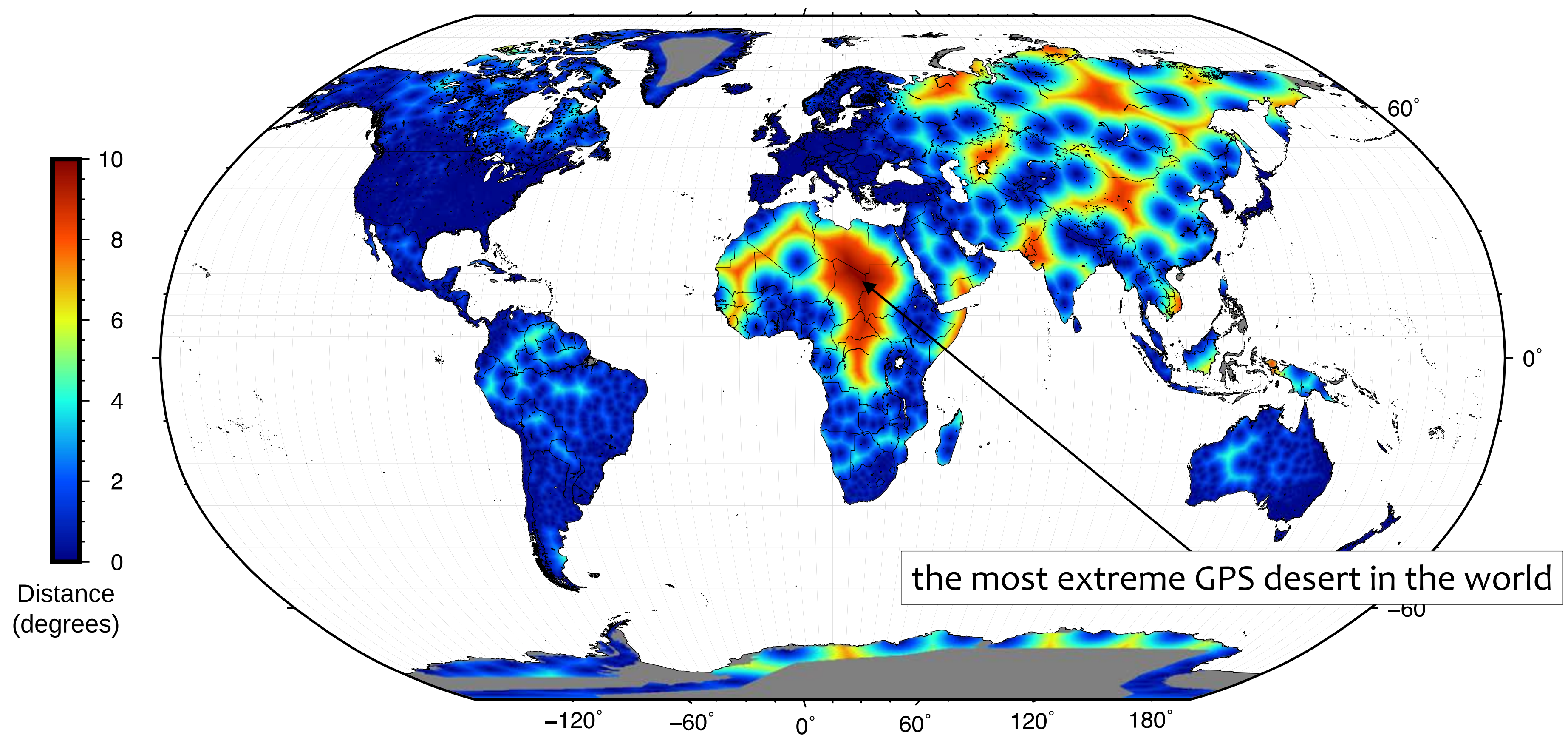
- The biggie: GIA uplift, fore bulge collapse and hinge line.
- Fore bulge from southern Alberta to the southeast US Atlantic Coast
- Gulf coast subsidence
- Yellowstone Caldera magmatic uplift
- Heavy subsidence in CA Central Valley
- Sierra Nevada/California Coast Range from drought-enhanced hydrological unloading
- Cascadia Interseismic strain accumulation
- Some of these impact coastal areas

Vertical Land Motion: United States



Global Vertical Land Motion: How Well Can We Do This?

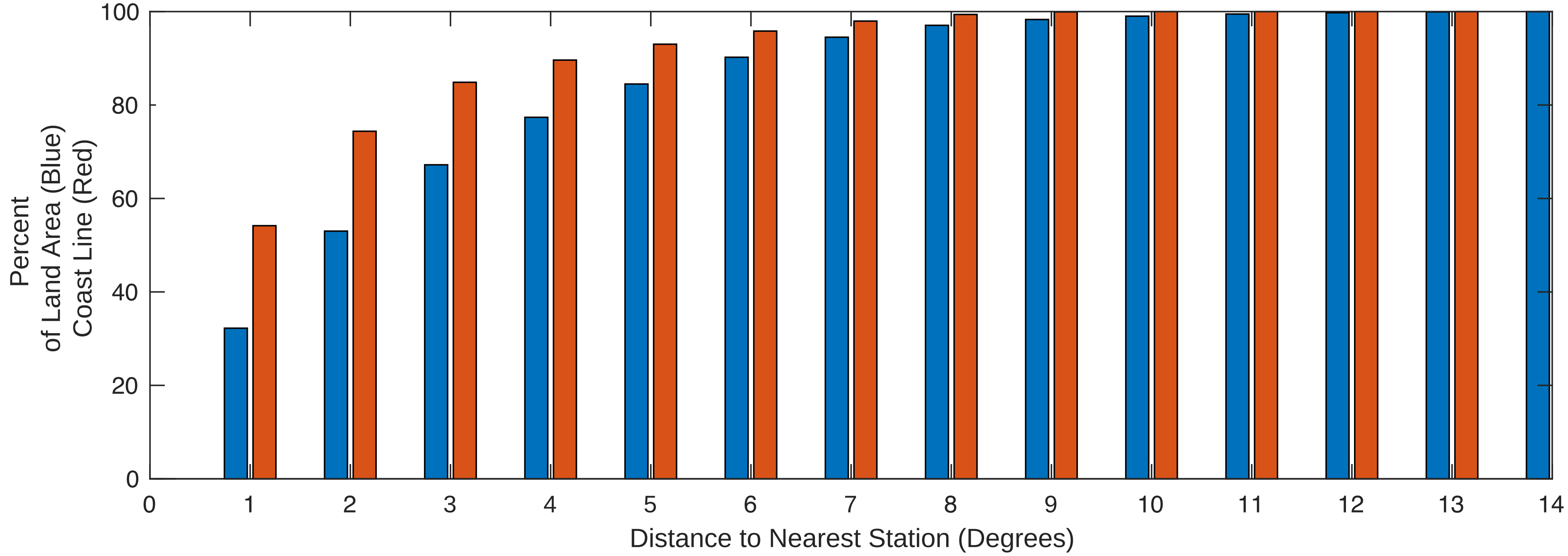
Distance to nearest GPS station in NGL archive for every point on land



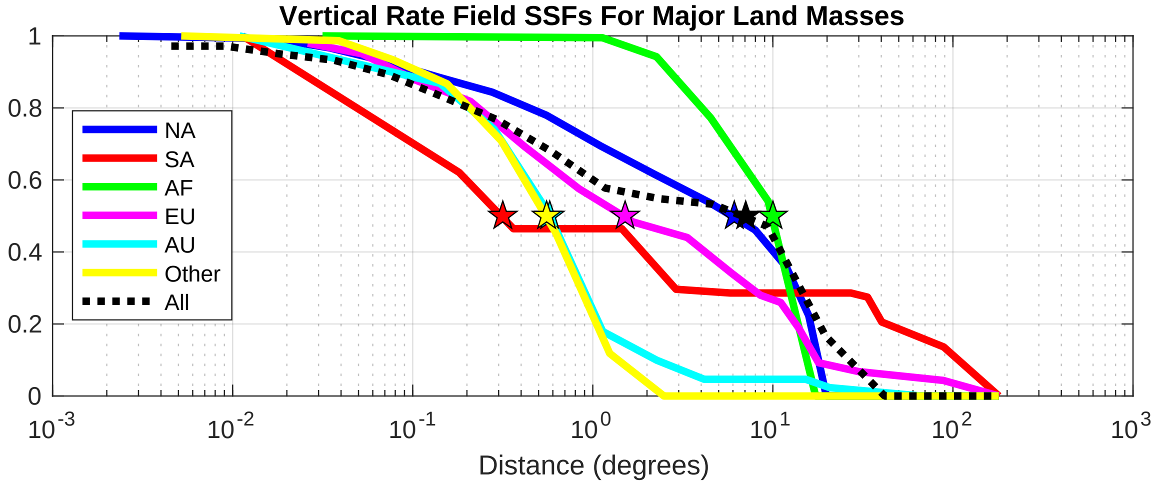
by Land Area = Blue Bars
by Coastline = Red Bars

