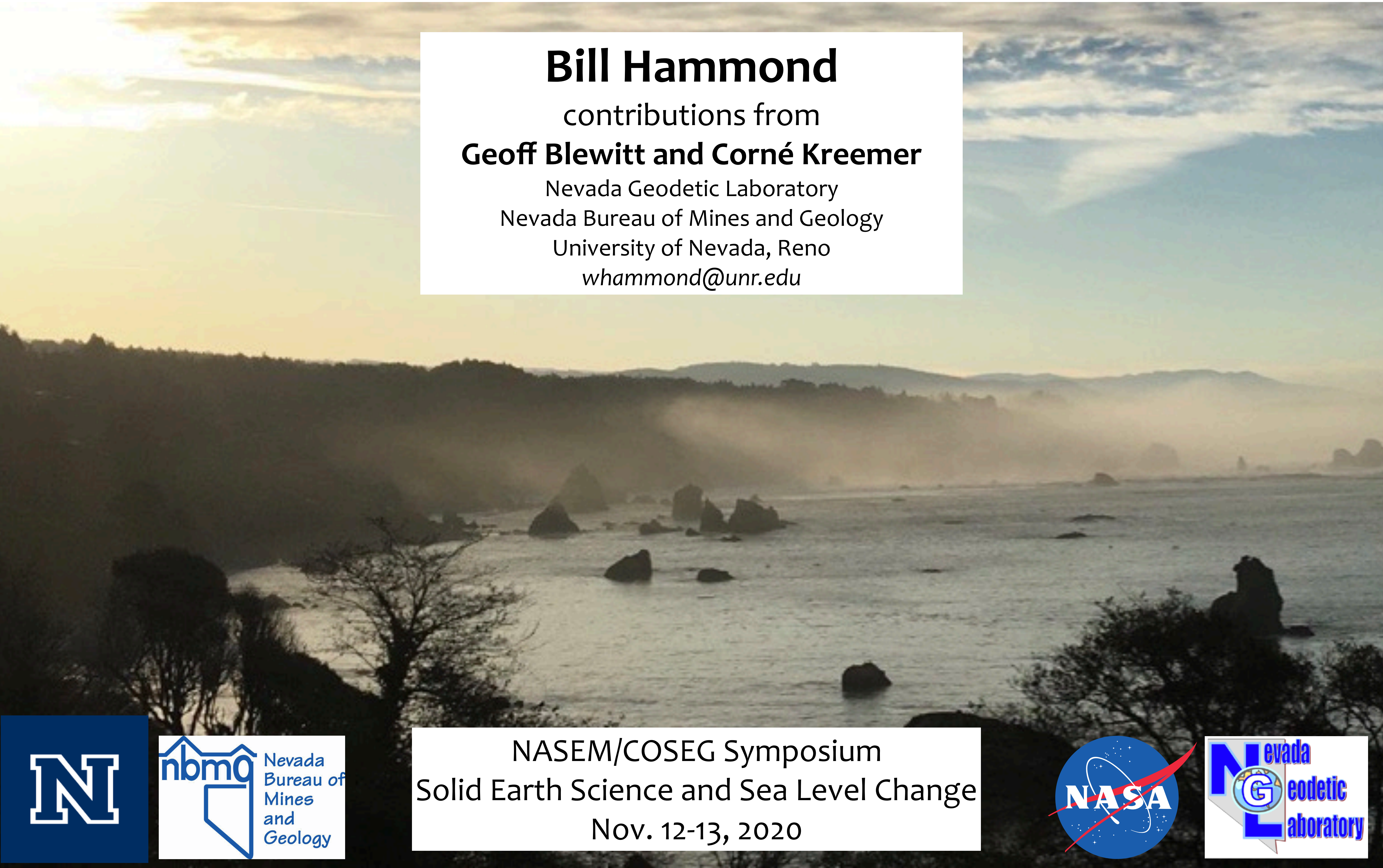
# Using GPS Networks to Measure Global Vertical Land Motion and its Impact on Sea Level Rise

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contributions from

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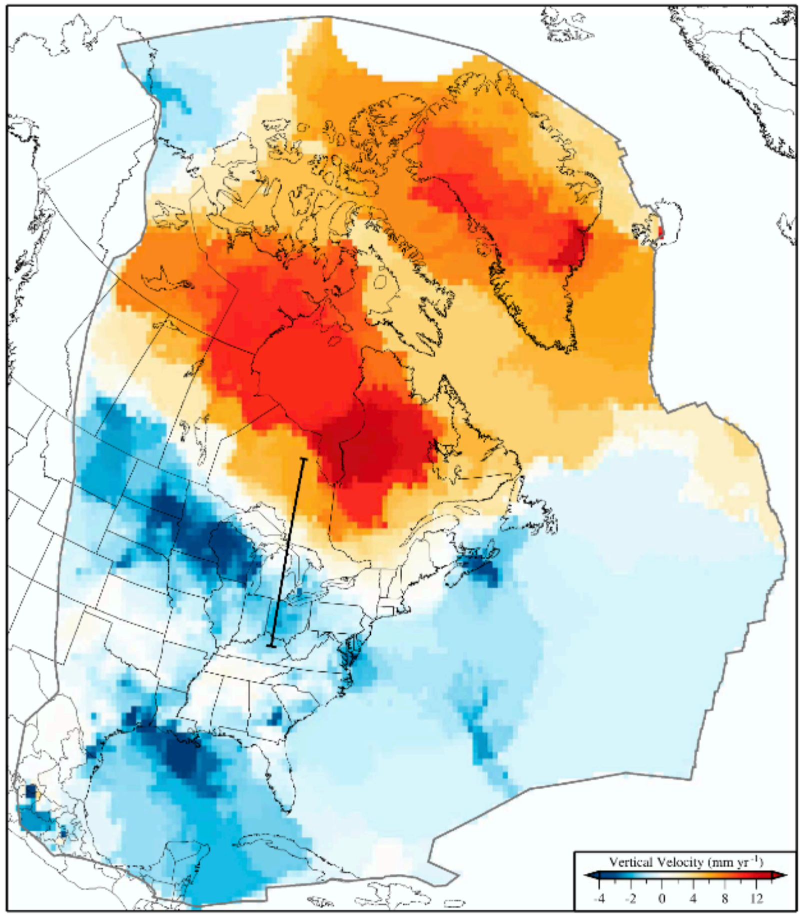
Nevada Bureau of Mines and Geology

# 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 >10⁴ yrs)

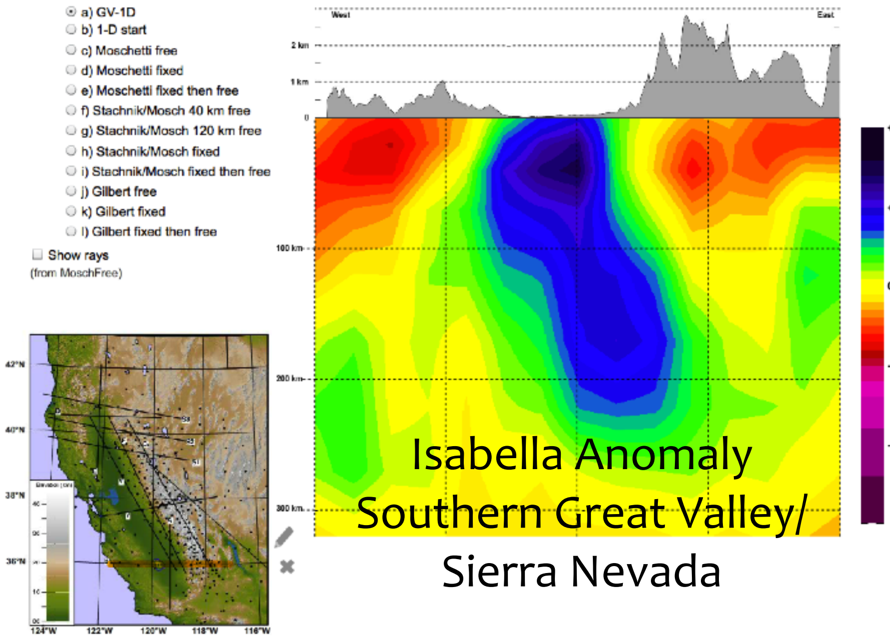



Kreemer et al, 2018 *JGR*

## Mantle Flow/ Dynamic Topography
(long term >10⁶ yrs)

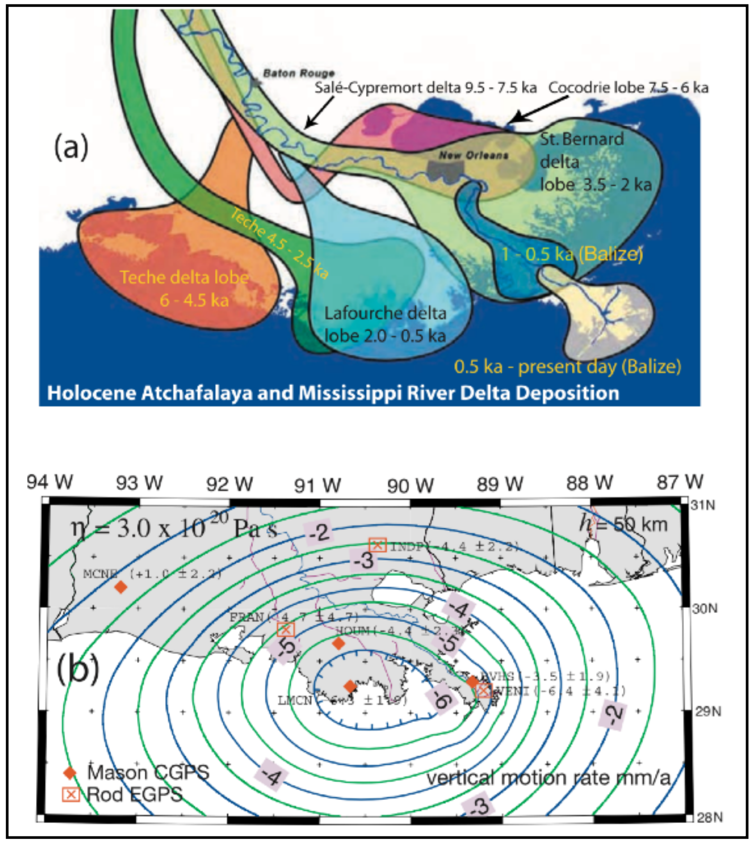
e.g. slabs, drips, delaminations, plumes, super plumes, rolls, channel flow

Not static, but *changing* part




Jones et al., 2014 *Geosphere*

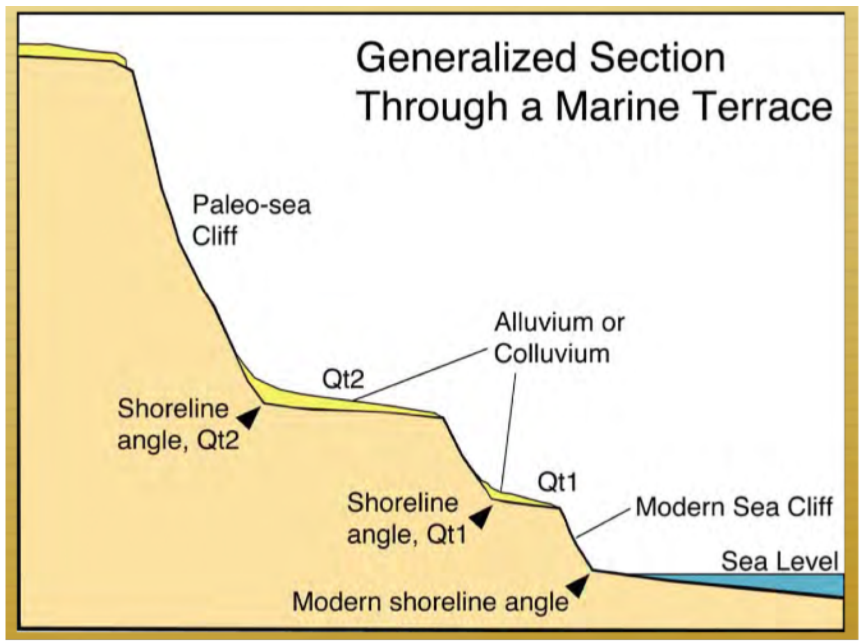
## Sediment Loading
(long term >10⁴⁺ yrs)

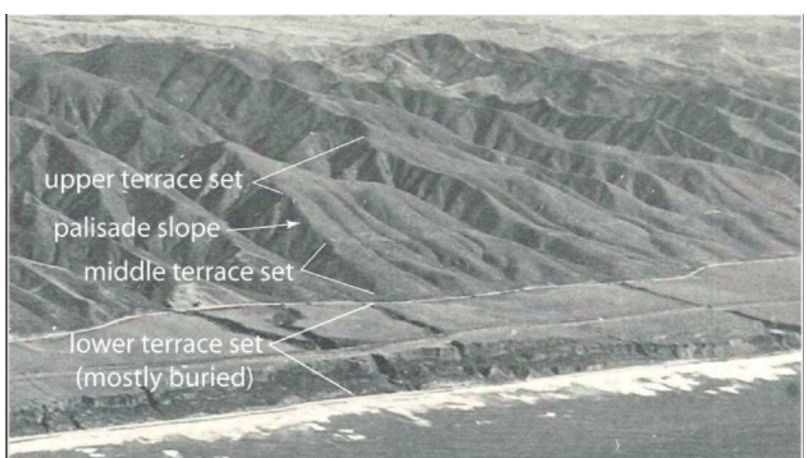



Ivins et al, 2007 *GRL*

# Vertical Land Motion: Example Processes

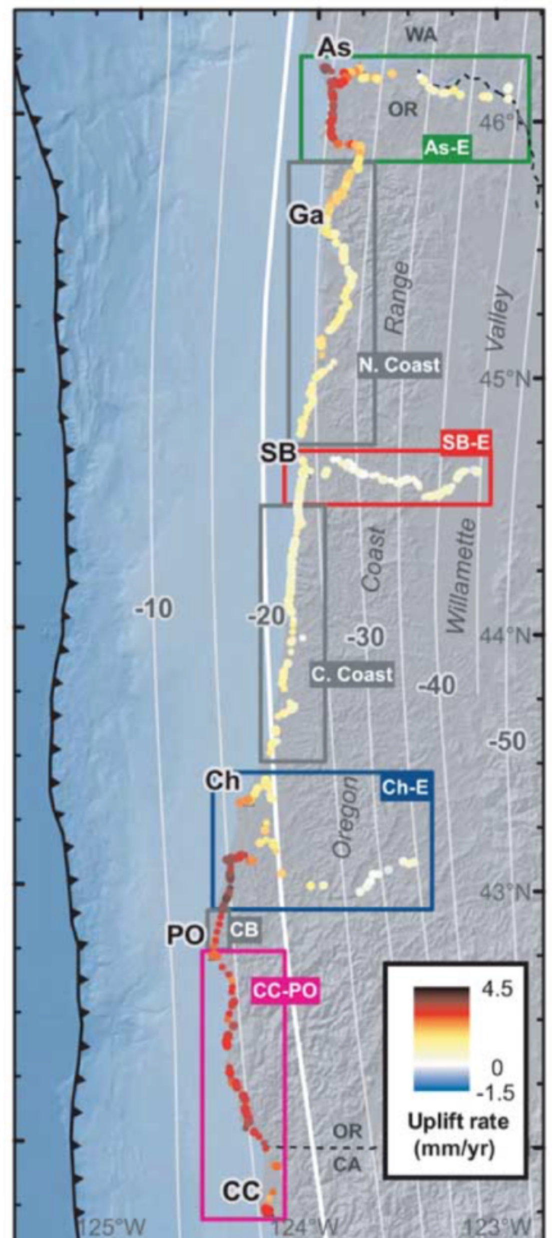
## Tectonics Long Term
(longest term >$10^6$ yrs)



