What Do We Really Know About 20th Century GMSL?

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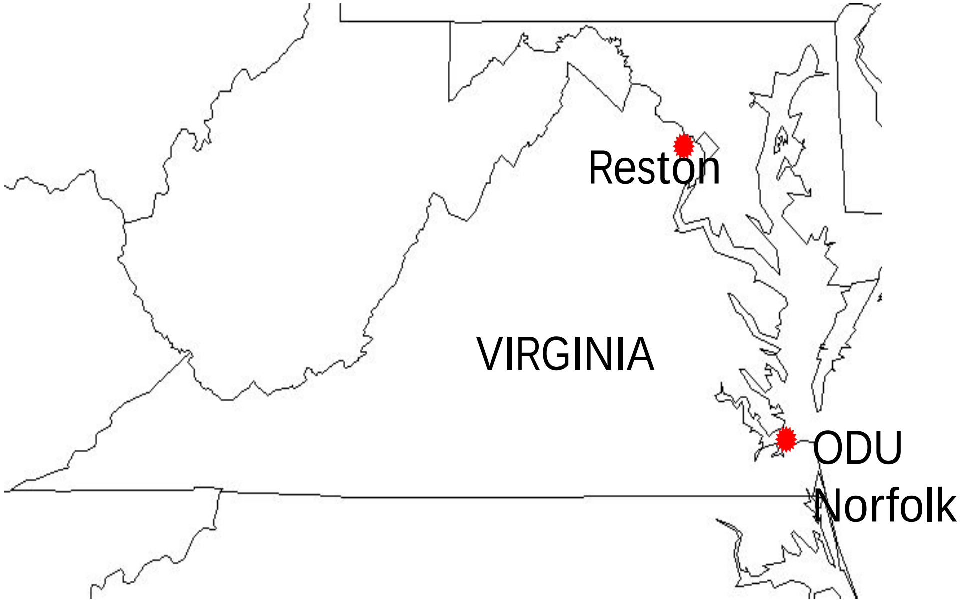
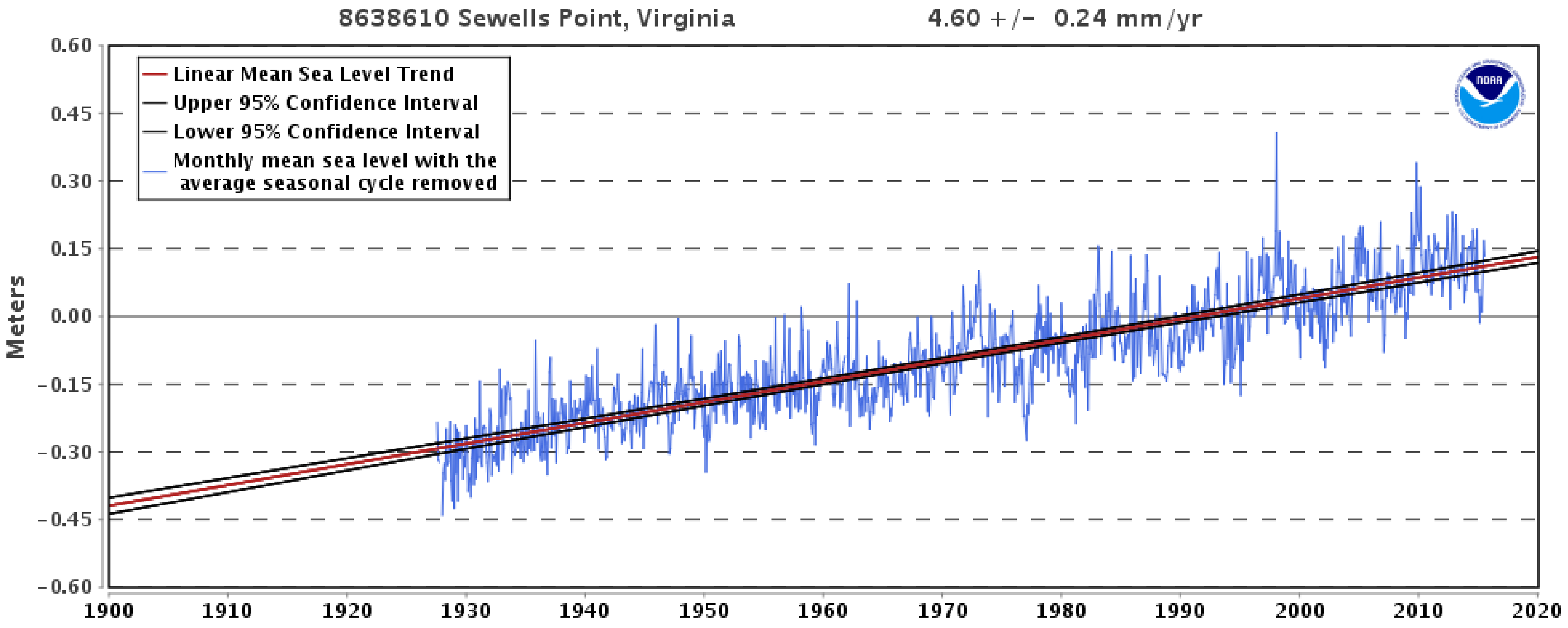


Norfolk, Virginia



- How much of the trend is a result of regional variability?
- How much of the trend is a result of glacial isostatic adjustment (GIA)?
- How much of the trend is a result of local subsidence?
- *Does this tide gauge reflect the long-term trend in GMSL?*