74% of coast within 2°
93% of coast within 5°
of a GPS station

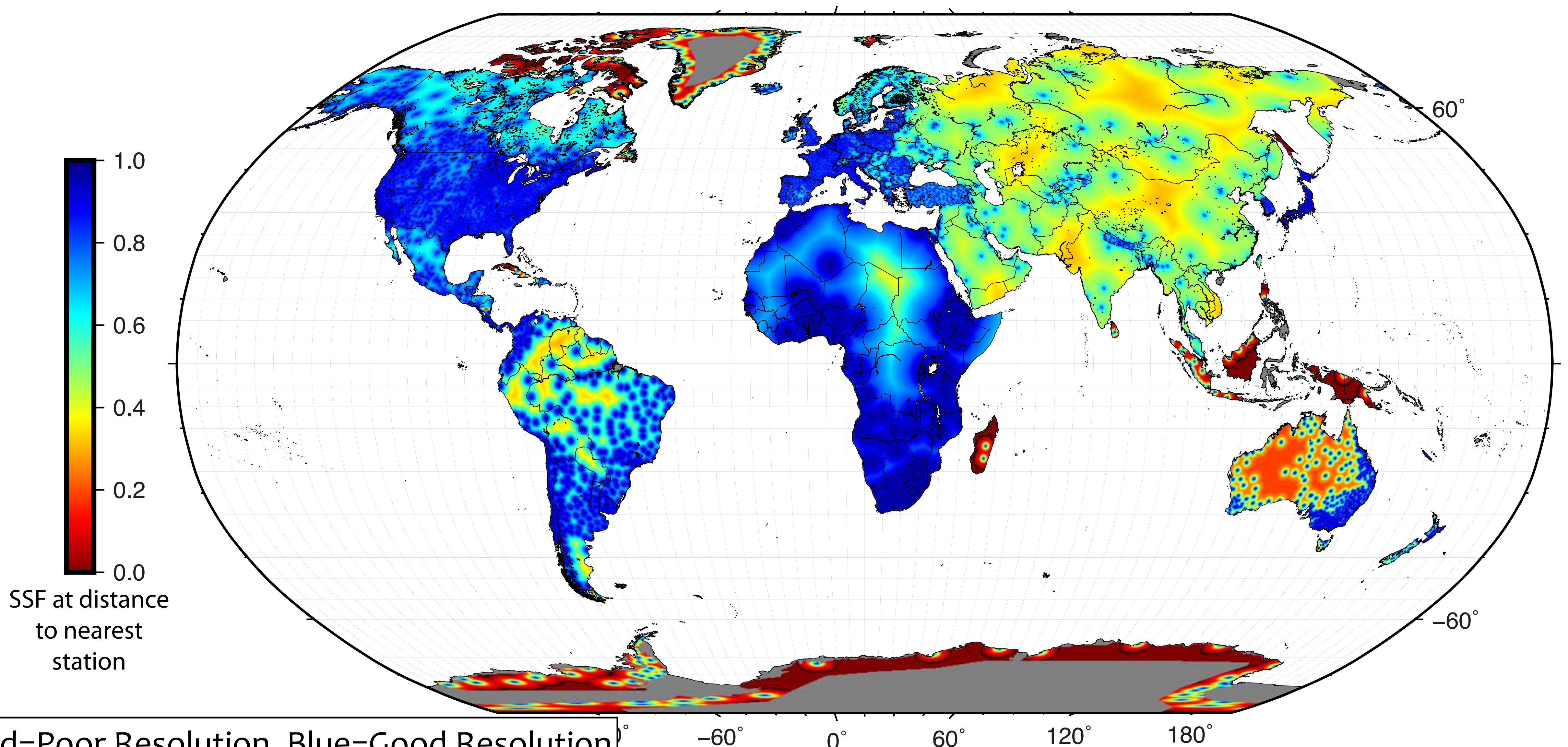
Coast better covered because most big empty areas are in continental interiors.



Vertical Land Motion: Wavelength of Uplift Signals



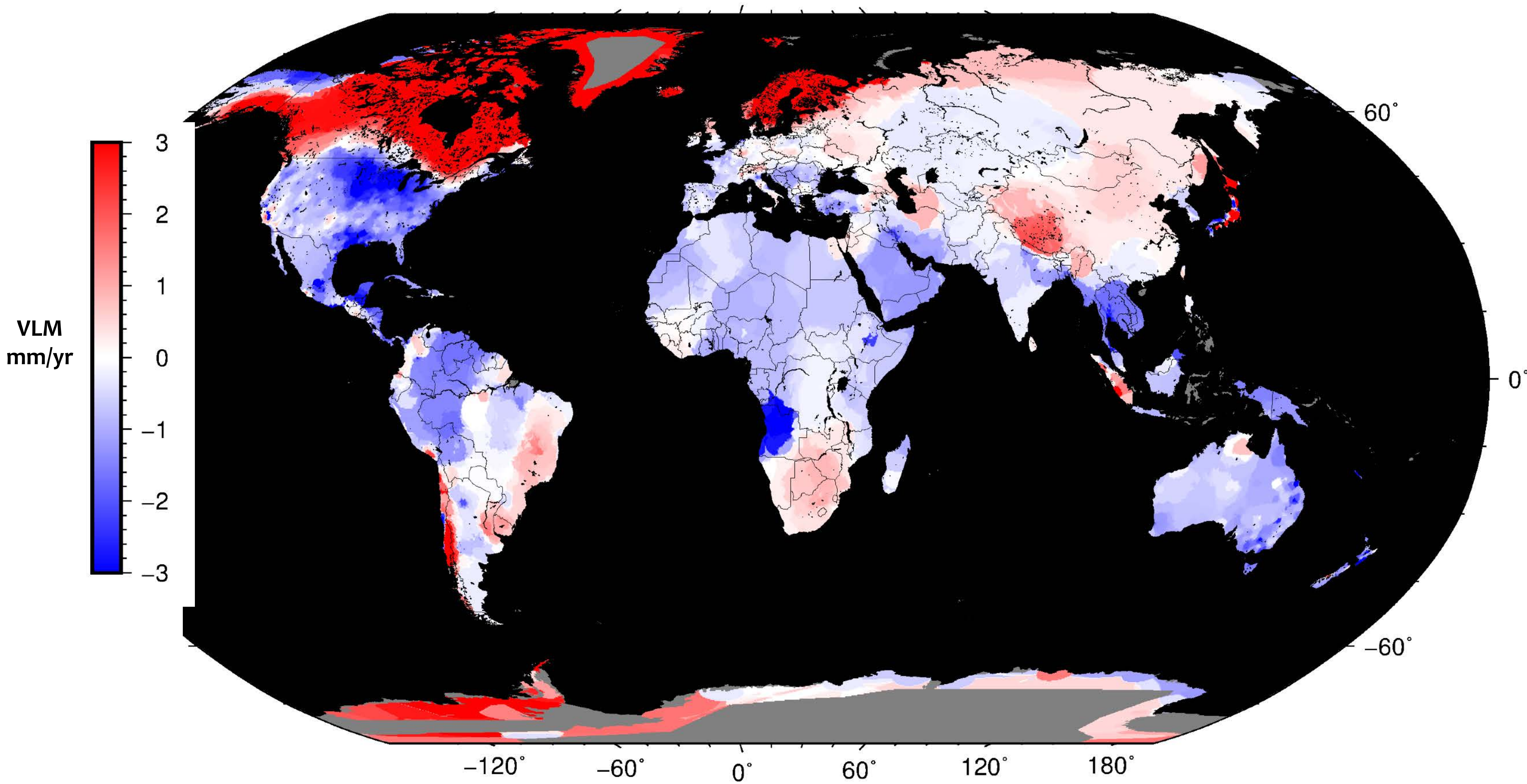
- From data derive function that measures spatial wavelength of dominant signals in VLM field
- Spatial Structure Function is VLM similarity as a function of distance
- Function varies across VLM domains
- Assesses network strength wrt signals