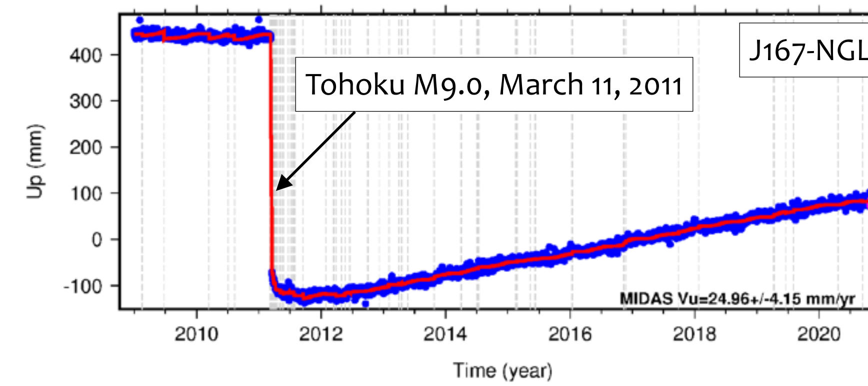

Rockwell 2013 *SONGS SSHAC Talk*

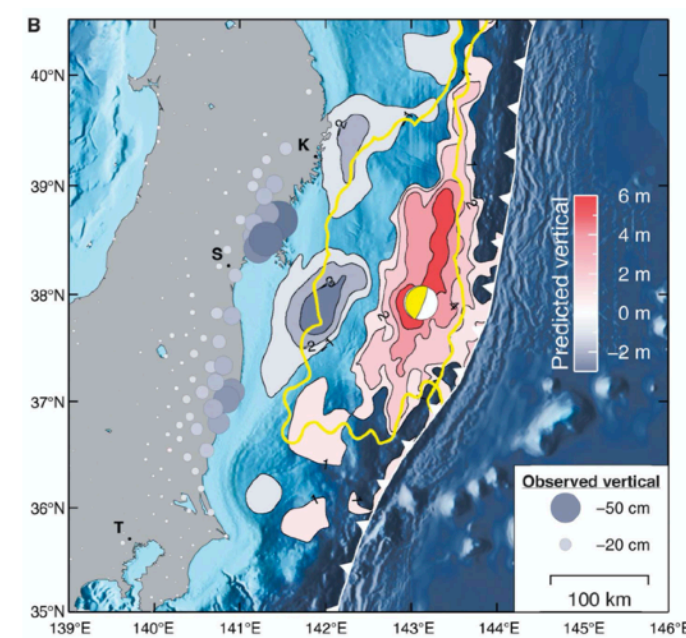
## Tectonics Interseismic
(medium term $10^2$-$10^4$ yrs)




Burgette et al, 2009 *JGR*

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



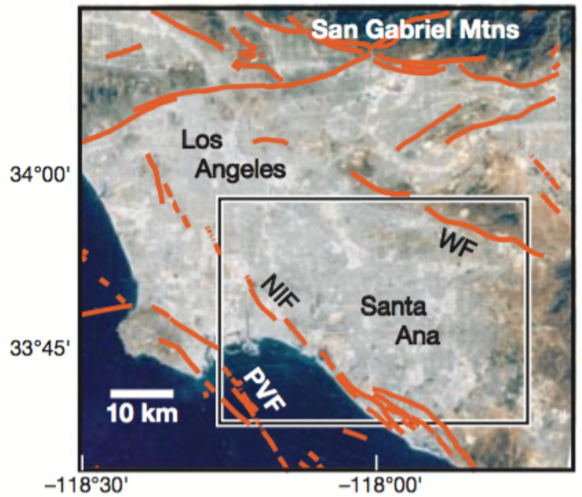



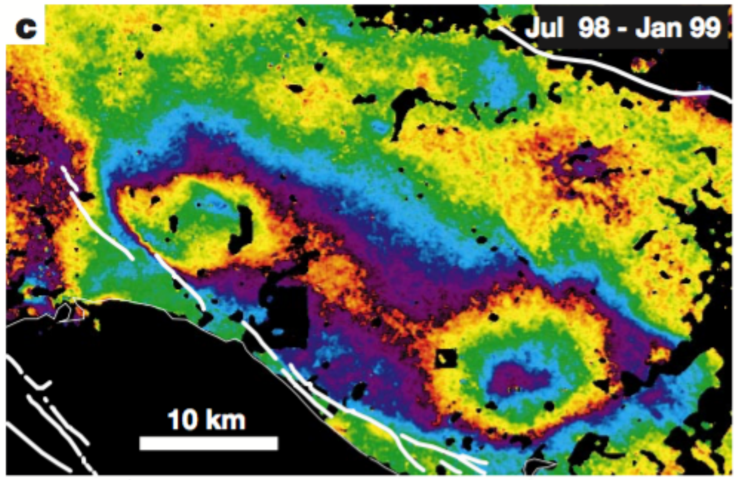

Simons et al, 2011 *Science*

# Vertical Land Motion: Example Processes

## Groundwater Pumping/Recharge

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

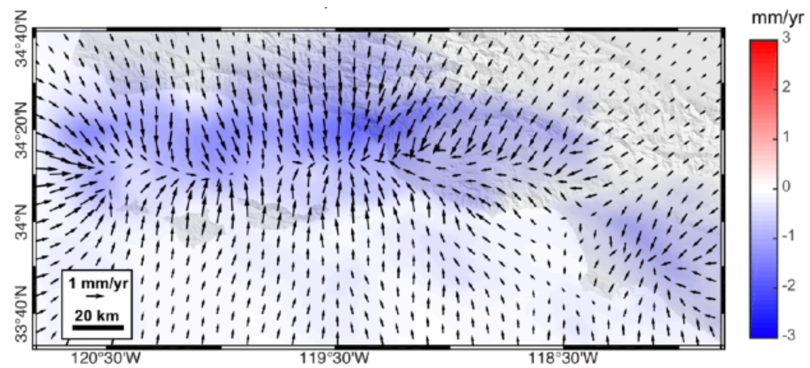


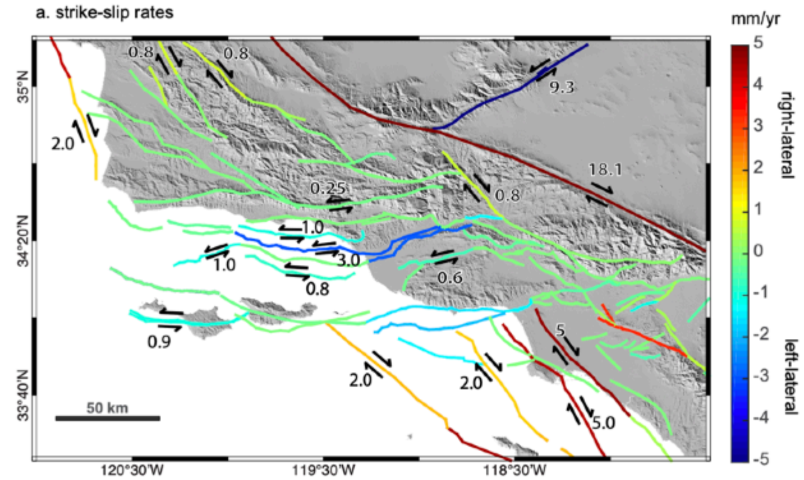




Bawden et al, 2001 *Nature*

## Sediment Compaction

(sometimes anthropogenic)
(short to long term )

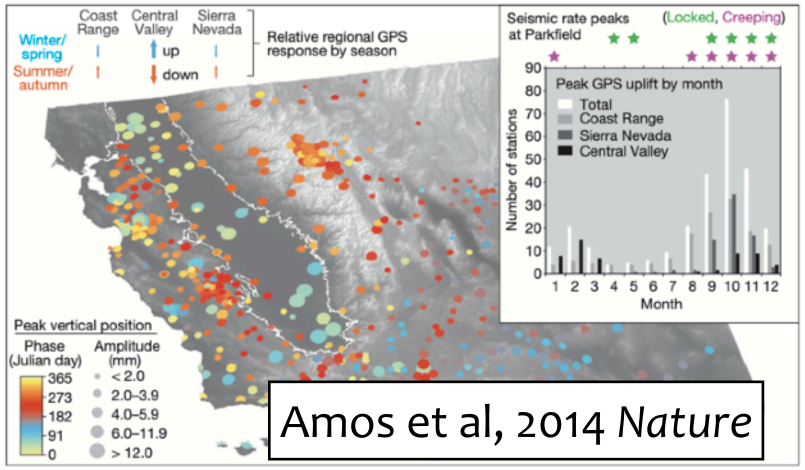


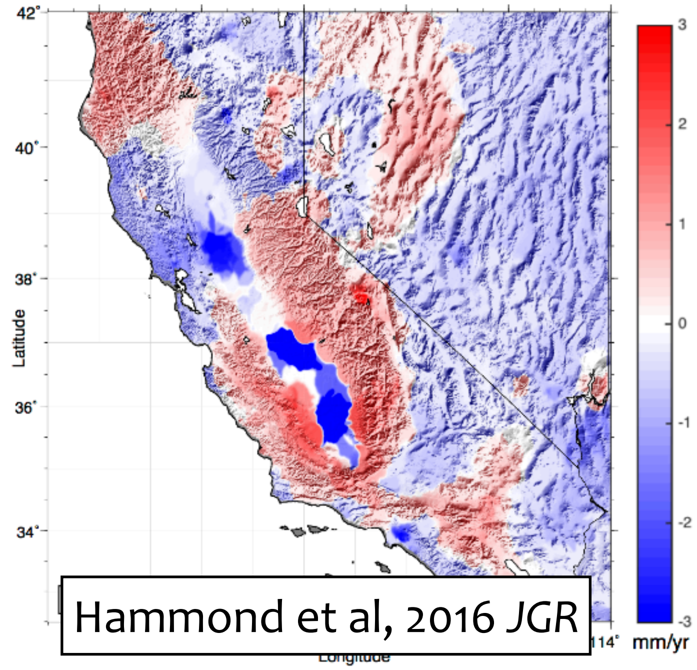

Johnson et al, 2020 *JGR*

## 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.

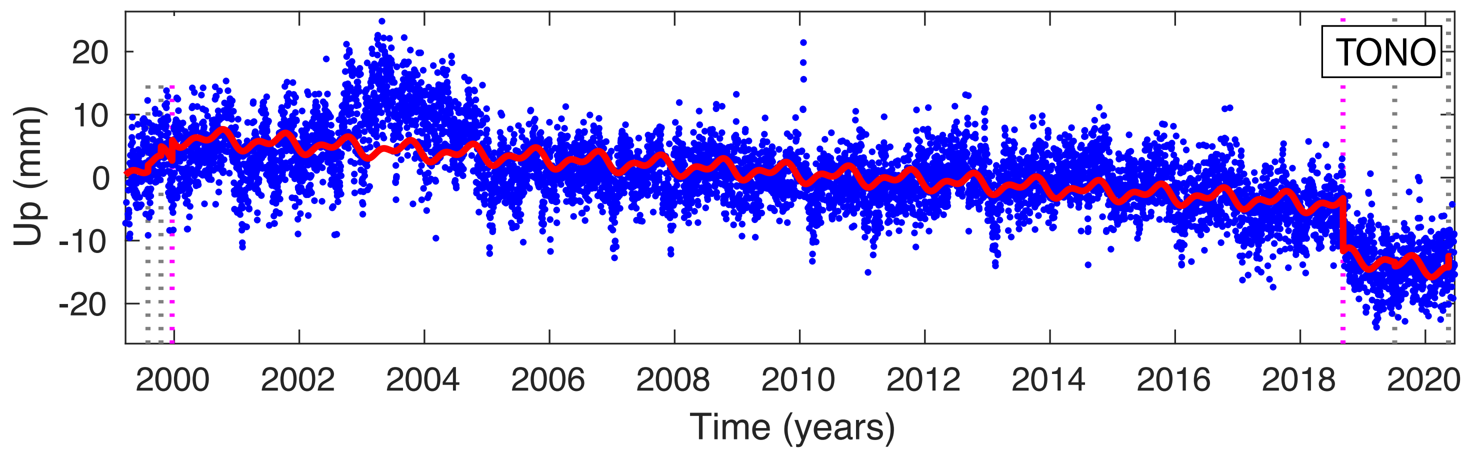
P534 - NSF NOTA station north of Santa Cruz, CA
Pacific Ocean in background

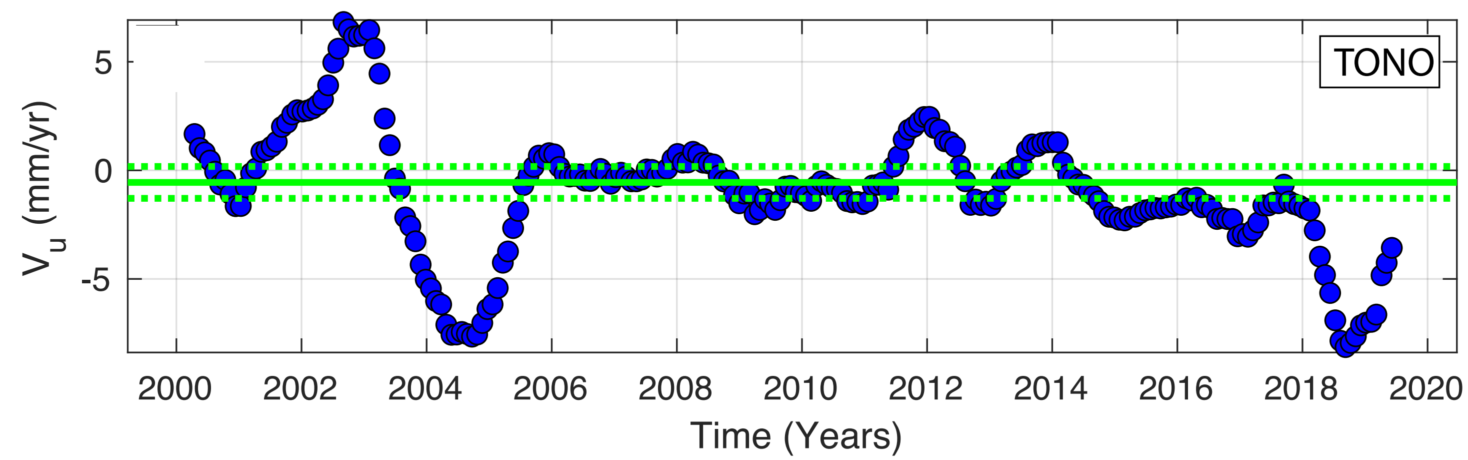
Station operated by UNAVCO

# 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

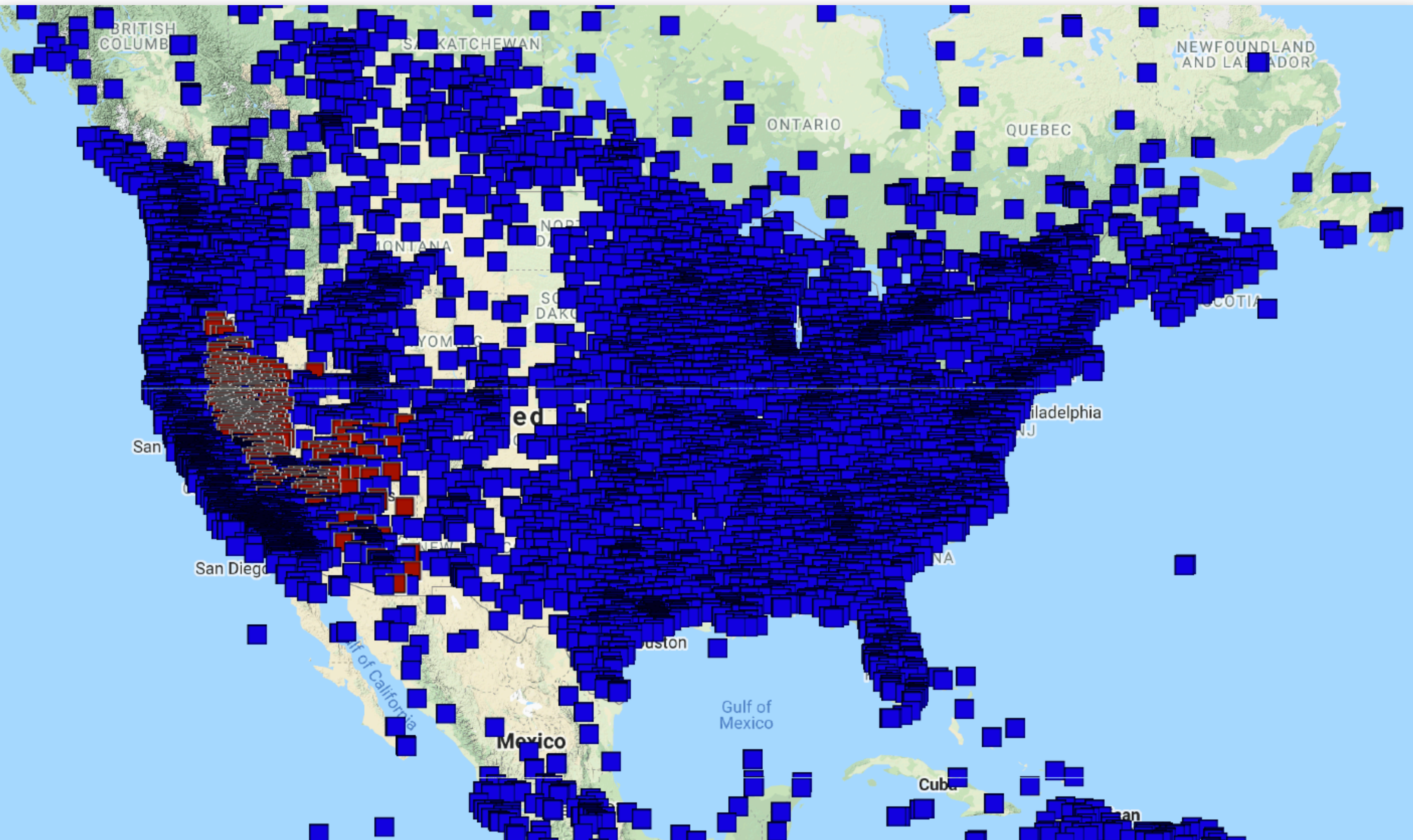
A Example GNSS Vertical Position Time Series



# 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

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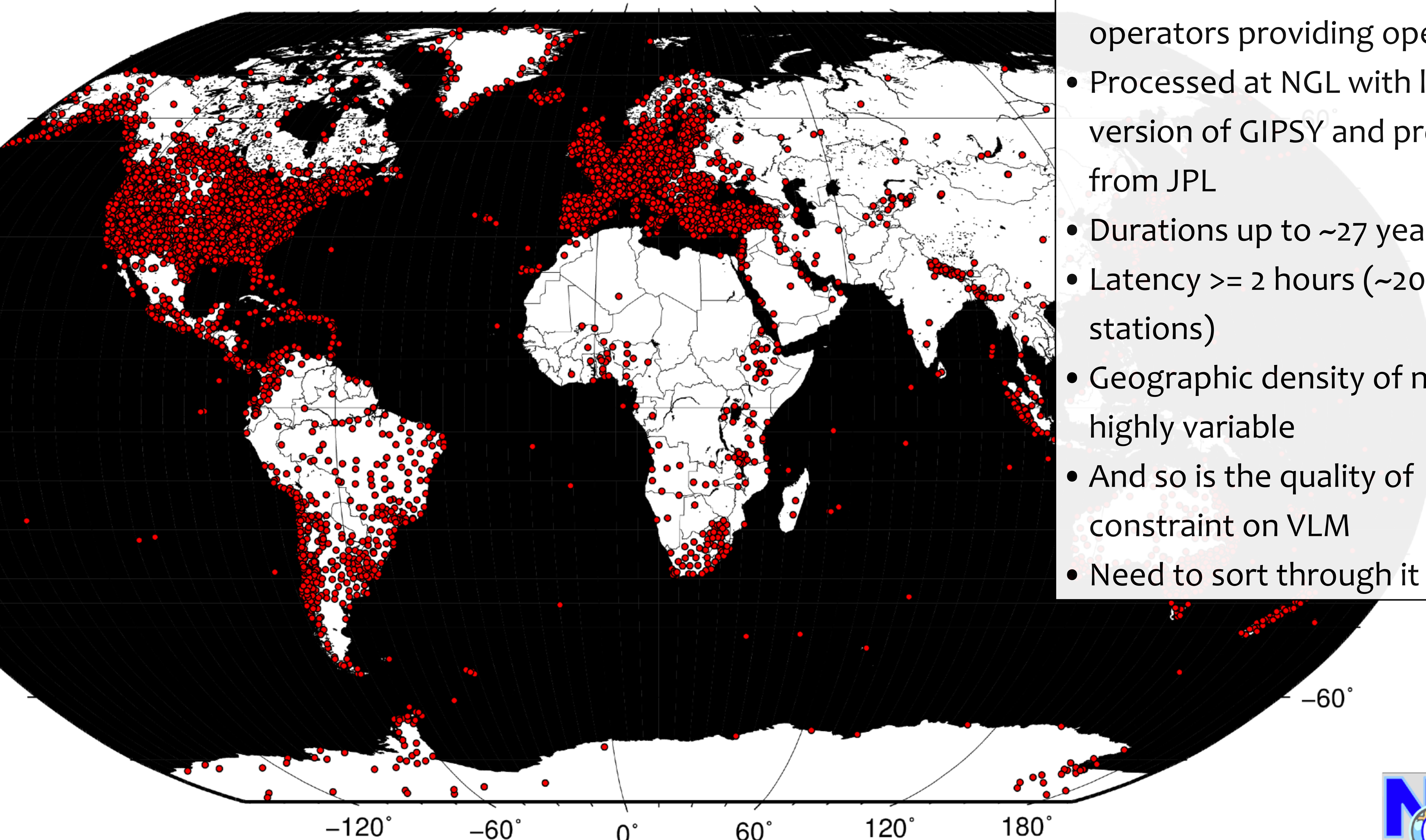


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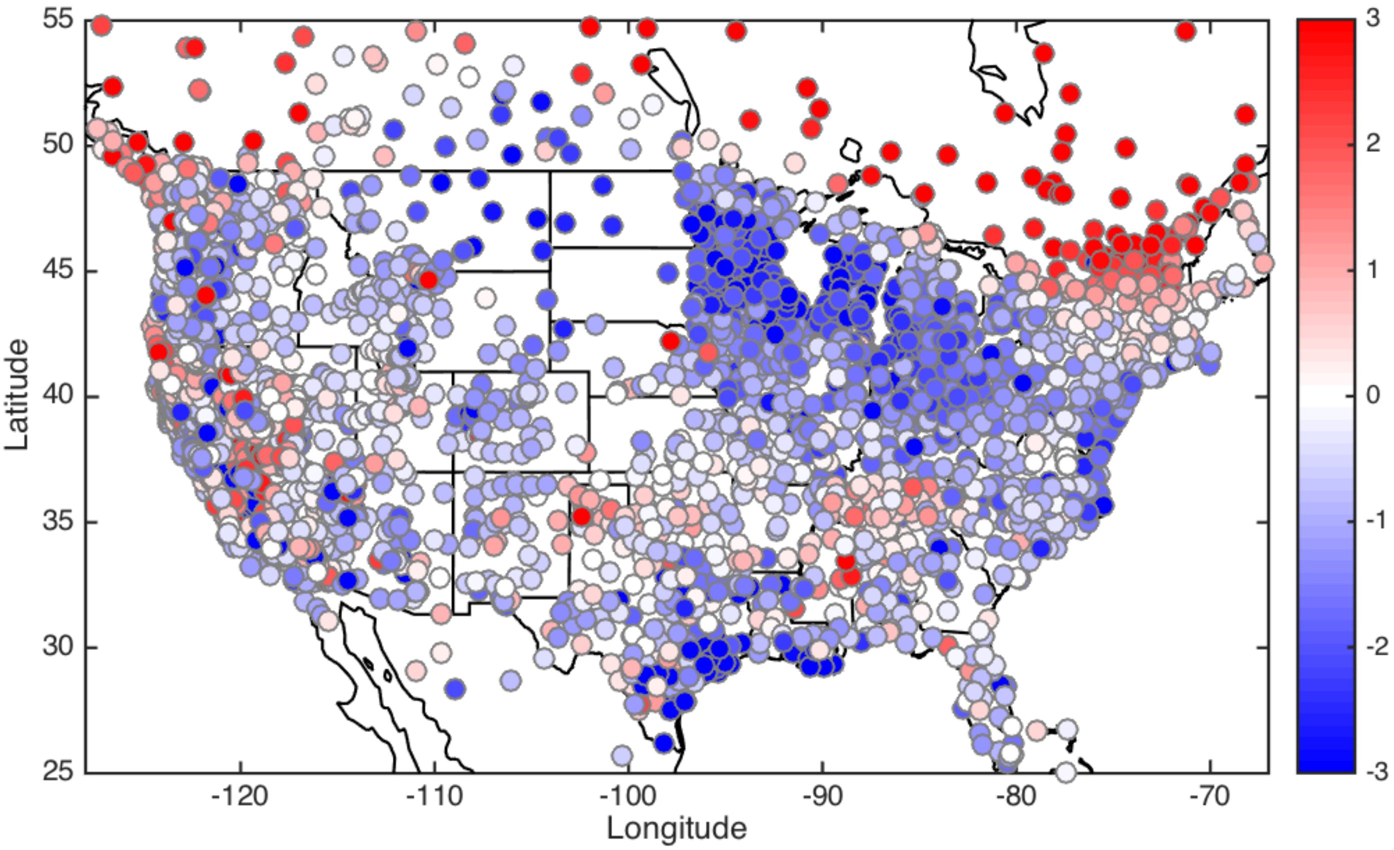
# Vertical Land Motion: Imaging




- Robust derivation of vertical rates with **MIDAS** trend estimator (Blewitt et al., 2016)
  - 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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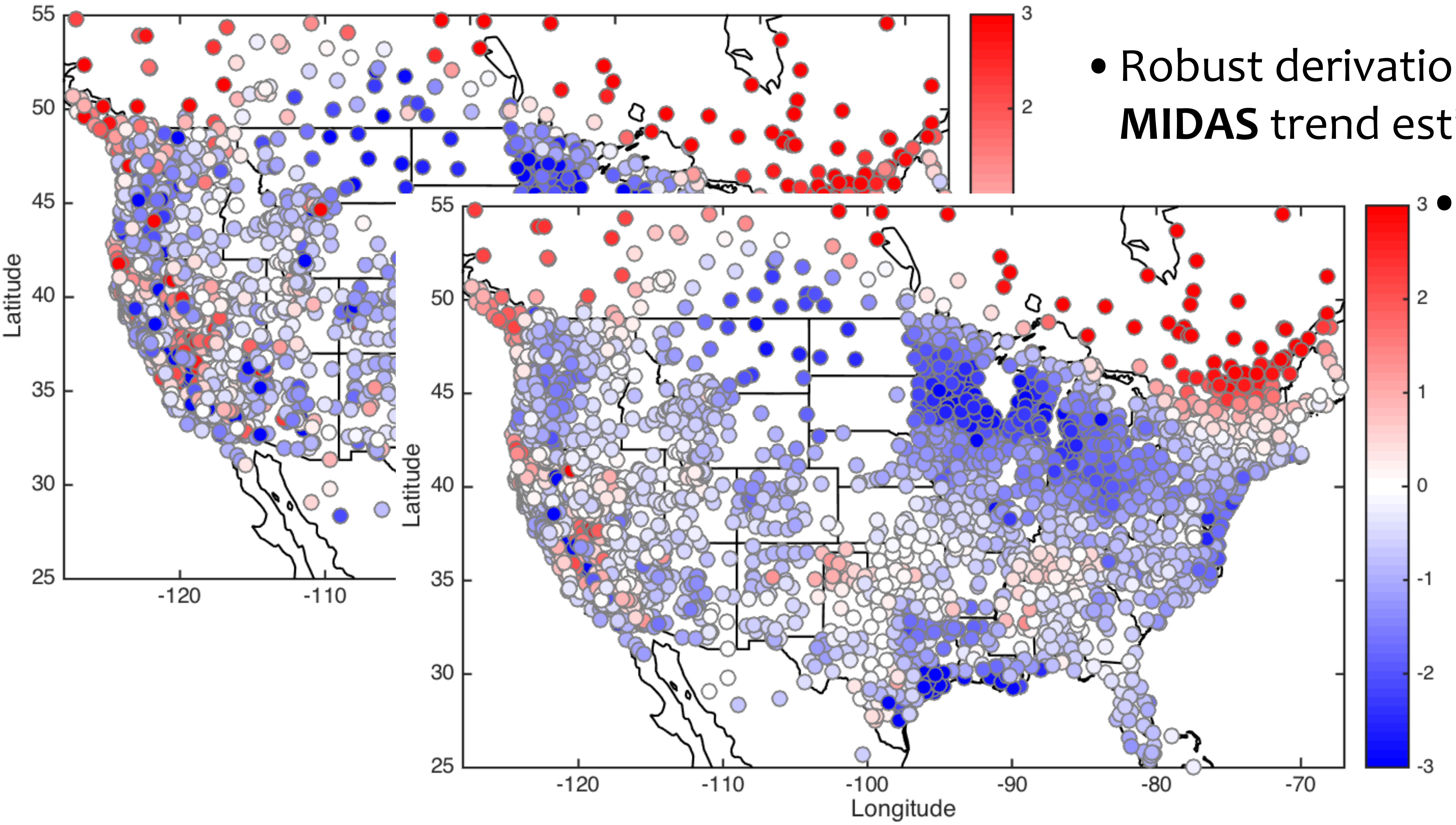


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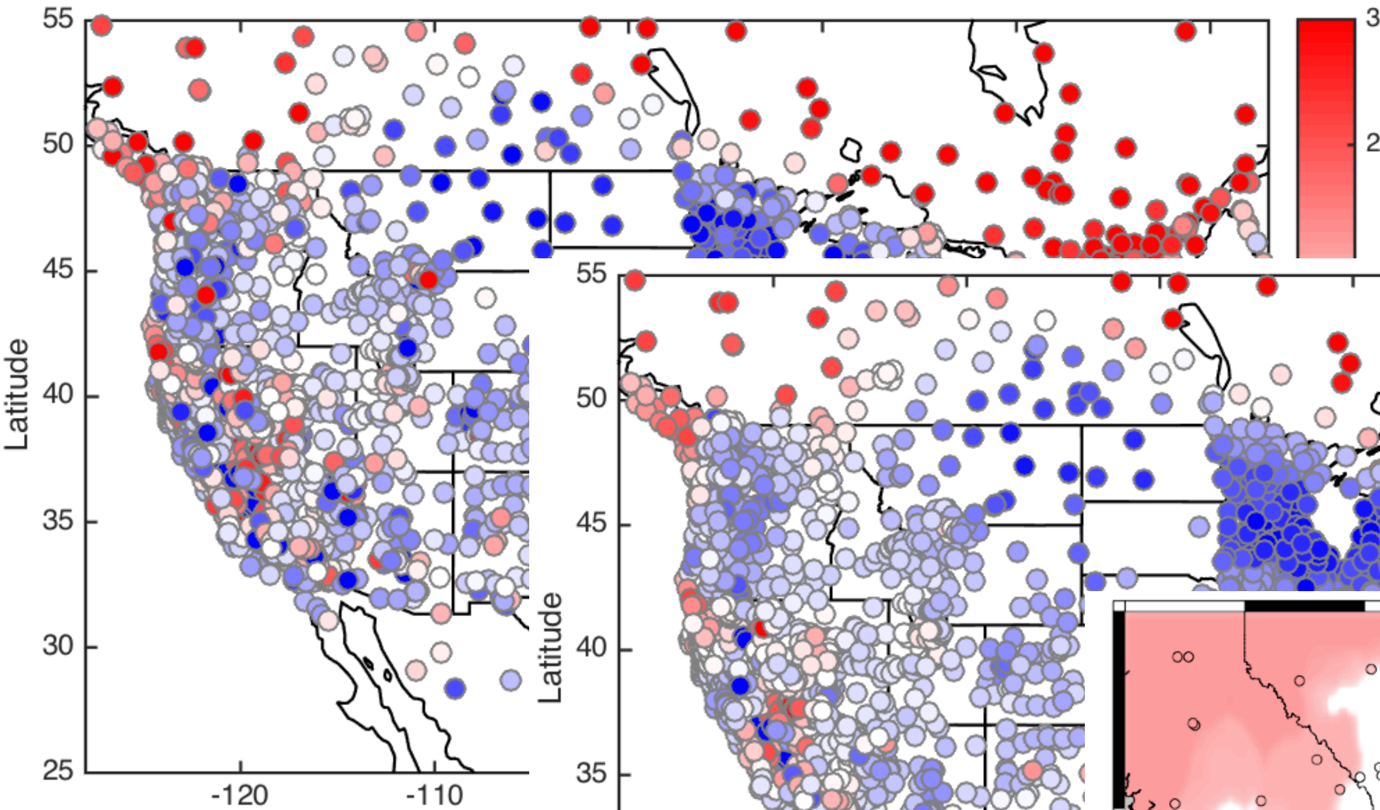