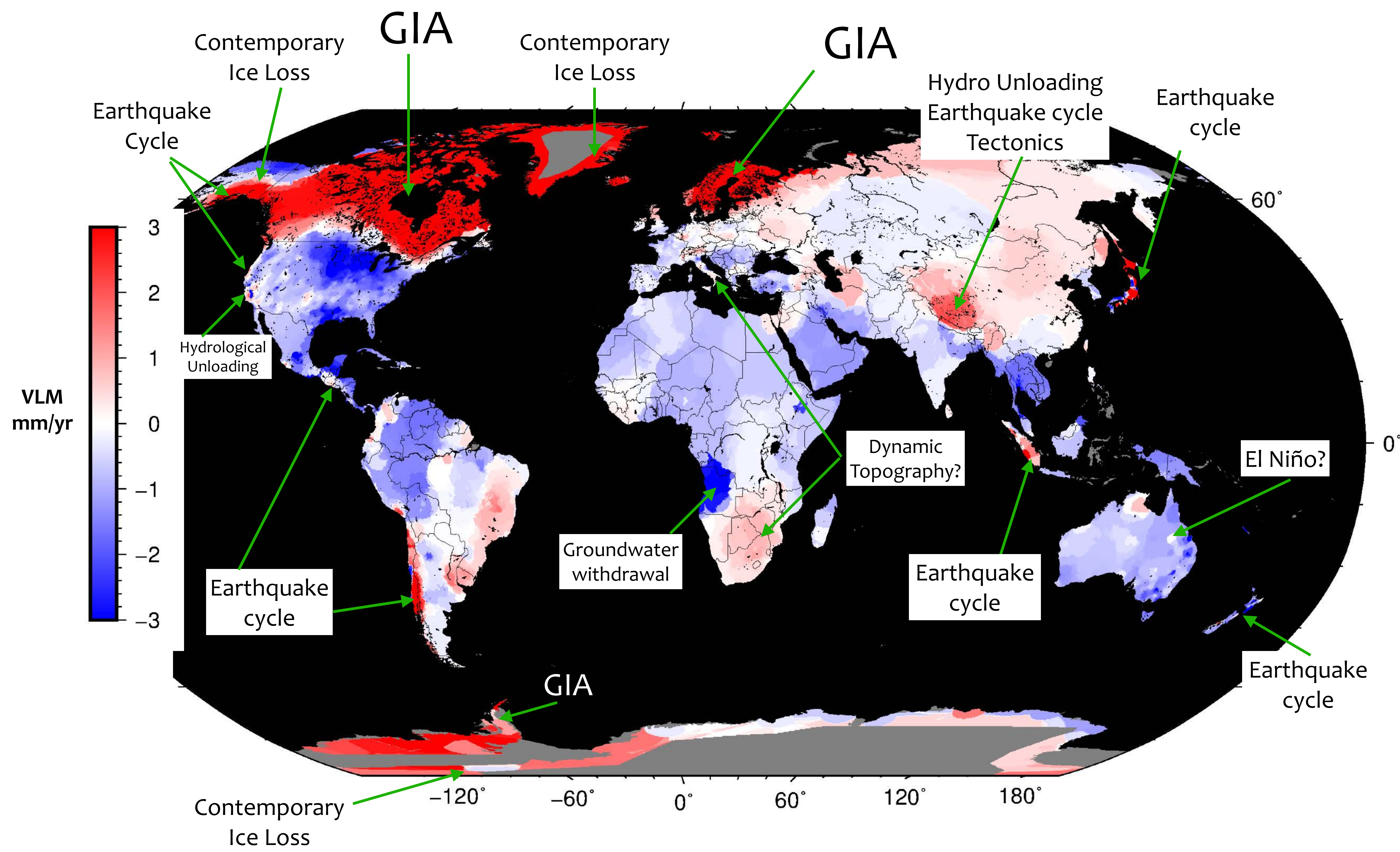
Red=Poor Resolution, Blue=Good Resolution

Vertical Land Motion: Global

Spatial Variability

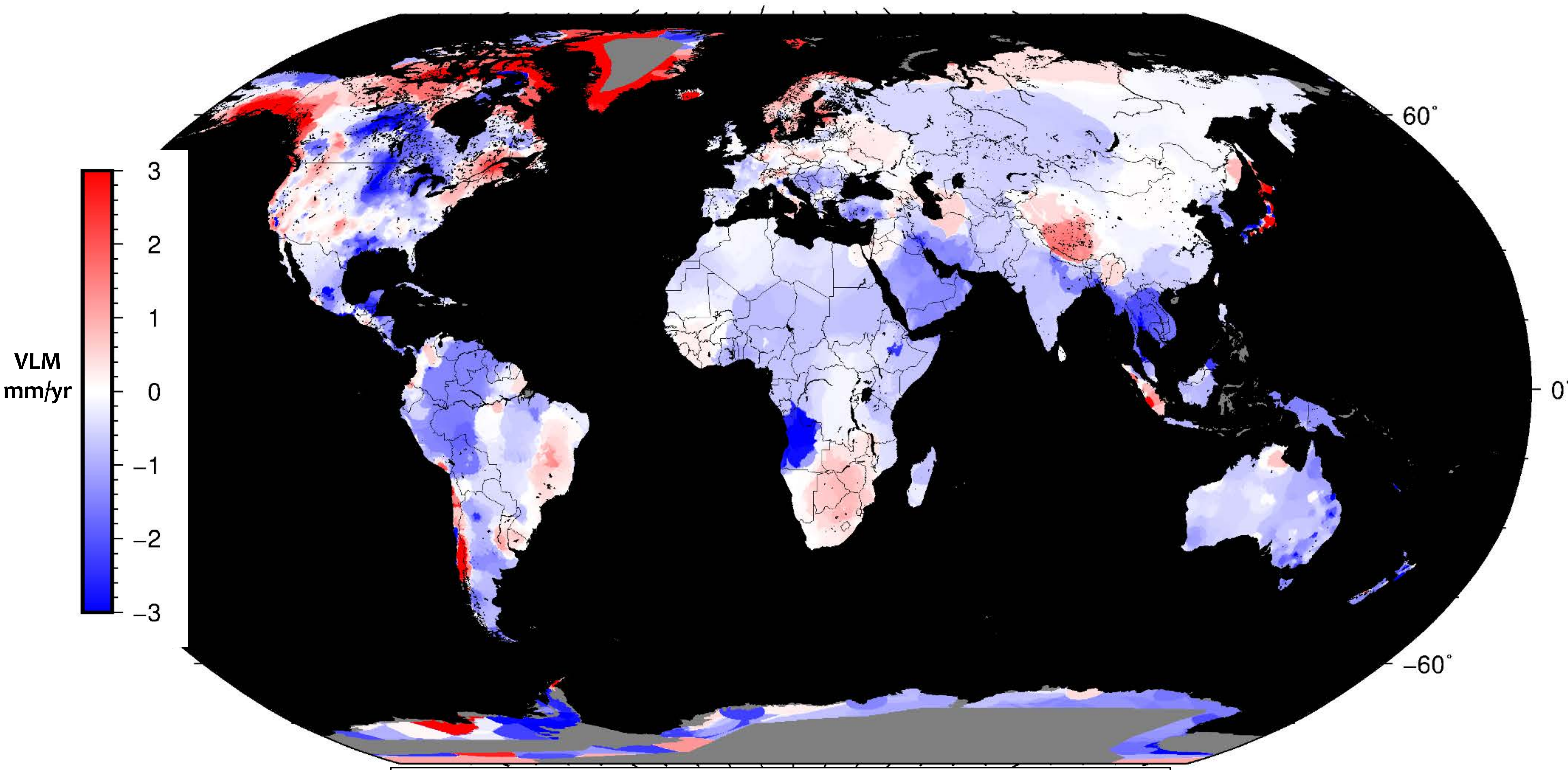


Vertical Land Motion: Global



Vertical Land Motion: Global - GIA Removed

Subtracted predictions of ICE-6G C
Peltier et al., 2015, Argus et al., 2014



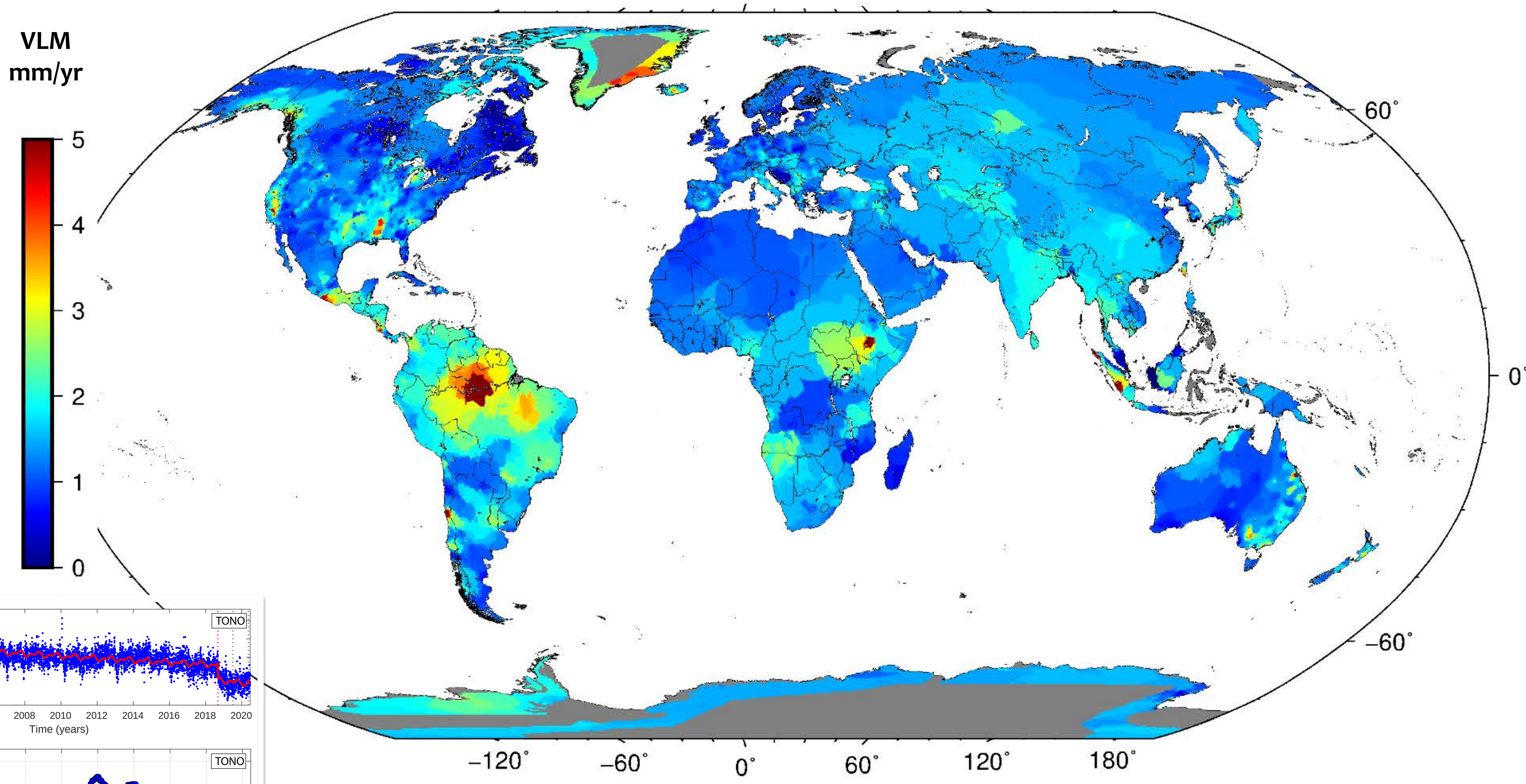
There is a lot of VLM left over after removing GIA.
But how much? How important is it?

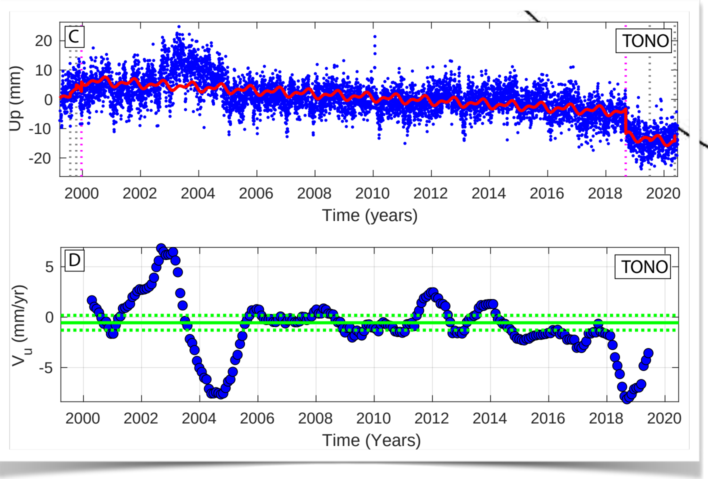
Vertical Land Motion: What Drives the Uncertainty?

One Example: Temporal Variability

i.e. Wiggliness of the GPS Time Series

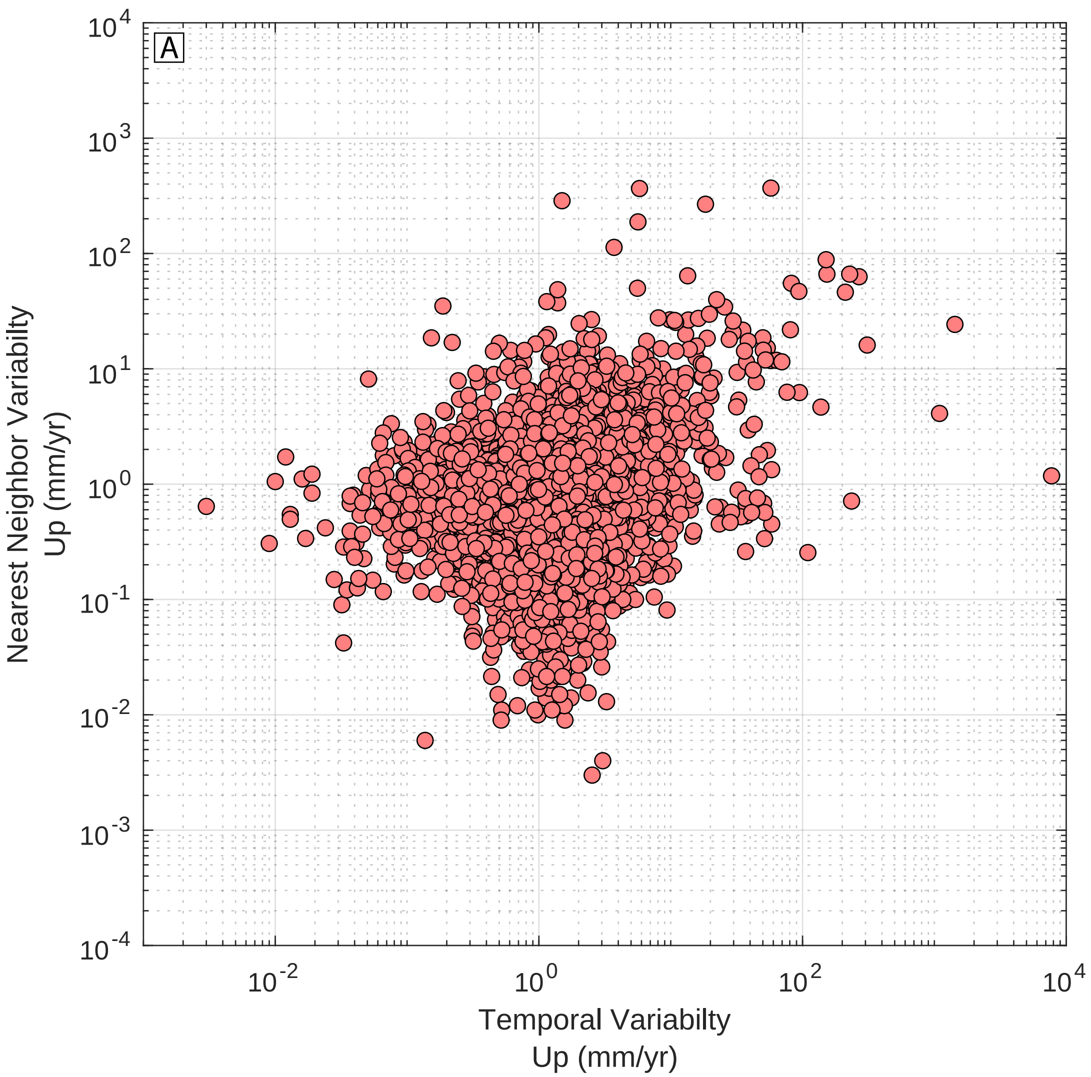
as measured by the median absolute deviation of Vu(t)



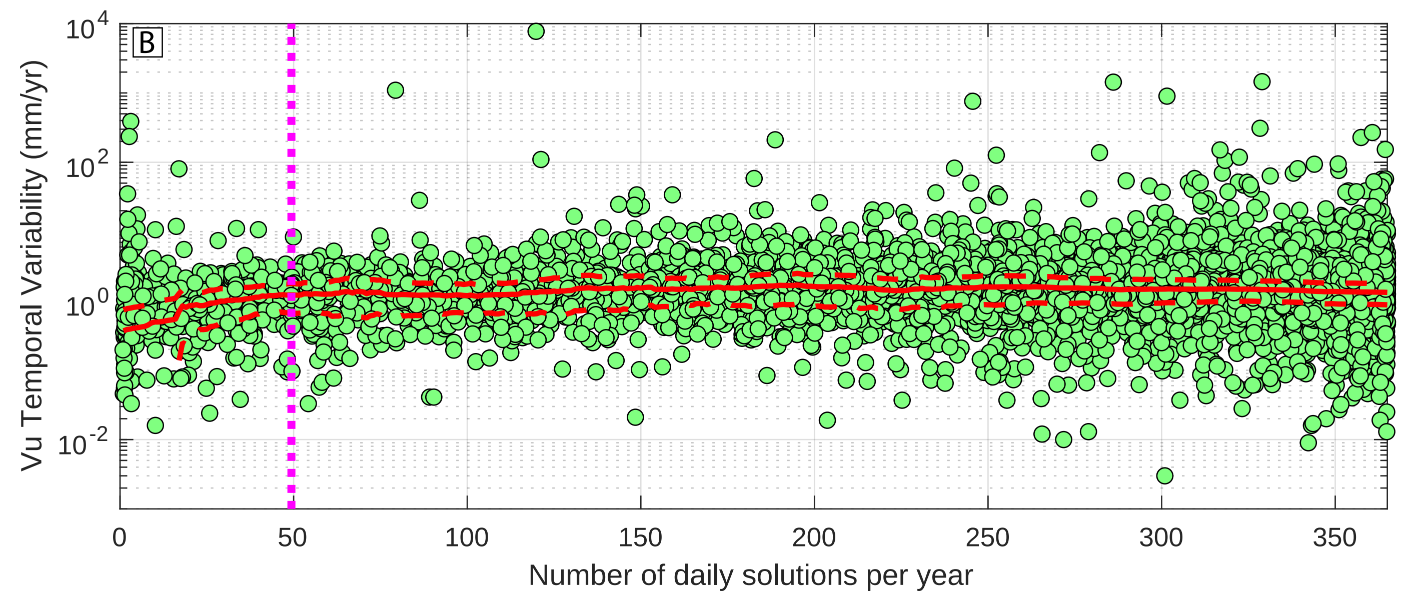


Vertical Land Motion: What Drives the Uncertainty?