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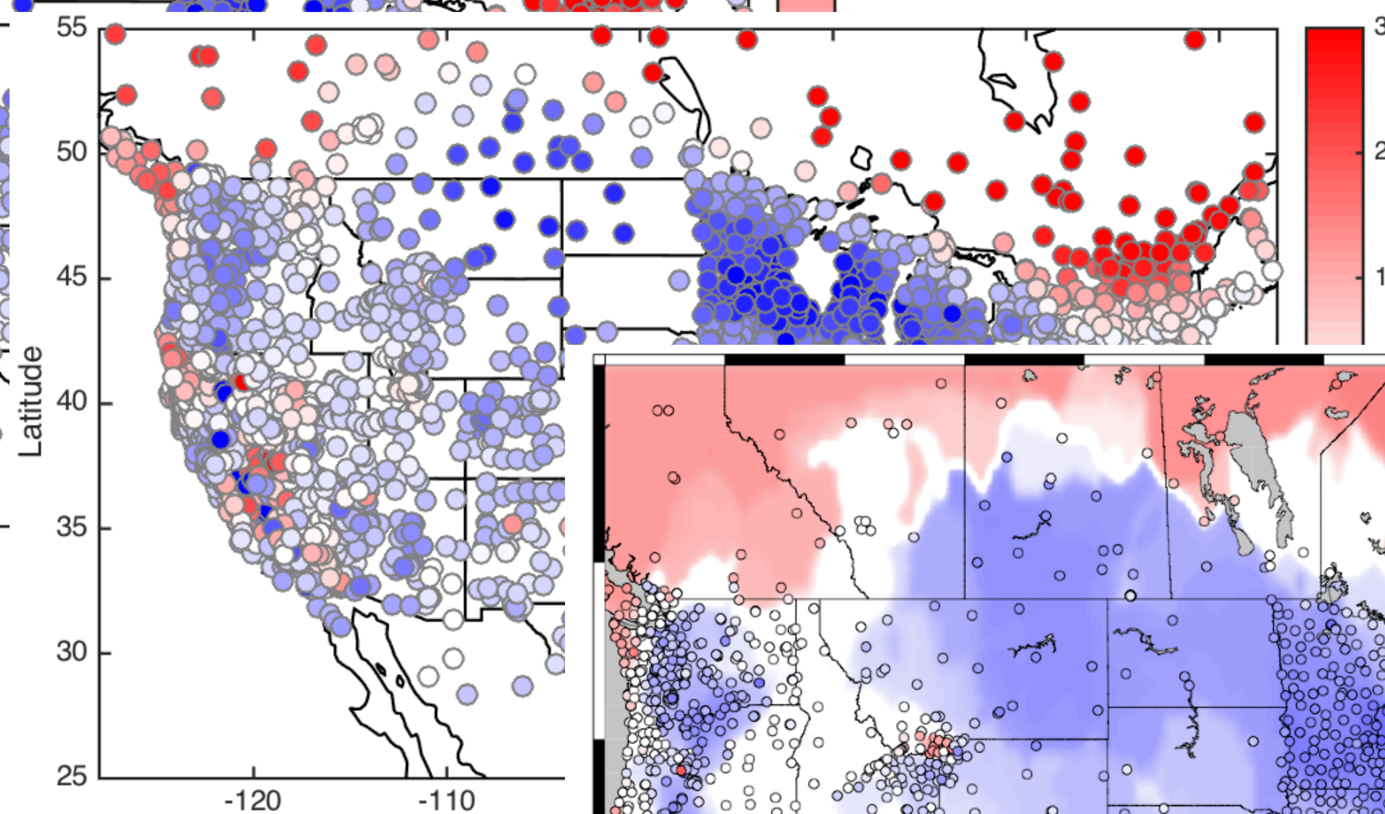


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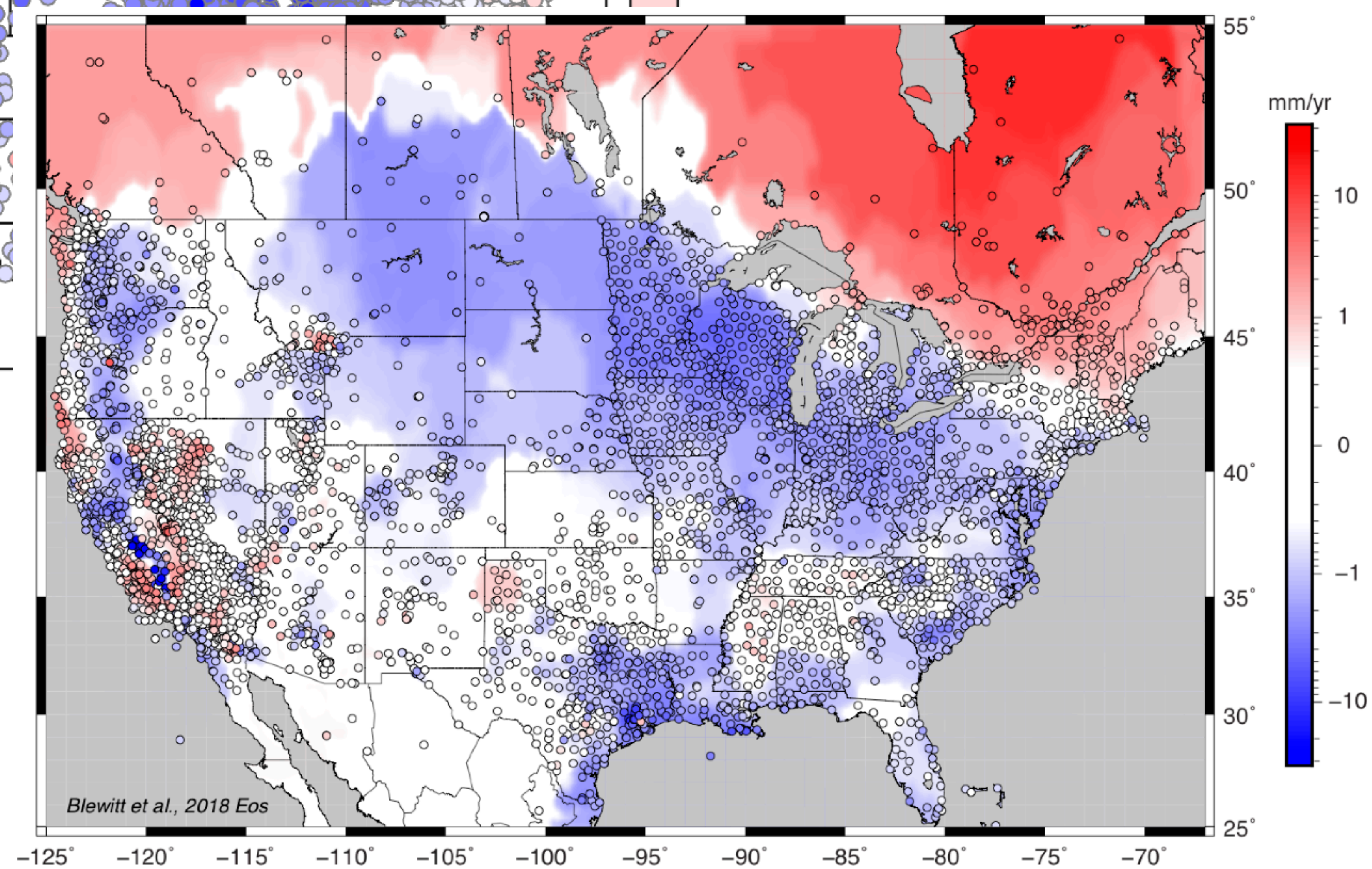


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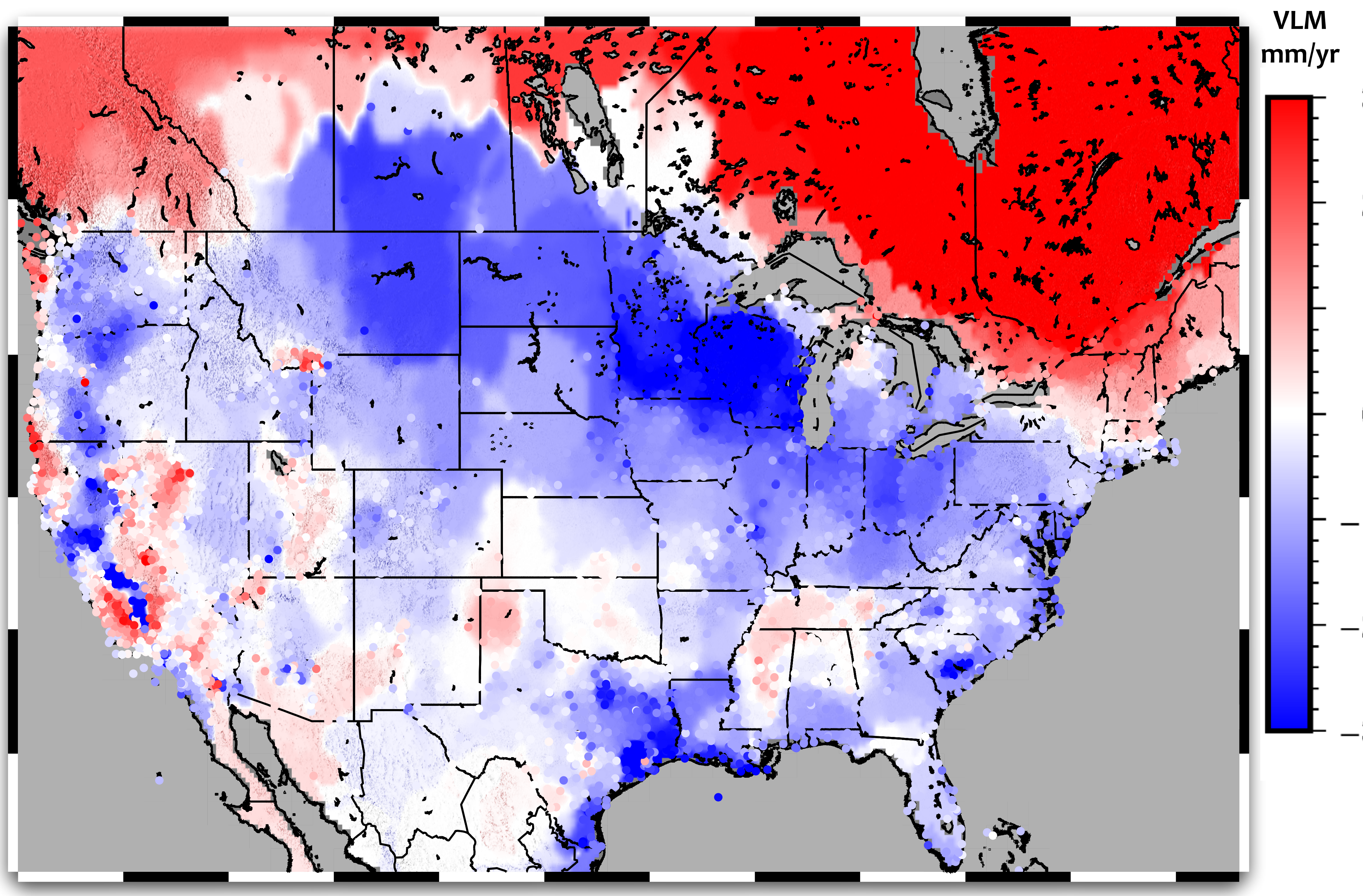
# Vertical Land Motion: Imaging

Some things we see

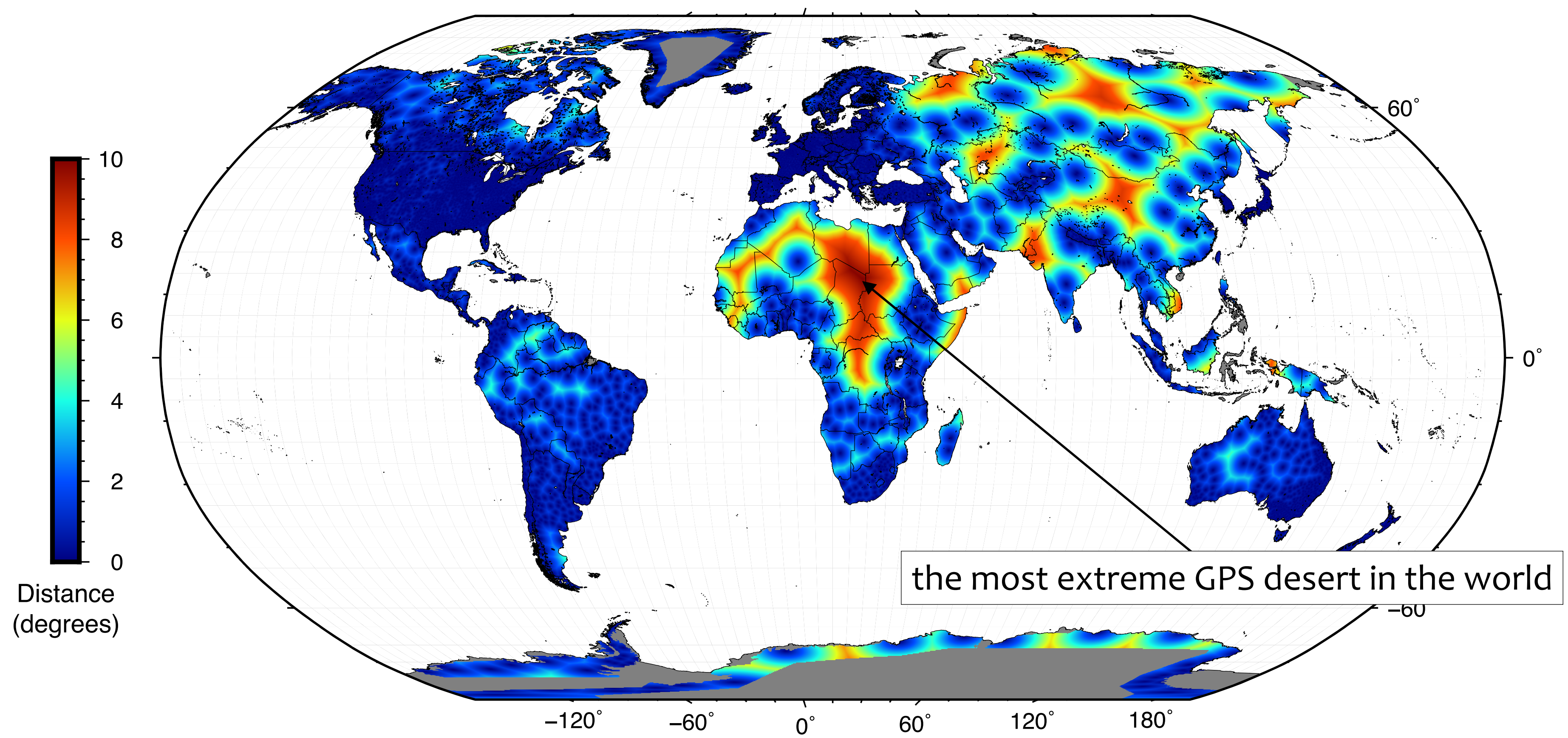
- The biggie: GIA uplift, fore bulge collapse and hinge line.
- Fore bulge from southern Alberta to the southeast US Atlantic Coast
- Gulf coast subsidence
- Yellowstone Caldera magmatic uplift
- Heavy subsidence in CA Central Valley
- Sierra Nevada/California Coast Range from drought-enhanced hydrological 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?