Temporal and Spatial Variability
are not well correlated



Temporal Variability
Not driven by sparse time series

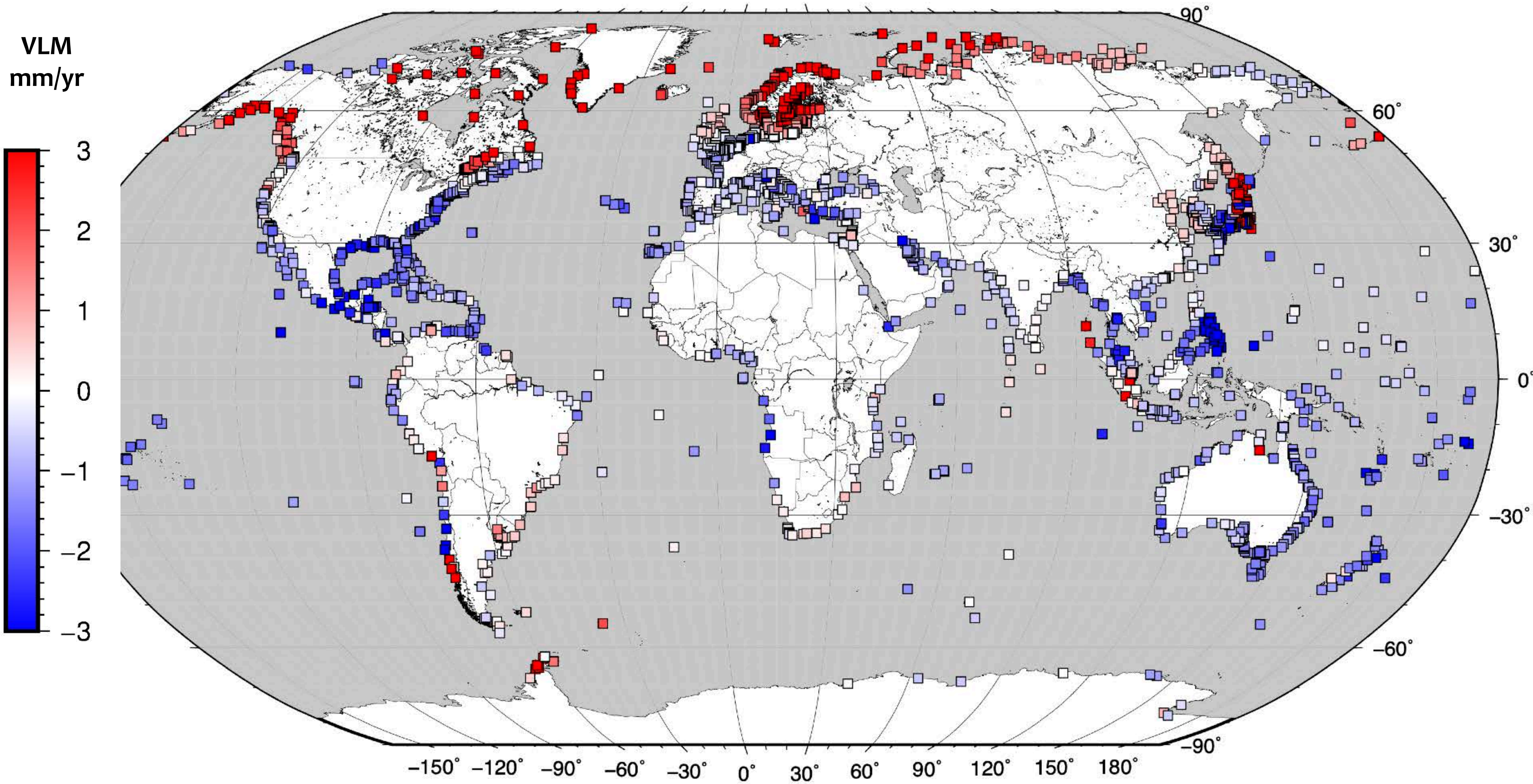


So can have:

- High temporal and low spatial variability
- Or low temporal and high spatial variability
- Or any combination
- Need to have knowledge of both
- Can use GPS to show where both are low

Vertical Land Motion at Tide Gauges

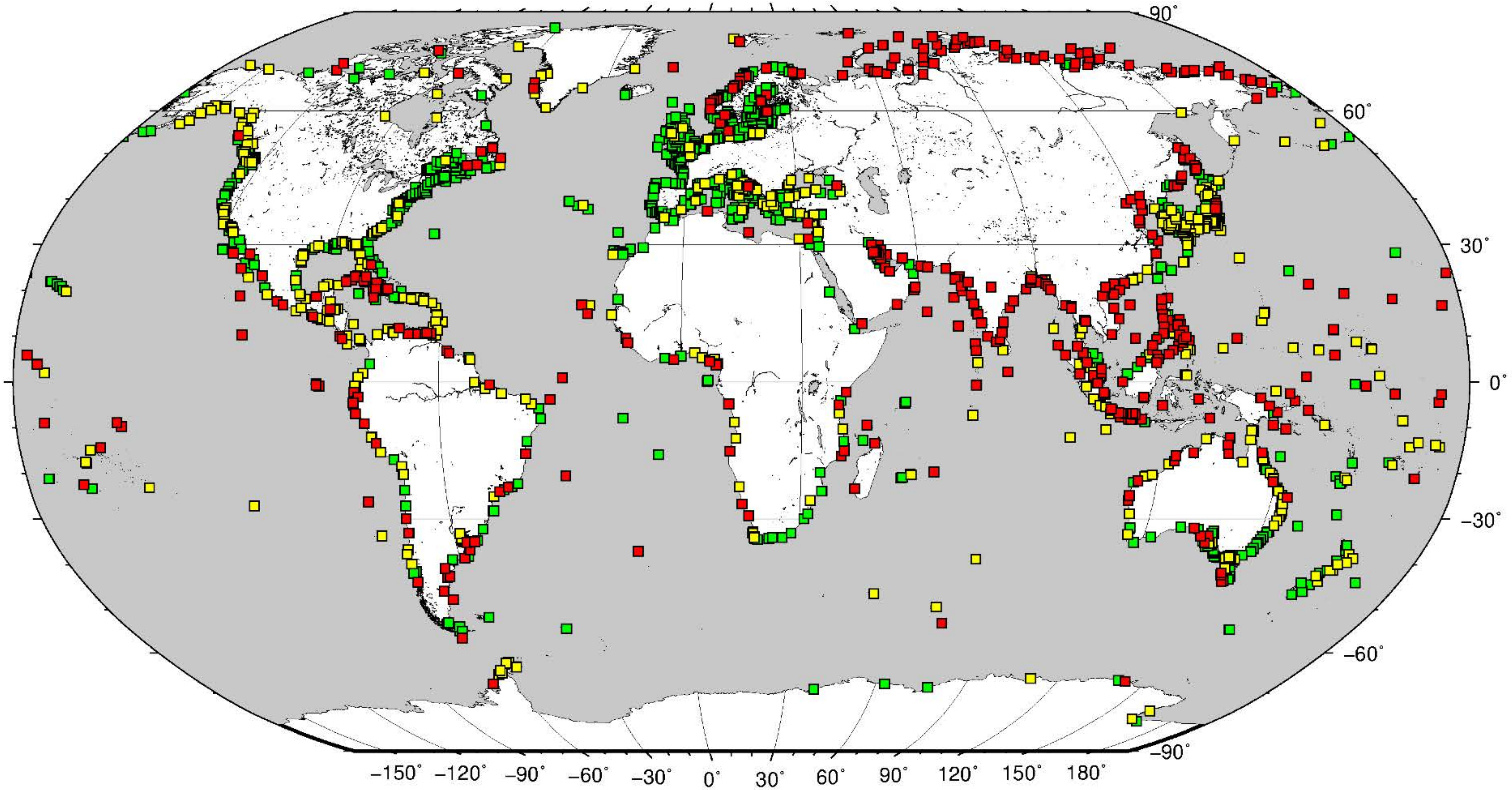
Tide gauges provide direct constraint on relative SLR.
They provide a primary observable that connects SLR to coastal impact.