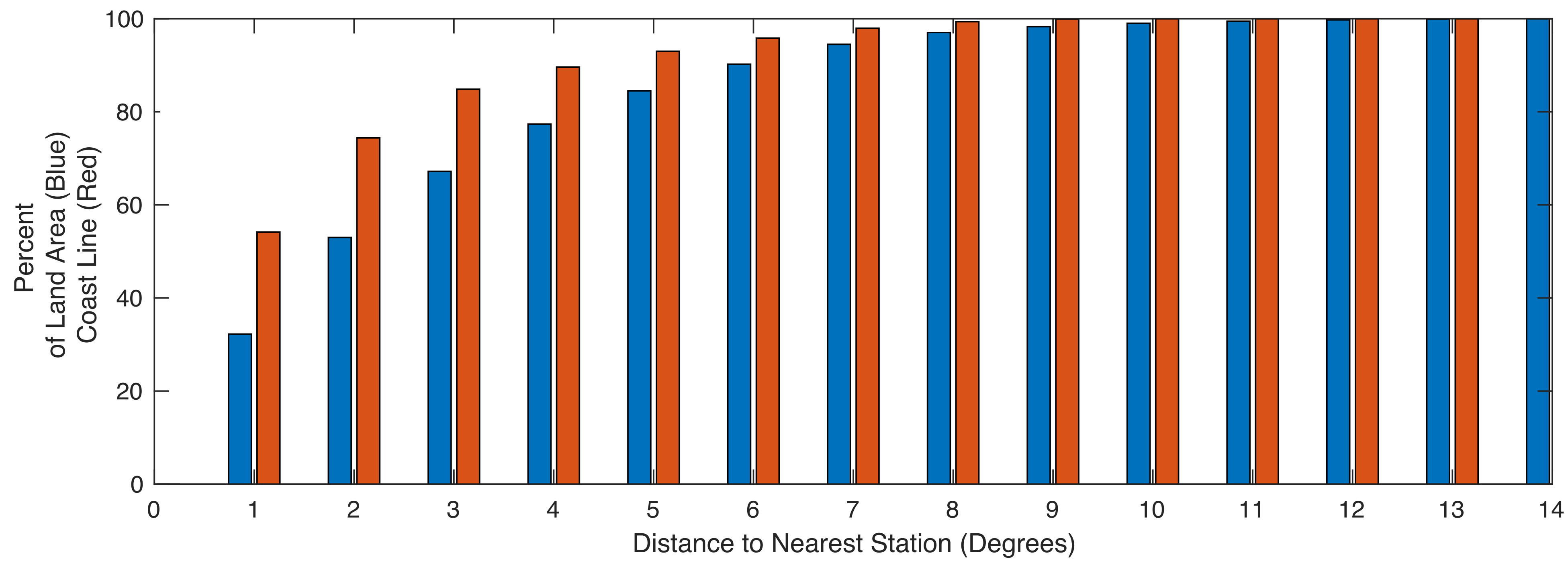
Distance to nearest GPS station in NGL archive for every point on land



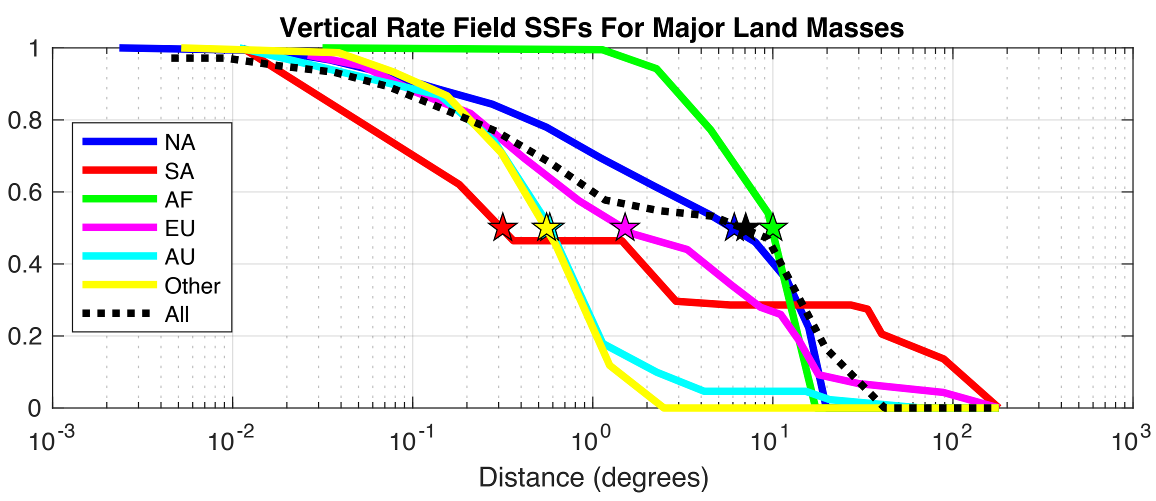

by Land Area = Blue Bars
by Coastline = Red Bars

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

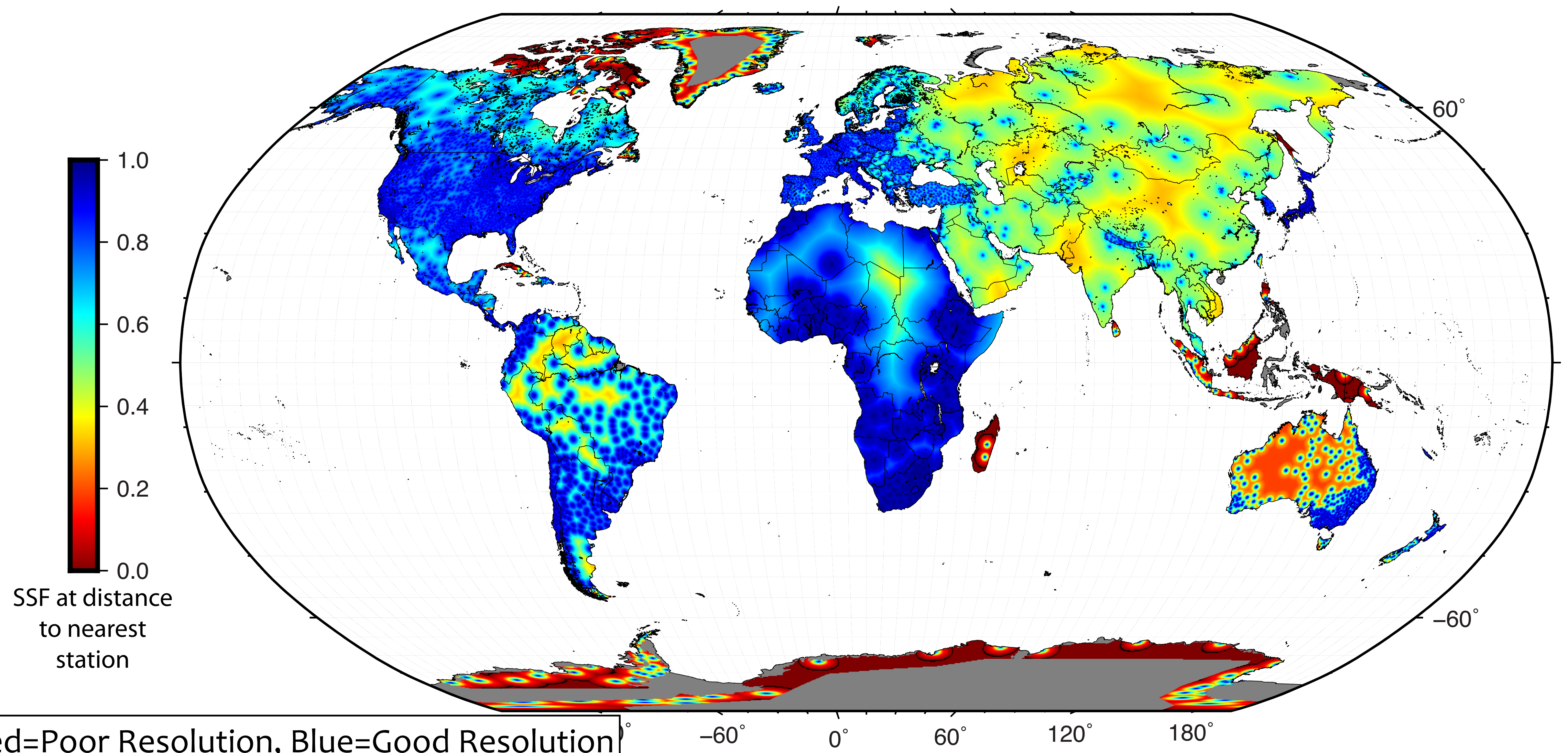
Coast better covered because most big empty areas are in continental interiors.



# Vertical Land Motion: Wavelength of Uplift Signals



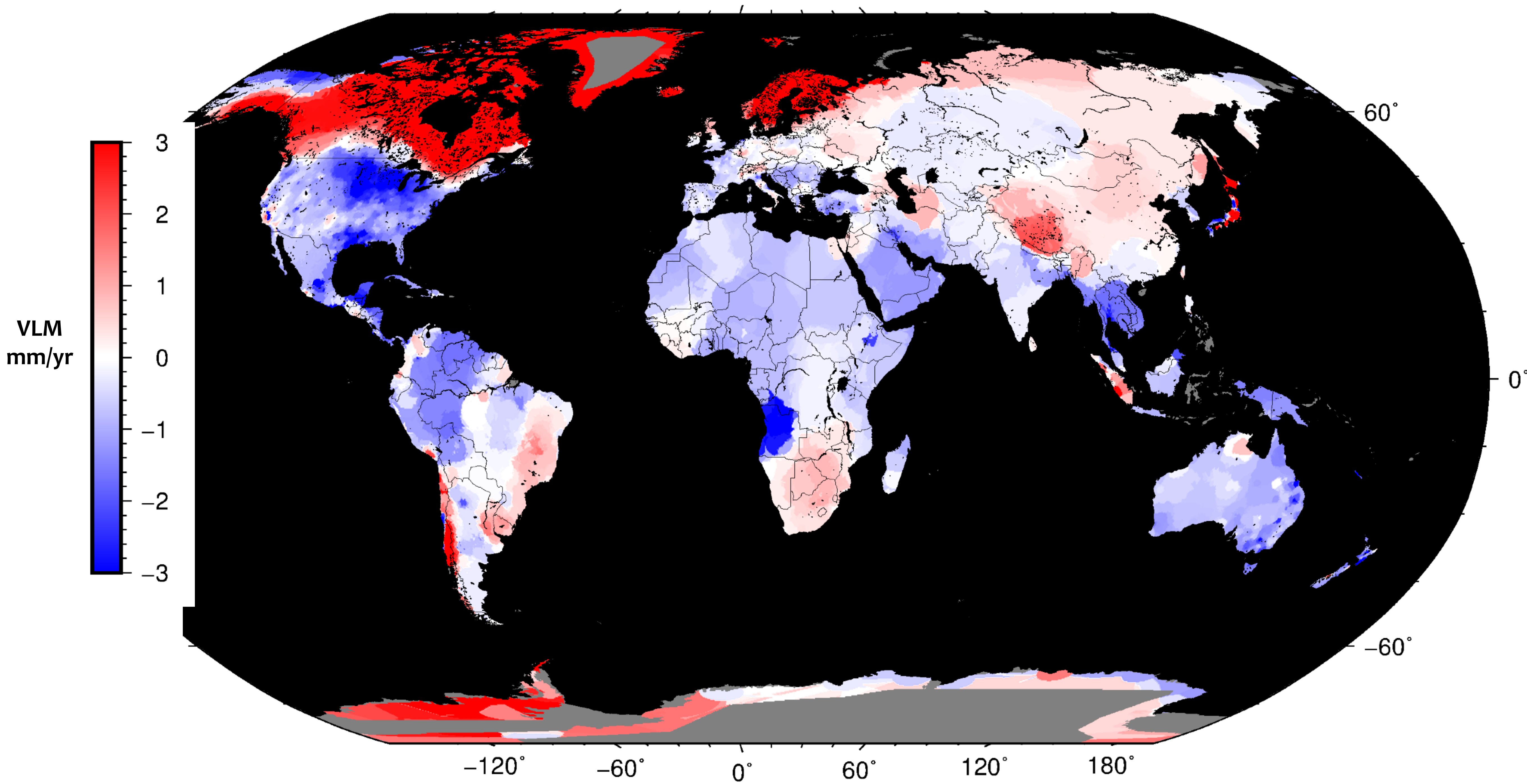

- From data derive function that measures spatial wavelength of dominant signals in VLM field
- Spatial Structure Function is VLM similarity as a function of distance
- Function varies across VLM domains
- Assesses network strength wrt signals