Unfortunately, we don't have a GPS station at every tide gauge.
Error associated with distance between GPS and tide gauge.

Vertical Land Motion at Tide Gauges

So how well does GPS data constrain VLM at their locations?



Good (52%)	: $\sigma_{Vu,GPSI} < 0.7$ mm/yr & $RMS(\sigma_{Vu}) < 4.0$ mm/yr & $\max(ssf) > 0.5$ & $MAD(Vu(t)) < 1.5$
Not So Good (27%)	: $\max(ssf) < 0.5$ **OR** $MAD(Vu(t)) > 5.0$
Medium (21%)	: all others

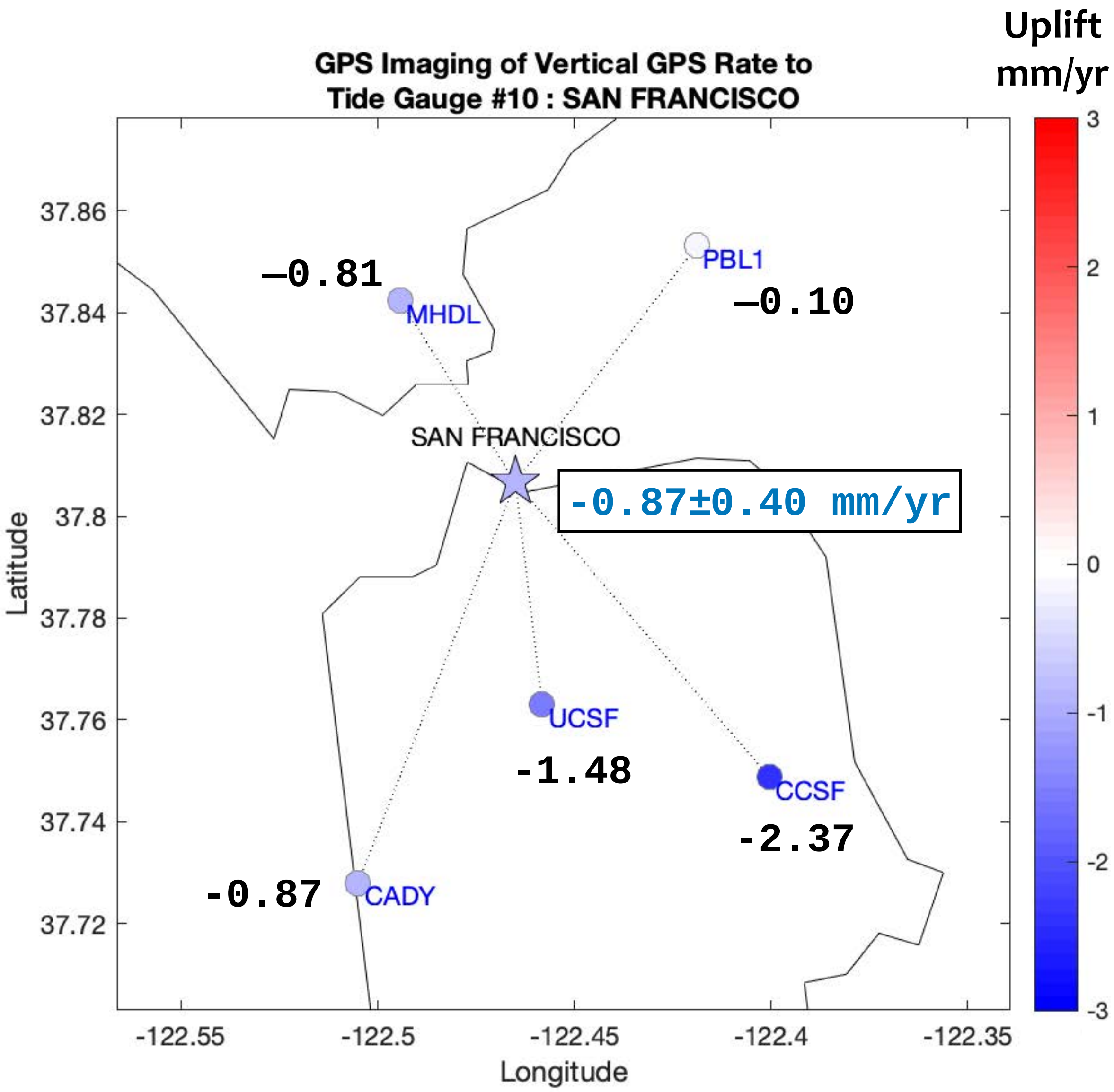
Vertical Land Motion at a Single Tide Gauge

Example: San Francisco Bay

No GPS/tide gauge collocation

But 5 nearest stations have trends

GPS VLM Assessment

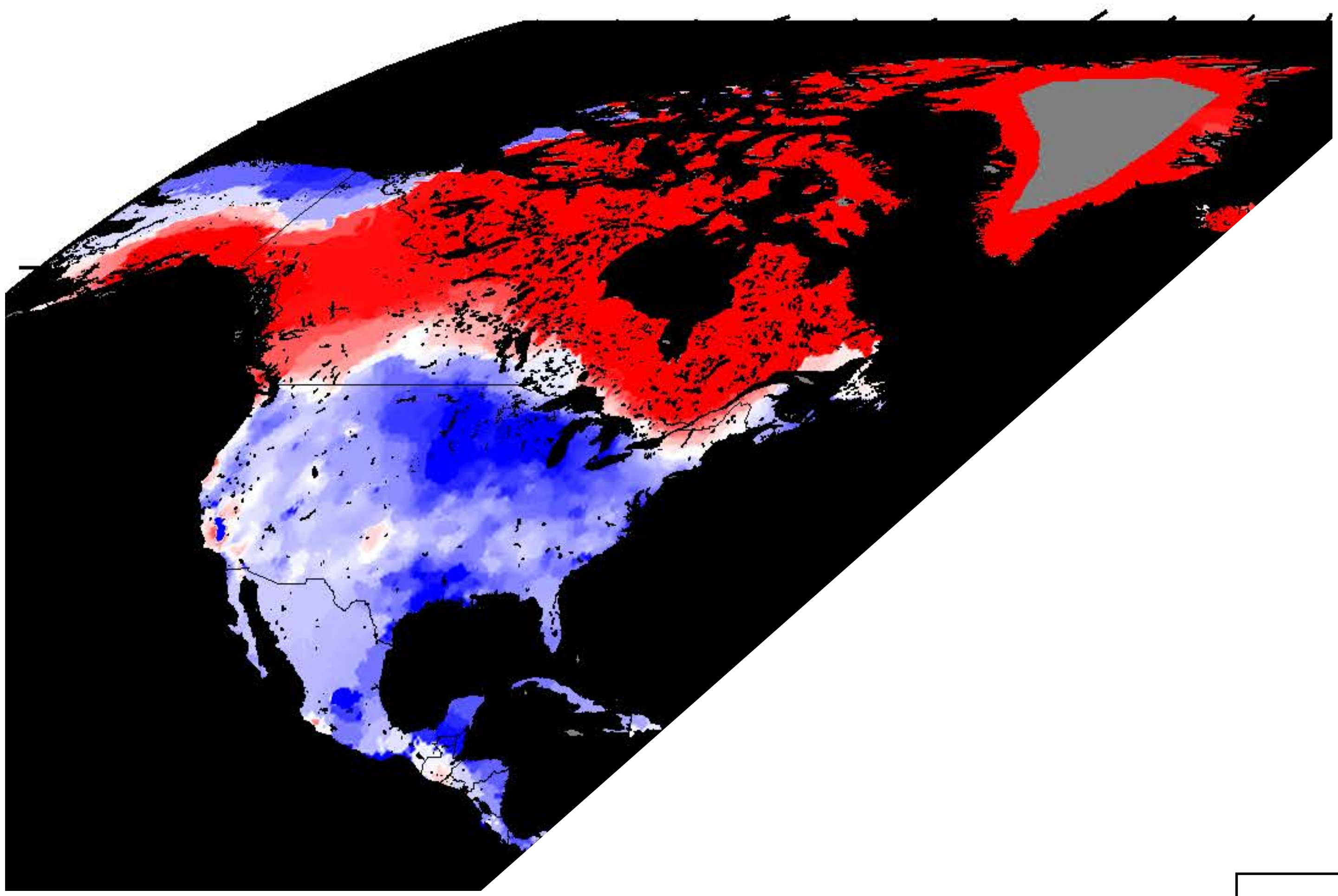


Vu	σ_{Vu}	$D_{(km)}$	ssf	$MAD(V(t))$	w	sta
-0.87	0.95	9.4	0.928	1.20	0.185	CADY
-2.37	0.93	8.6	0.934	1.39	0.191	CCSF
-0.81	0.99	4.7	0.982	3.30	0.187	MHDL
-0.10	0.91	6.6	0.959	2.32	0.200	PBL1
-1.48	0.78	4.9	0.980	1.53	0.237	UCSF

Estimate for VLM at tide gauge: $V_u = -0.87 \pm 0.40$ mm/yr

Vertical Land Motion: The Budget

How much VLM is left after removing GIA?



Start with North America

Up flux: 36.1 km^3 /year

+

Down flux: -16.3 km^3 /year

=

Net flux: 19.7 km^3 /year

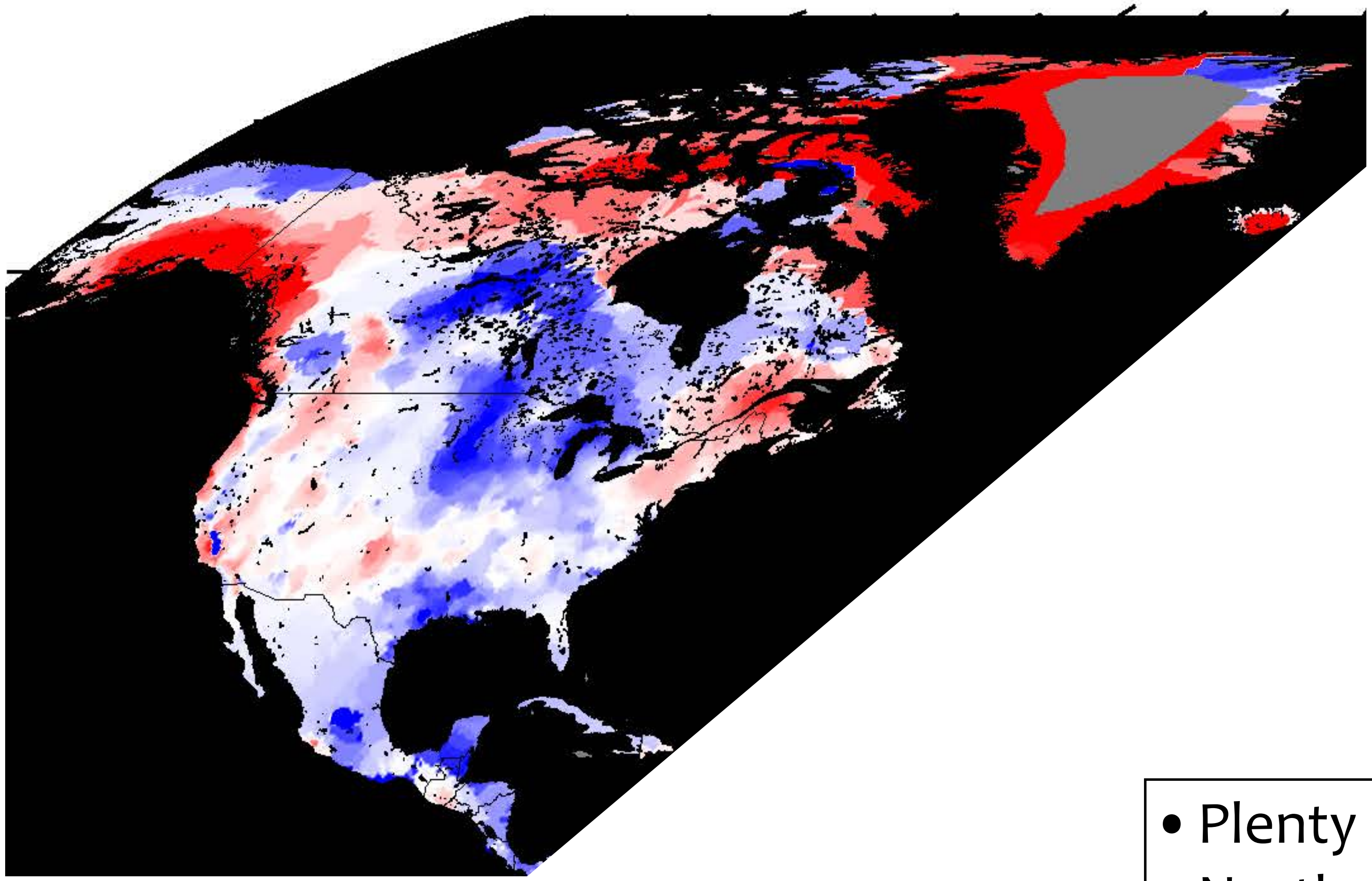
Integrate VLM to estimate volume flux

$$\text{Volume Flux} = \int_{\partial S} v_u(\vec{r})\,dA$$

- North America has net uplift!
- Mantle flowing horizontally into space underneath NA lithosphere
- Earth not growing in size, so…
- Somewhere else is going down, offshore where we can't see with GPS (yet)

Vertical Land Motion: The Budget - Corrected for GIA

How much VLM is left after removing GIA?



Start with North America

Up flux: -5.4 km^3 /year

+

Down flux: -6.0 km^3 /year

=

Net flux: -11.4 km^3 /year

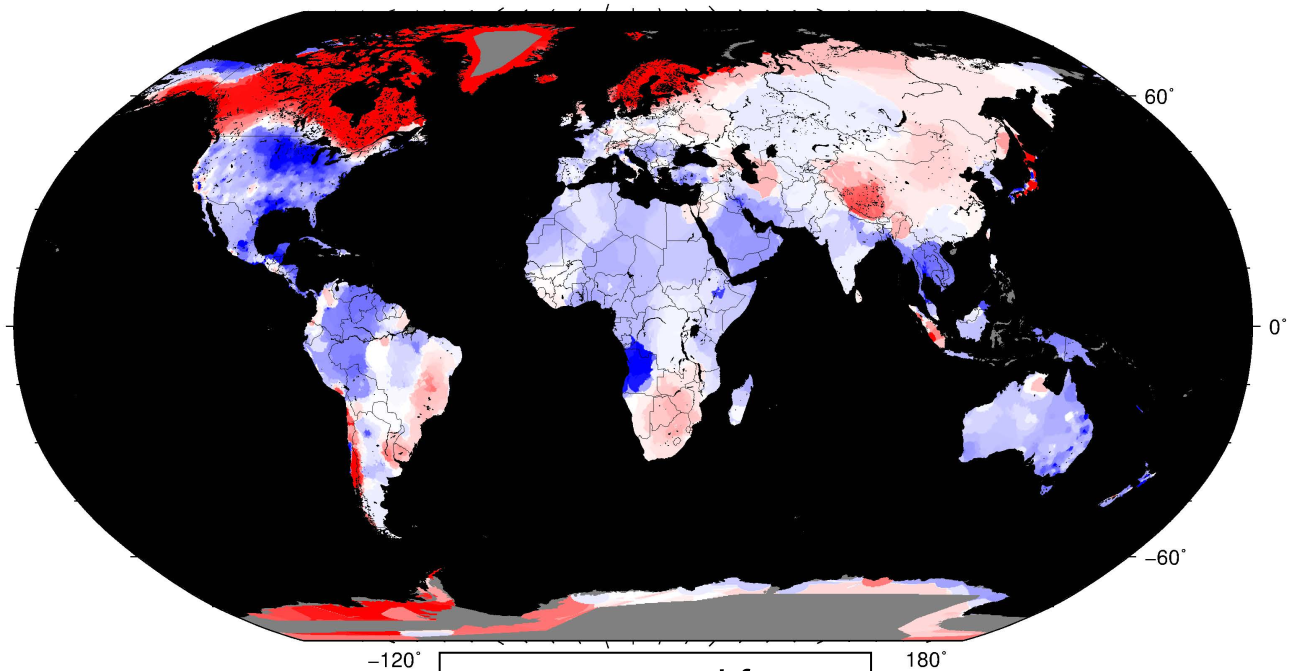
- Plenty of signal left.
- North America corrected for GIA is net subsidence.
- Some attributable to error in GIA model.
- Though GIA model is not overcorrecting in both directions.
- Earth not shrinking in size, so…
- Somewhere else in the non-GIA field is going up…