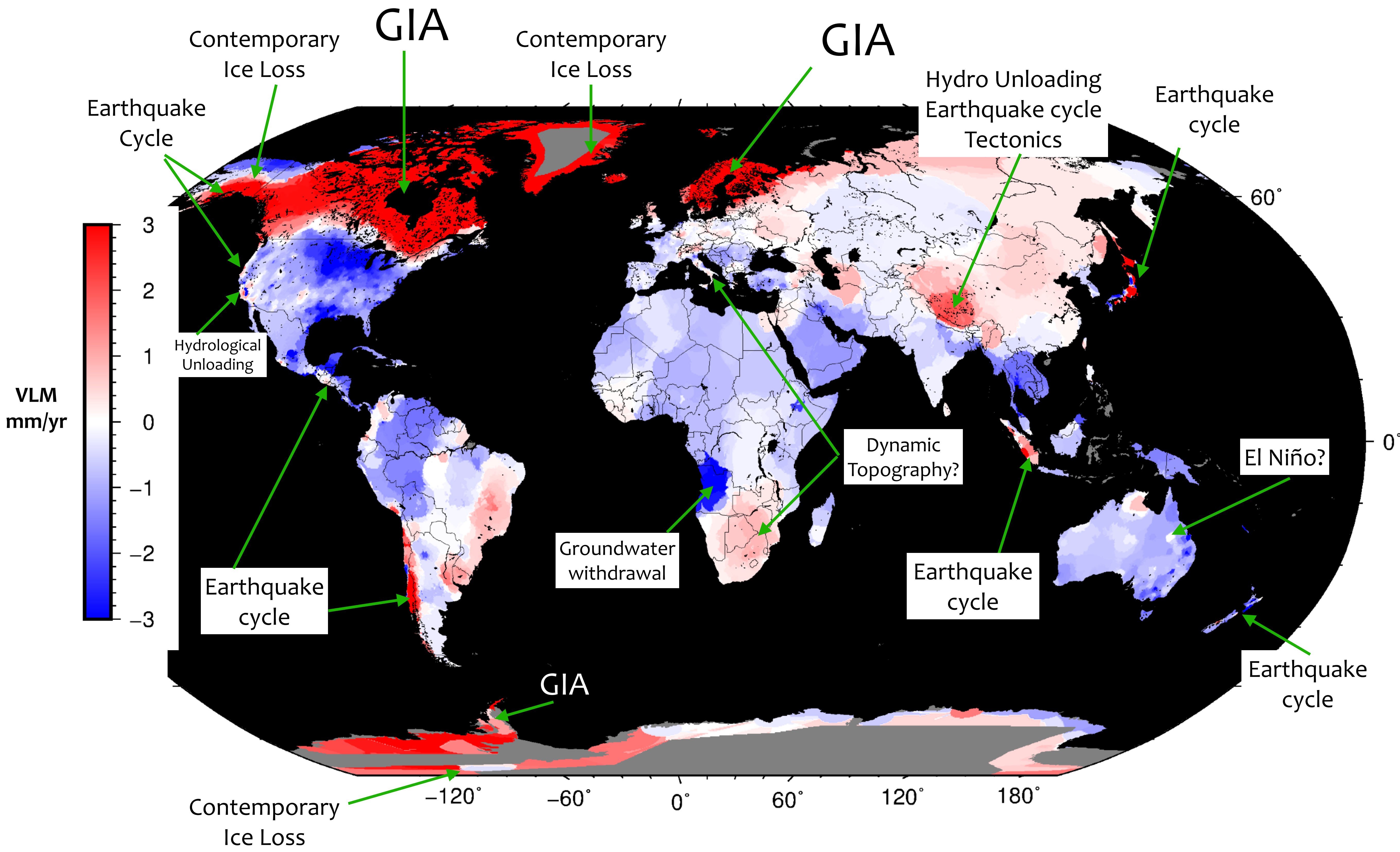

Red=Poor Resolution, Blue=Good Resolution

# Vertical Land Motion: Global

## Spatial Variability

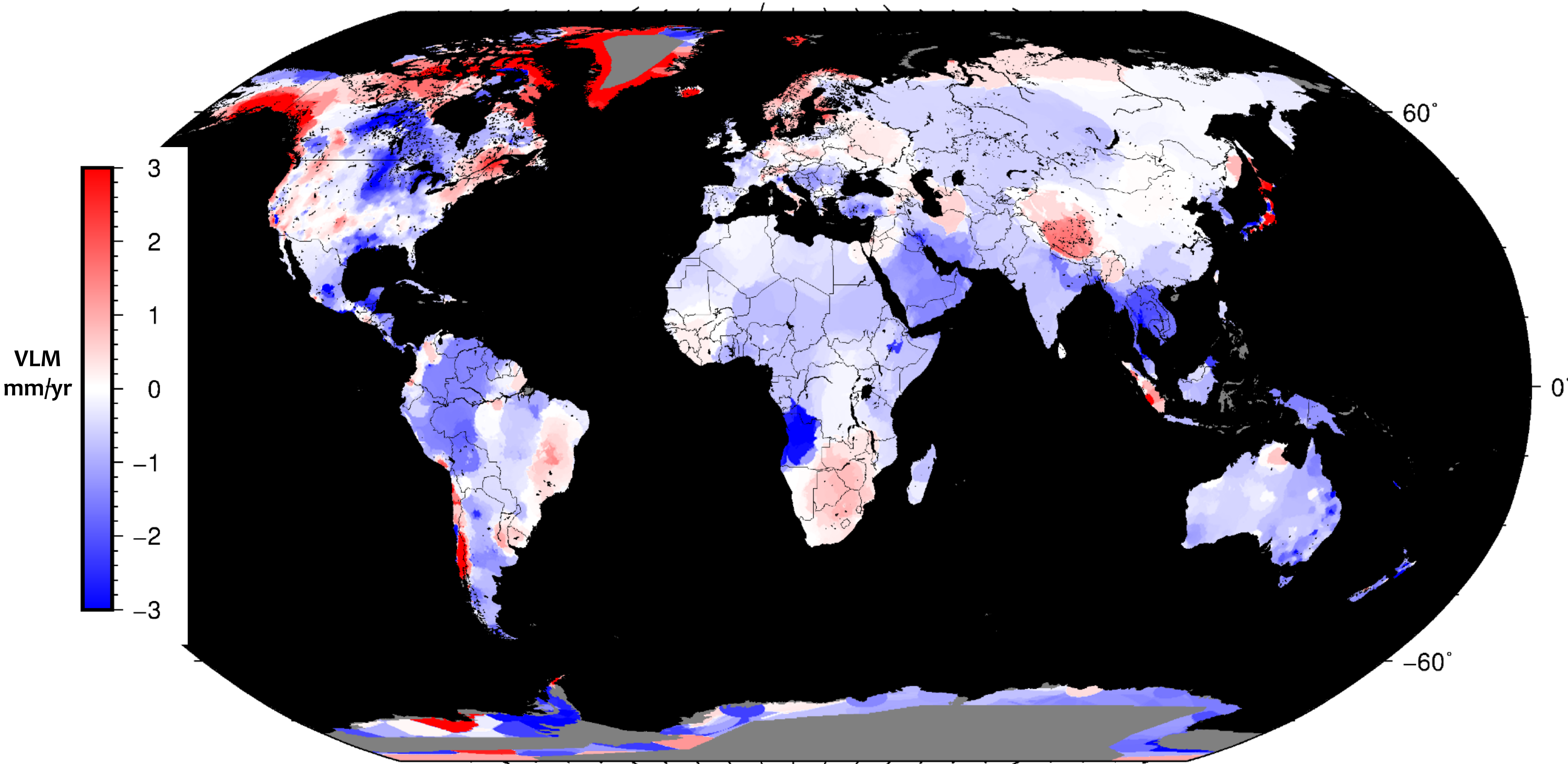


# Vertical Land Motion: Global



# Vertical Land Motion: Global - GIA Removed

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

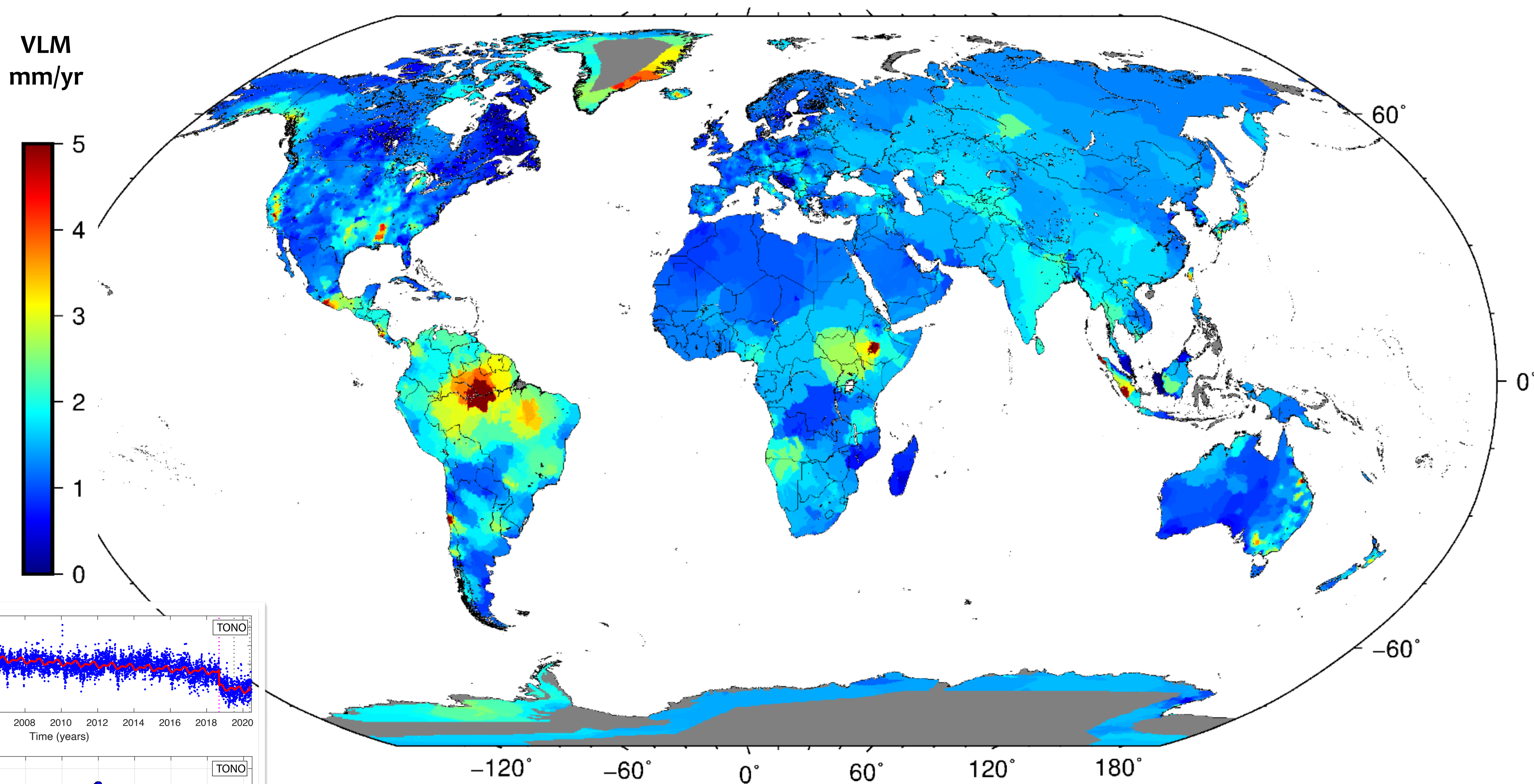


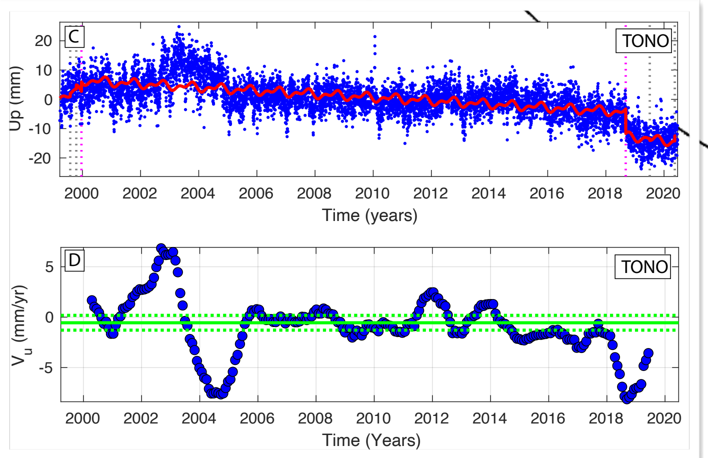

There is a lot of VLM left over after removing GIA.
But how much? How important is it?

# Vertical Land Motion: What Drives the Uncertainty?

## One Example: Temporal Variability

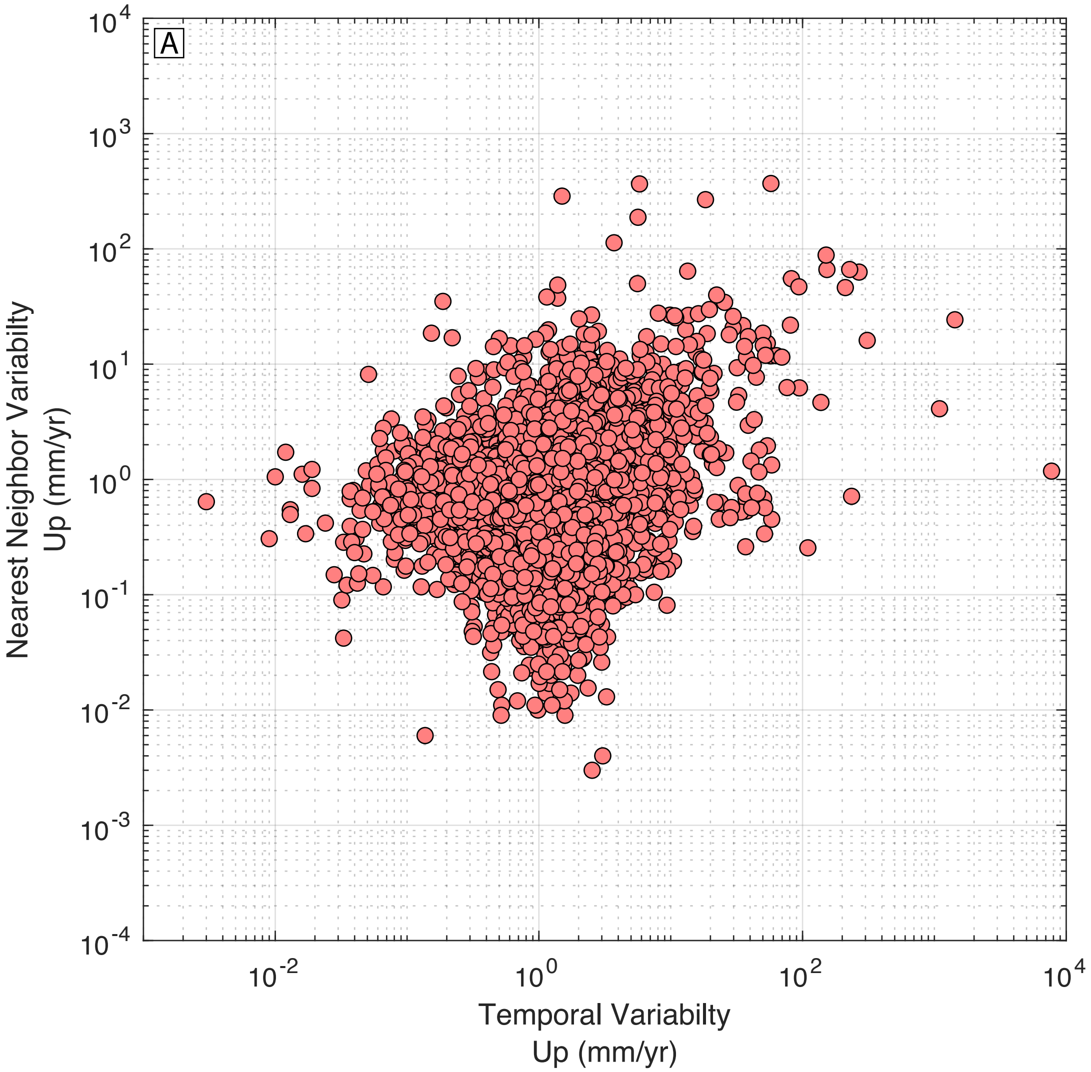
i.e. Wiggliness of the GPS Time Series
as measured by the median absolute deviation of Vu(t)