Integrate VLM to estimate volume flux

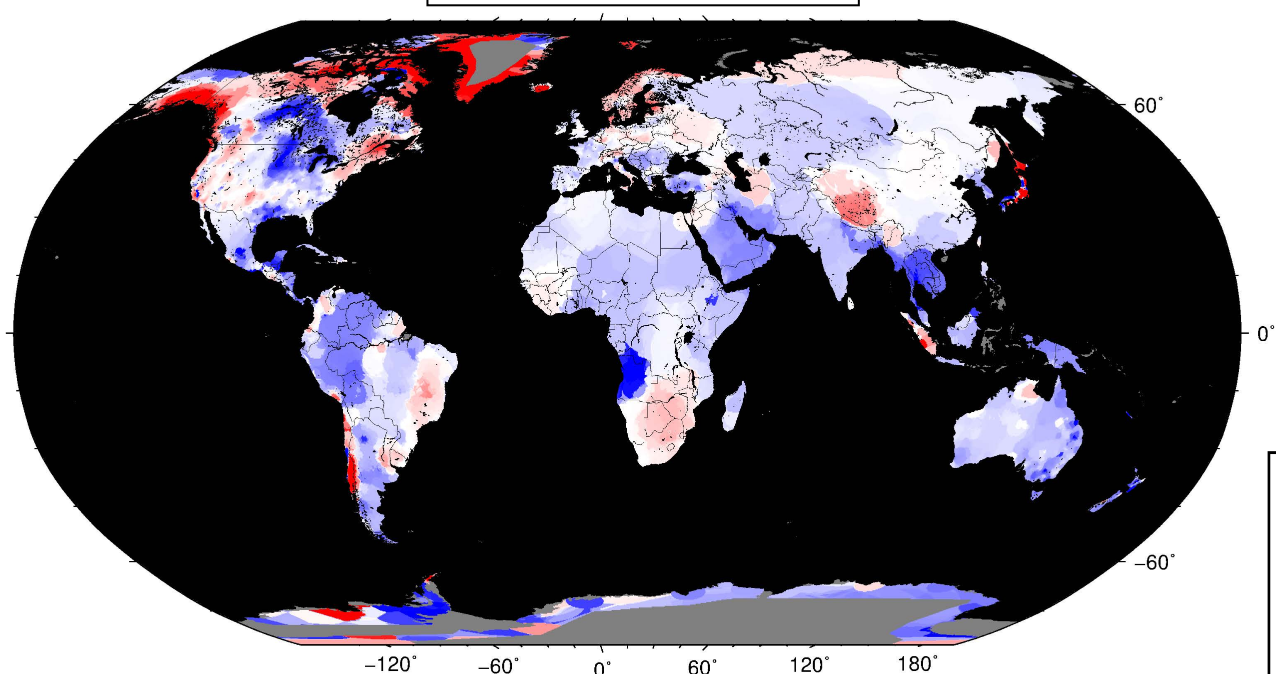
$$\text{Volume Flux} = \int_{\partial S} v_u(\vec{r})\,dA$$

Global Vertical Land Motion: The Budget

Observed VLM



VLM Corrected for GIA



Now the Globe

Up flux: 81.6 km^3 /year

+

Down flux: -64.3 km^3 /year

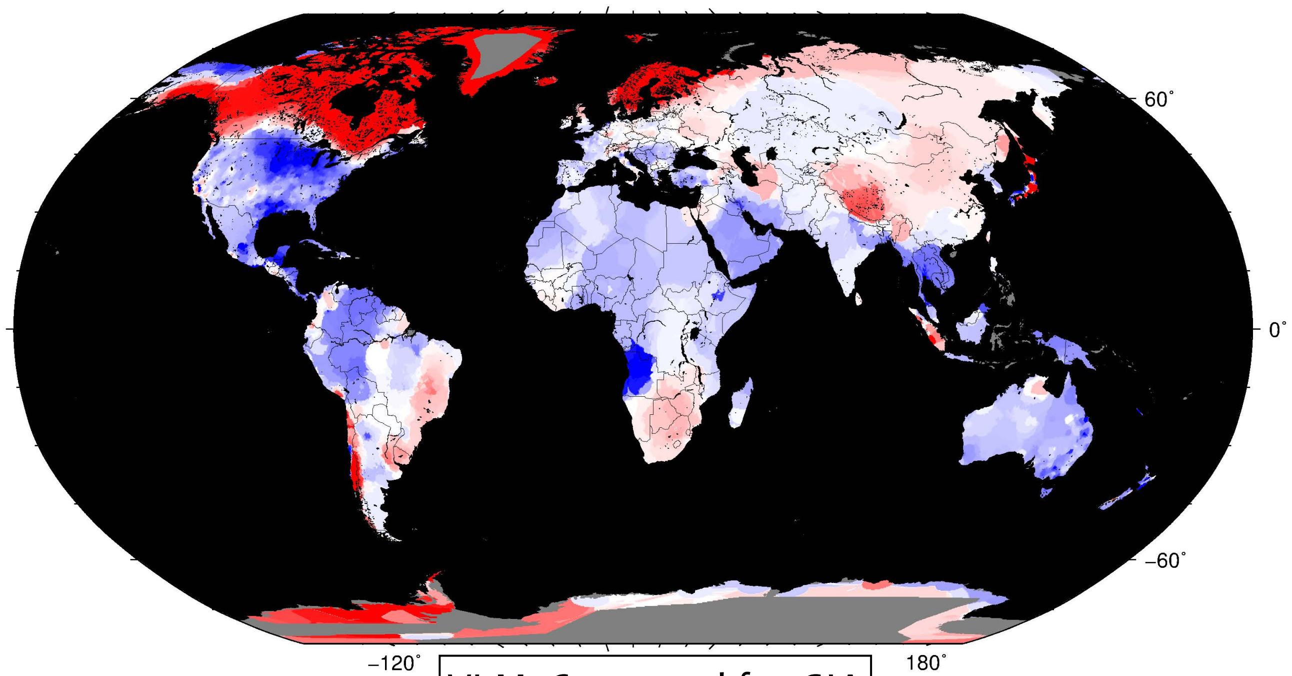
=

Net flux: 17.3 km^3 /year

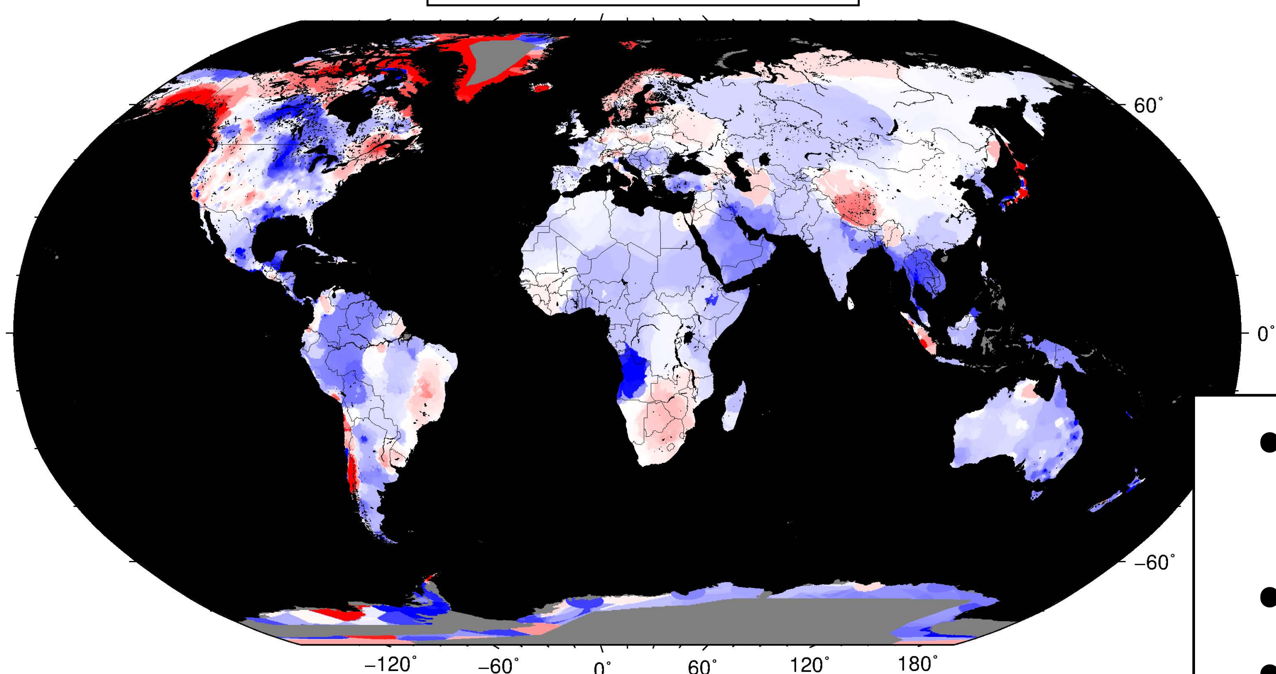
- Net uplift of GPS-observed continents.
- Assuming Earth is net zero volume change…
- Implies net downward motion of sea floor of -0.03 to -0.05 mm/yr
- Mostly from GIA

Global Vertical Land Motion: The Budget

Observed VLM



VLM Corrected for GIA



Now the Globe corrected for GIA

Up flux: -0.8 km^3 /year

\+

Down flux: -50.6 km^3 /year

=

Net flux: -51.5 km^3 /year

- However, after correcting for GIA we get the opposite.
- Net subsidence on continents
- Assuming Earth is net zero volume change…
- Implies net uplift of sea floor.
- However, there is large uncertainty because of network weakness in Asia and Africa

Summary

- Vertical GPS position time series at ~19,000 locations constrain vertical land motion (VLM) to support studies of sea level rise
- Many physical processes on Earth contribute to VLM
- GIA is the biggest single contributor.
- But tectonics, earthquake cycle, aquifer compaction, hydrological loading, also contribute on widely varying spatial and temporal scales.
- GPS Imaging useful for:
  - Identifying and characterizing the physical processes driving VLM
  - Estimating and assessing uncertainty of VLM at tide gauges
  - Asking questions about the budget of uplift/subsidence around the world


Thanks!
Questions?