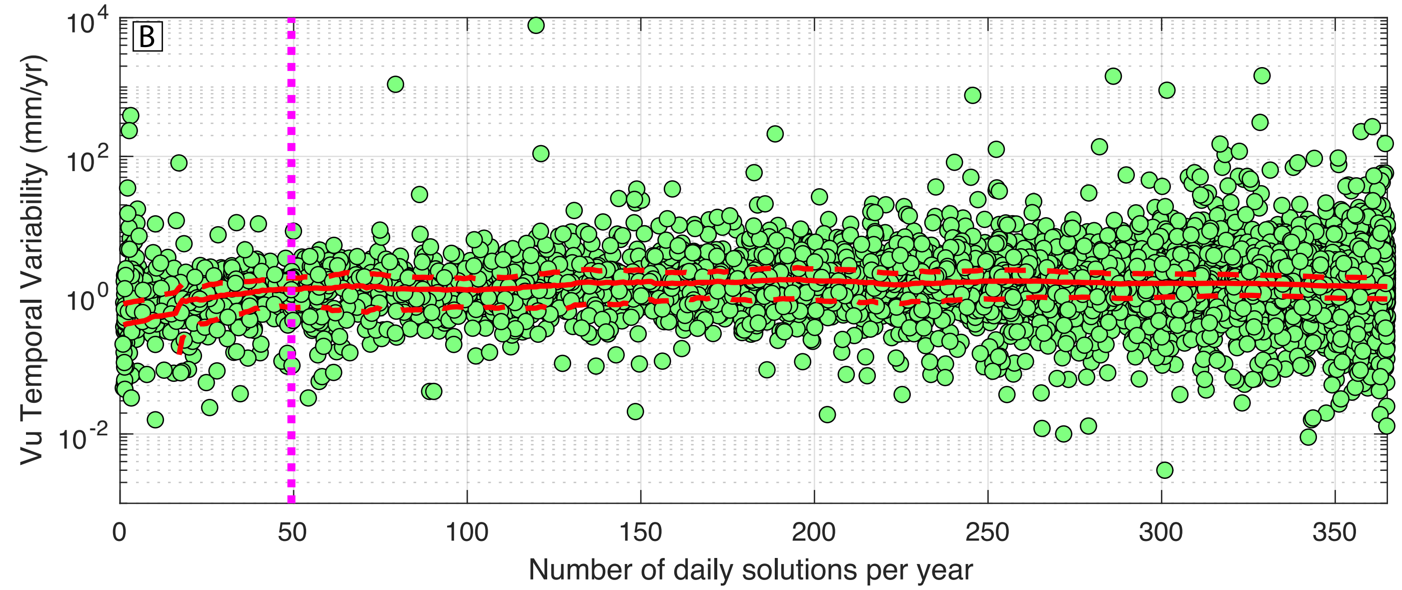



# Vertical Land Motion: What Drives the Uncertainty?

## Temporal and Spatial Variability are not well correlated




## Temporal Variability Not driven by sparse time series

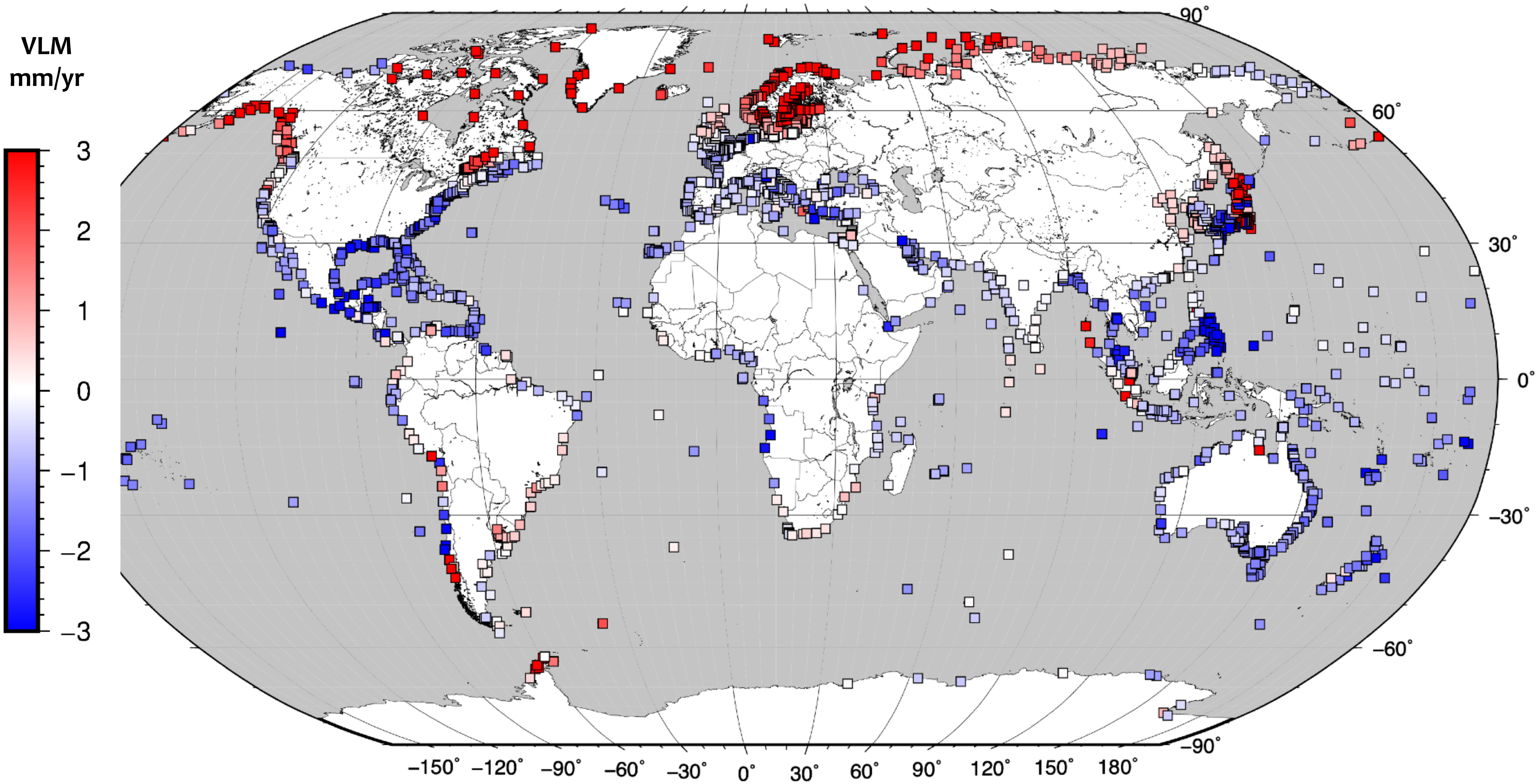



So can have:

- 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

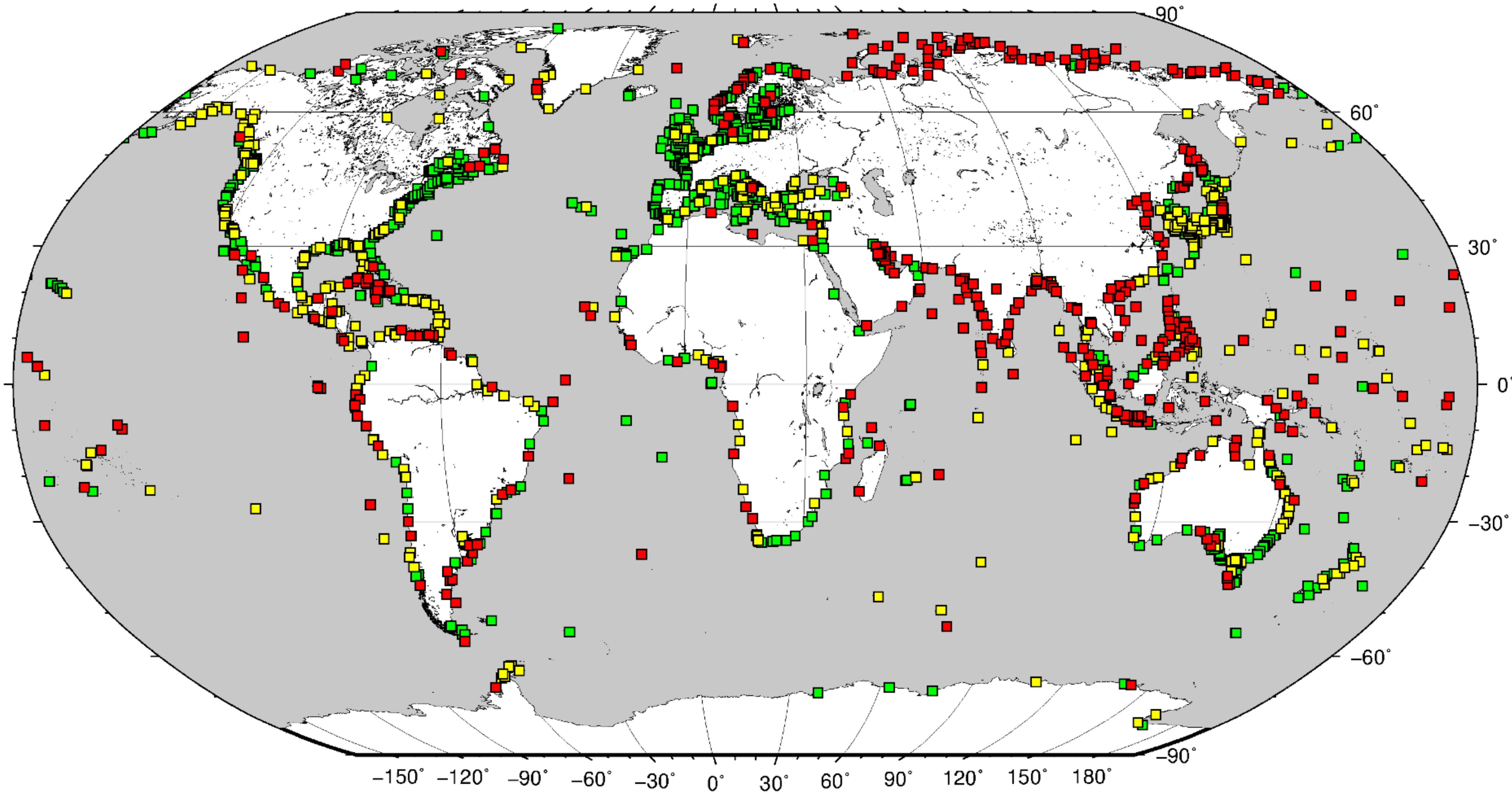
Tide gauges provide direct constraint on relative SLR.
They provide a primary observable that connects SLR to coastal impact.




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 |

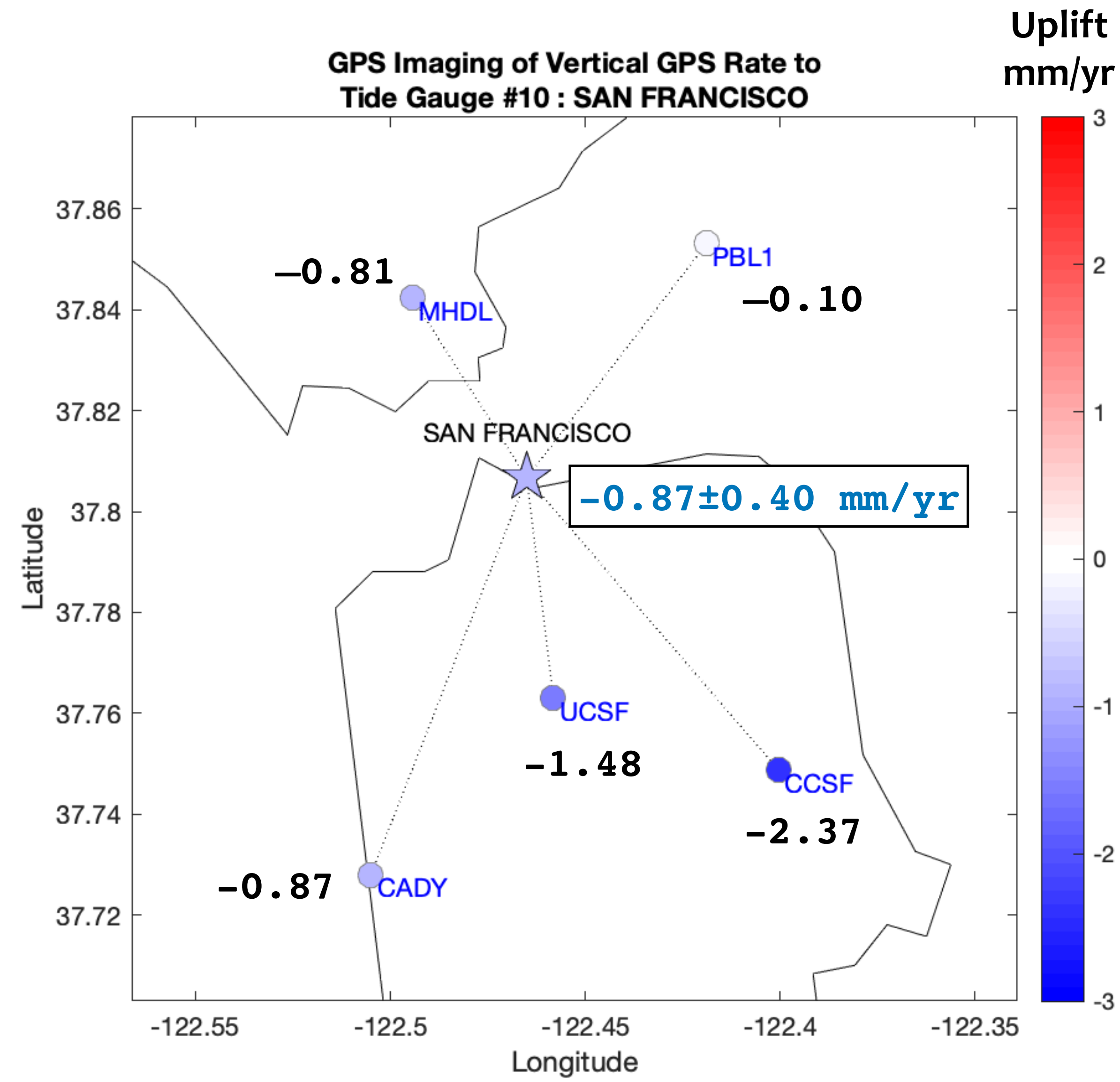
# Vertical Land Motion at a Single Tide Gauge

## Example: San Francisco Bay

No GPS/tide gauge collocation

But 5 nearest stations have trends


## GPS VLM Assessment

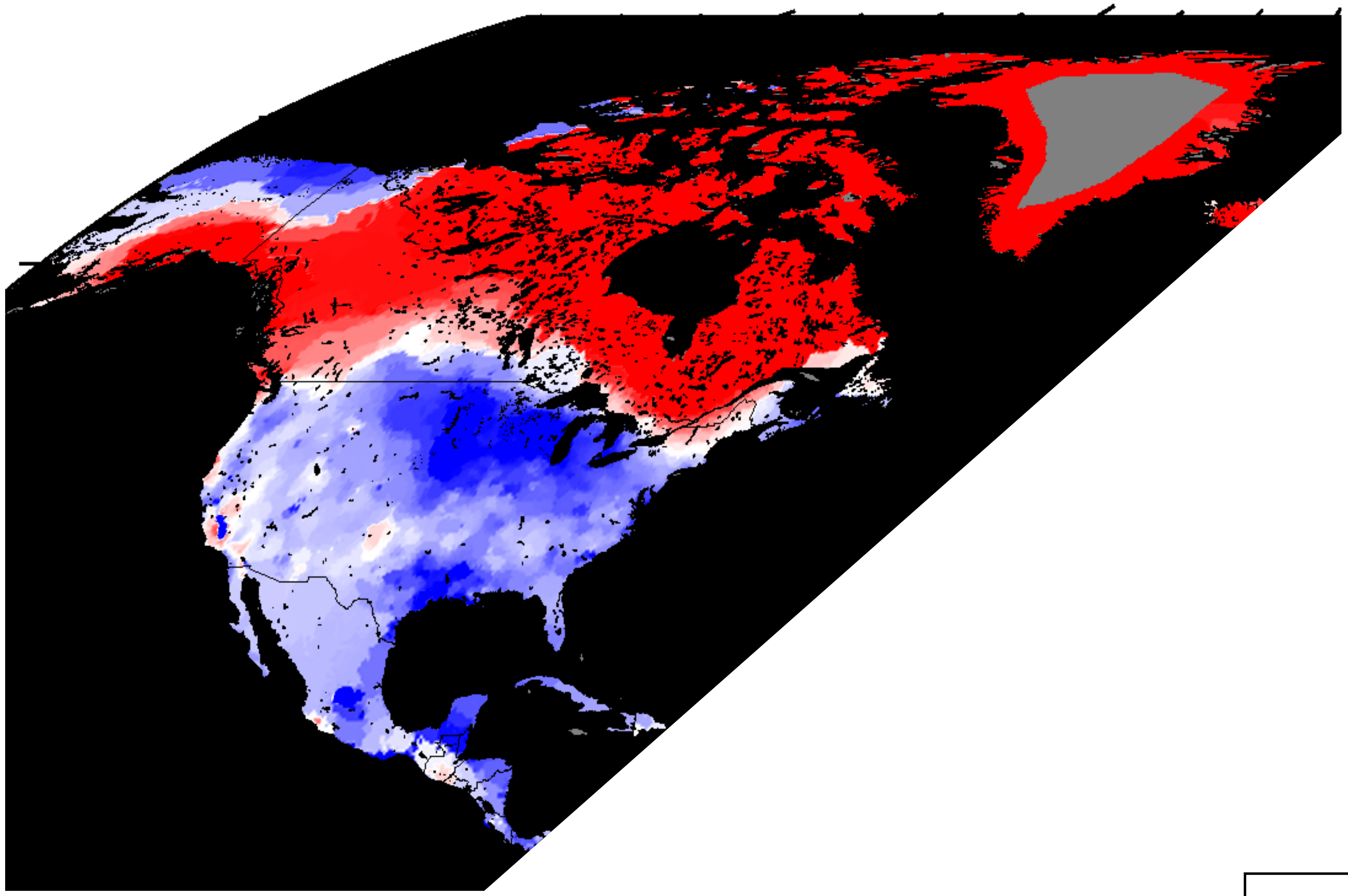



| Vu | $\sigma_{Vu}$ | $D_{(\mathrm{km})}$ | ssf | $MAD(V(t))$ | w | sta |
|---|---|---|---|---|---|---|
| −0.87 | 0.95 | 9.4 | 0.928 | 1.20 | 0.185 | CADY |
| −2.37 | 0.93 | 8.6 | 0.934 | 1.39 | 0.191 | CCSF |
| −0.81 | 0.99 | 4.7 | 0.982 | 3.30 | 0.187 | MHDL |
| −0.10 | 0.91 | 6.6 | 0.959 | 2.32 | 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

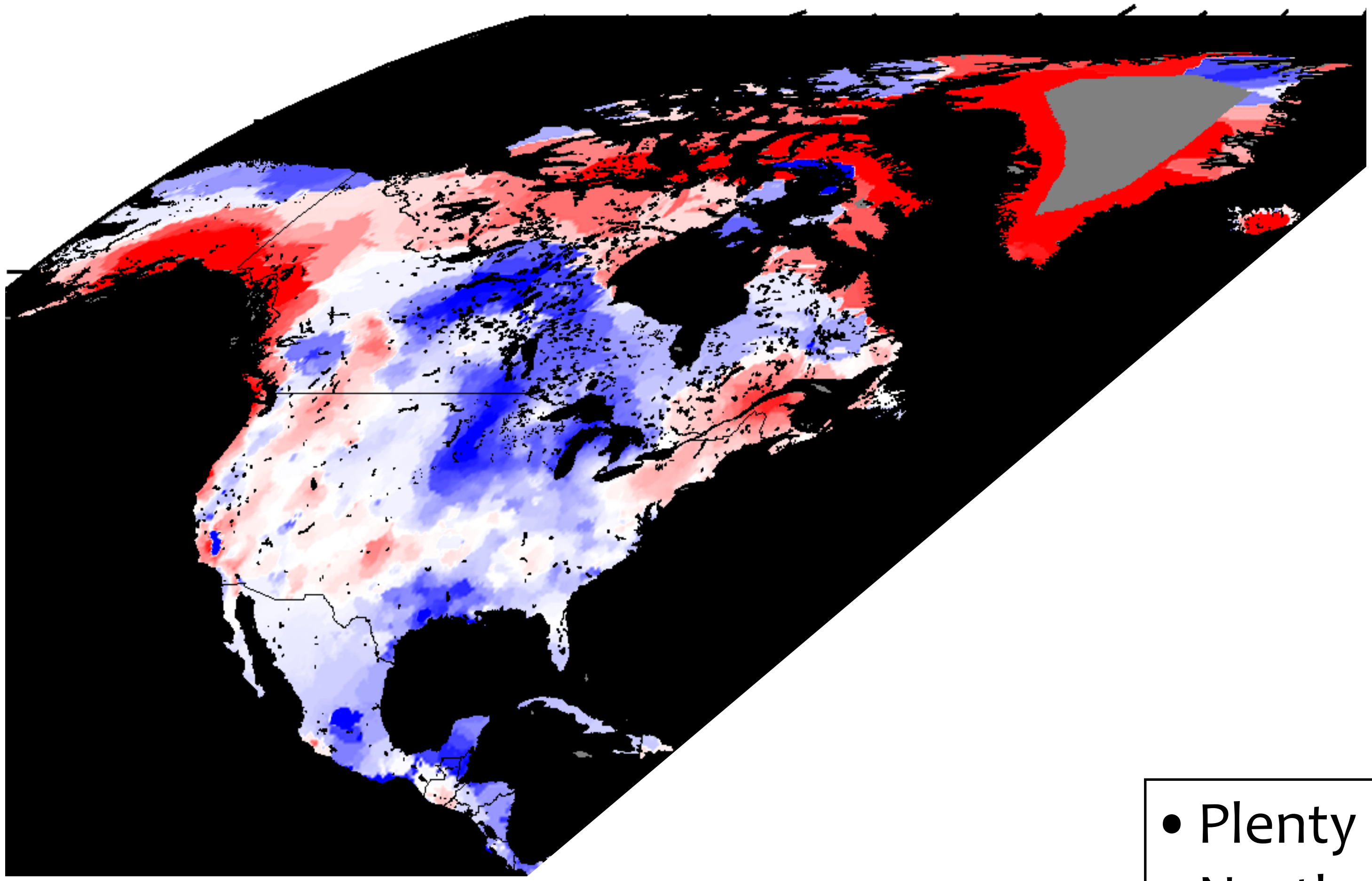
$$\text{Volume Flux} = \int_{\partial S} v_u(\vec{r})\,dA$$

- 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

## Start with North America

How much VLM is left after removing GIA?



Up flux: -5.4 $km^3$ /year

+

Down flux: -6.0 $km^3$ /year

=

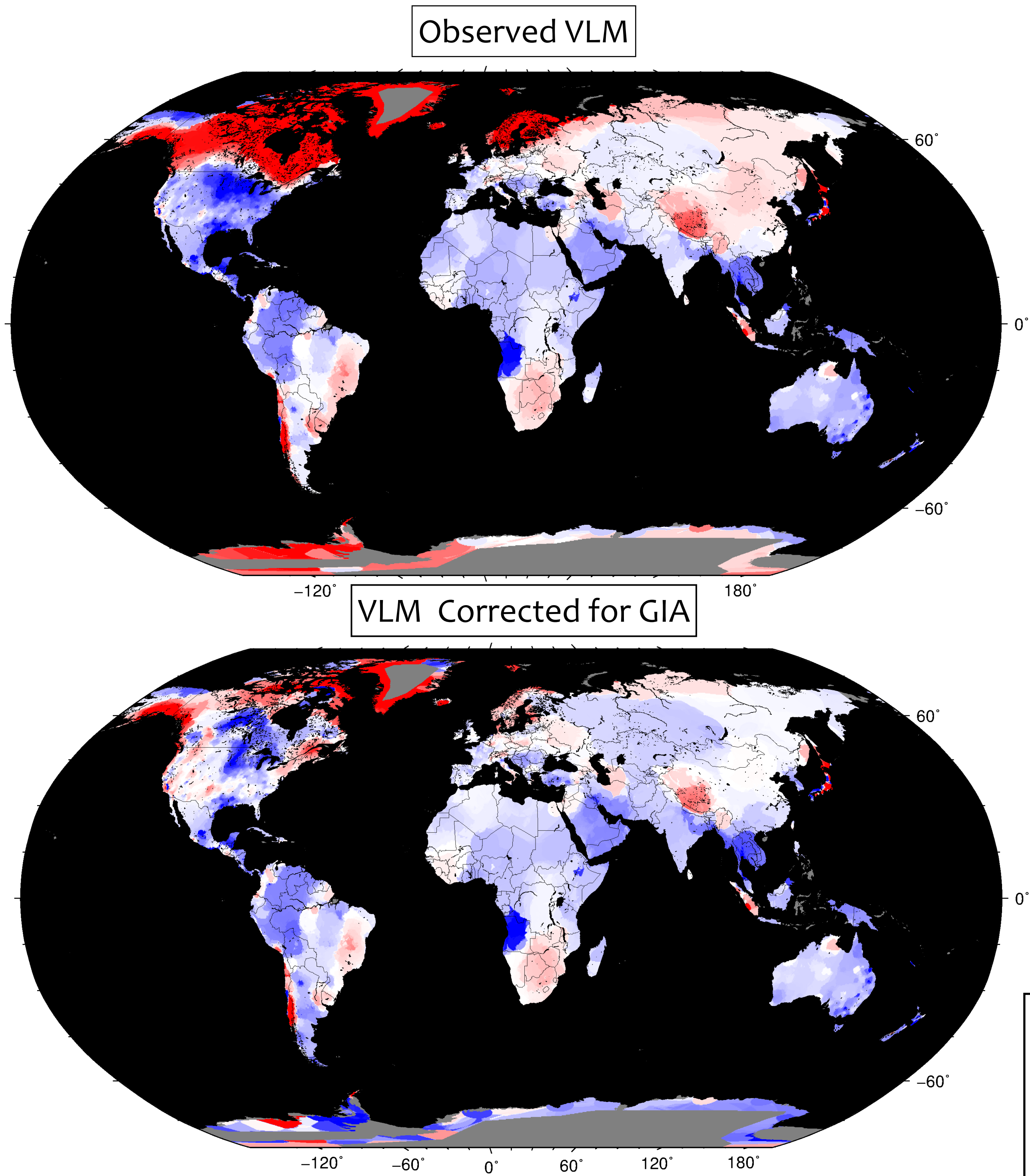
Net flux: -11.4 $km^3$ /year

- 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




## Now the Globe

Up flux: 81.6 $km^3$ /year

\+

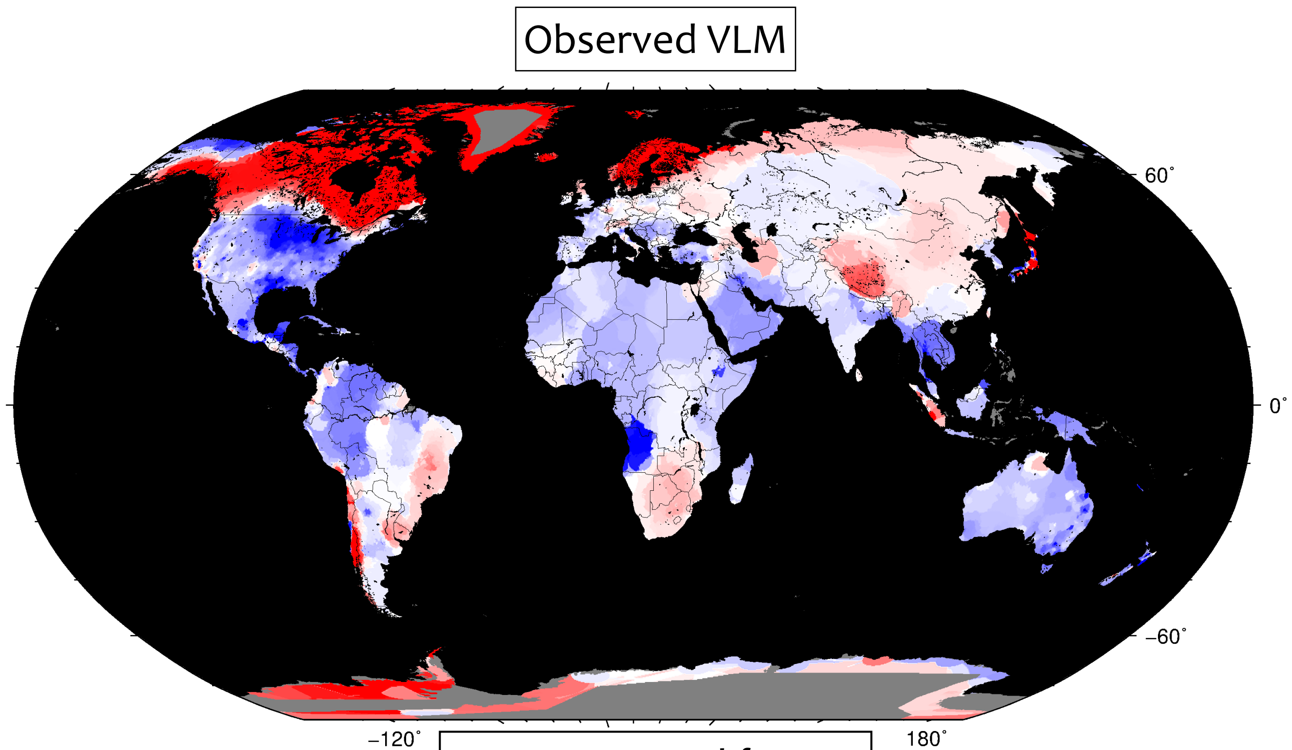
Down flux: -64.3 $km^3$ /year

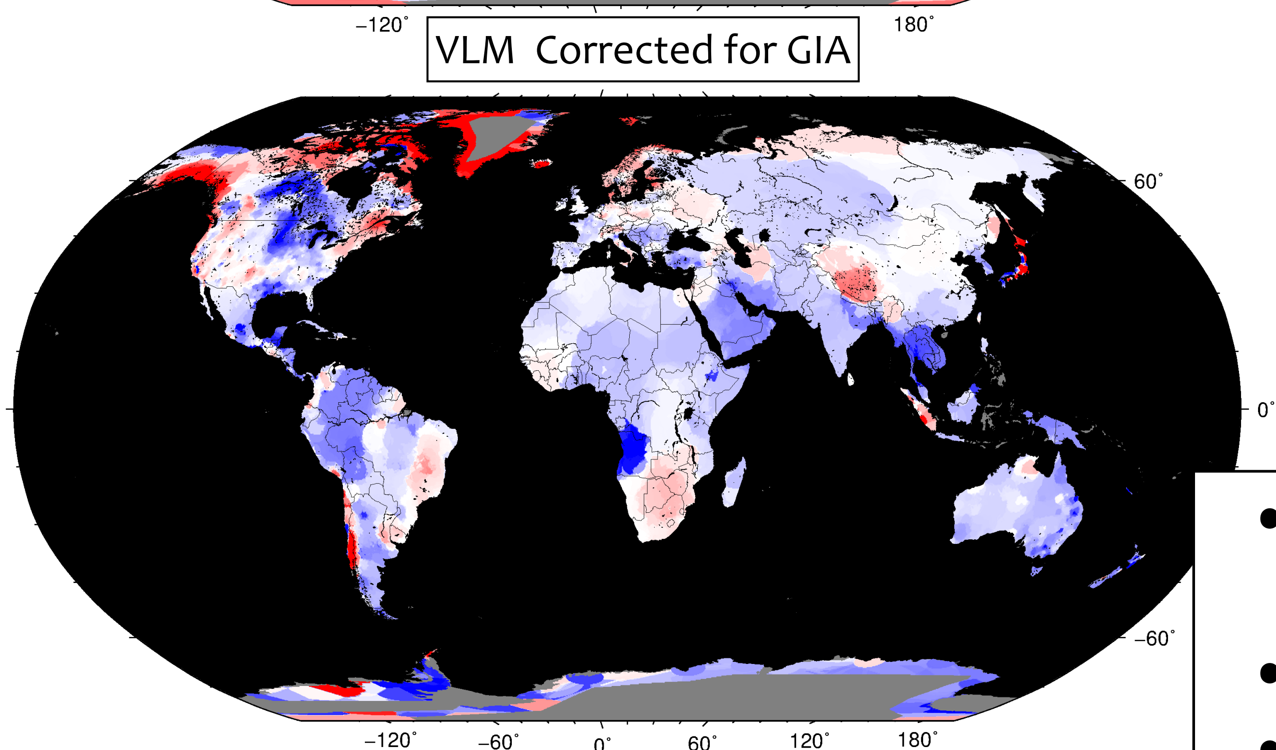
=

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




## 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?