Overview

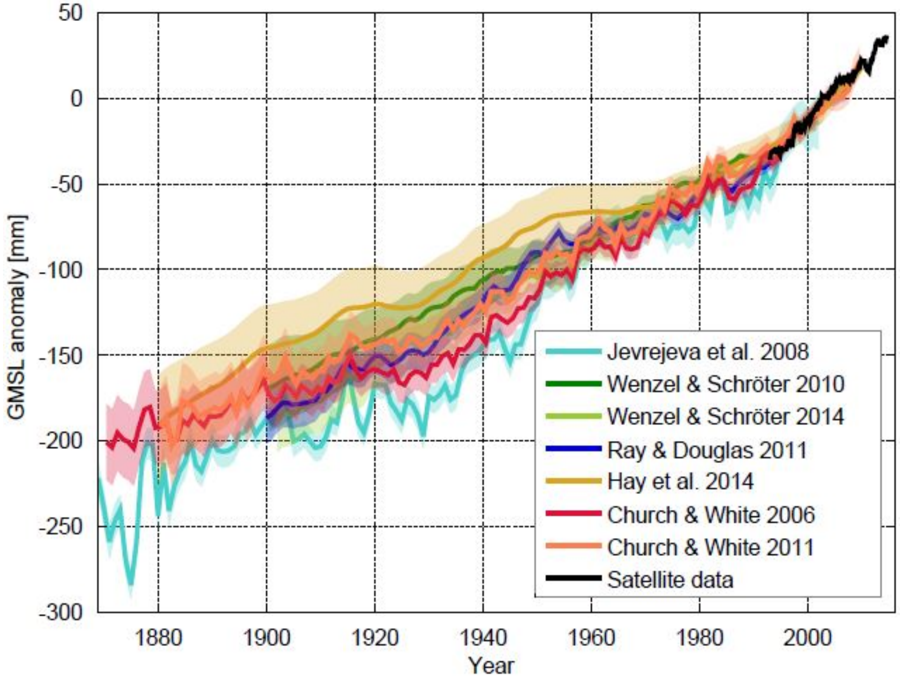
- Question: What can the ***tide gauge record*** tell us about 20th century GMSL?

- Here, we will attempt to assess the impact of the following on our ability to estimate GMSL:

    1. *Tide gauge distribution.*

    1. *Vertical land motion.*

Estimates of 20th Century GMSL

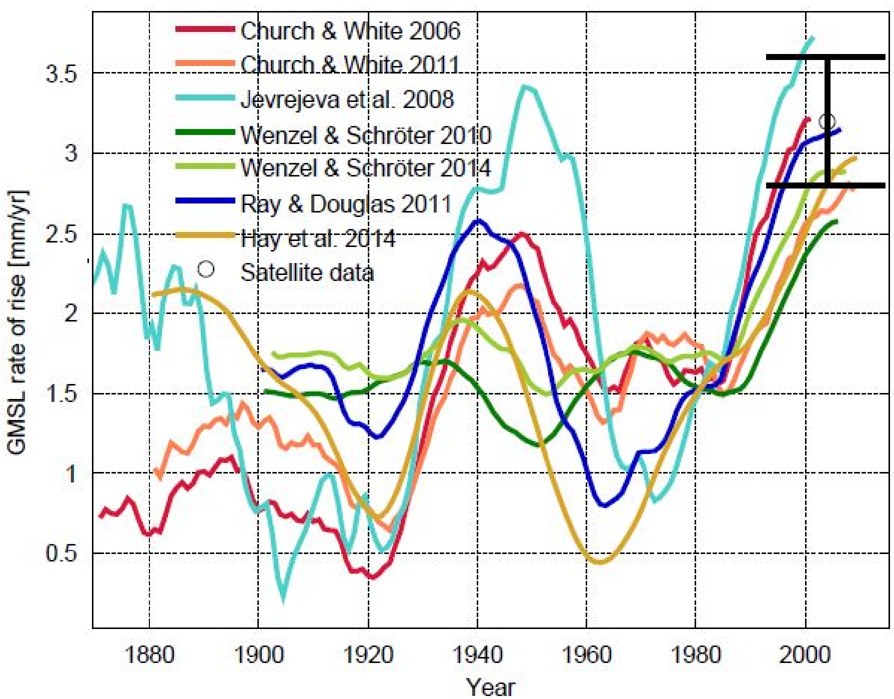


The “zoo of sea level curves”

– Stefan Rahmstorf, *RealClimate.org*

GMSL Trends 1900-1990

Jevrejeva et al. [2008]	1.9 mm/year
Church and White et al. [2011]	1.5 mm/year
Ray and Douglas [2011]	1.7 mm/year
Hay et al. [2015]	1.2 mm/year



Why do estimates of 20th century GMSL differ?

1. Methodology
   - EOF reconstructions (various flavors), virtual stations, neural networks, Kalman filters, area weighting, etc.
2. Historical Data Selection
   - Each of the GMSL estimates begins with the same PSMSL tide gauge dataset (1420 records), but …
   - The gauges selected for use vary substantially.
     - Ray and Douglas (2011) – 89 gauges
     - Church et al. (2011) – 491 gauges
     - Hay et al. (2015) – 622 gauges
       - Hamlington and Thompson (2015), Considerations for estimating the 20th century trend in global mean sea level, *GRL*, doi:10.1002/2015GL064177

Which of the reconstructions is the most realistic? (and how can we determine this?)

Assessing Estimates of 20th Century Sea Level Rise

- To determine which GMSL estimate may be more realistic, we start from the following premise:
    - Using only the longest, “high-quality” gauges, we can get a reasonable estimate of the long-term trend in GMSL (*e.g. Douglas, 1991; Holgate et al. 2007).*
        - In theory, only one gauge – in the right place - is necessary to estimate GMSL, assuming a long enough record and no unknown vertical land motion.
        - Using only long records removes uncertainty associated with short records affected by decadal-scale variability.

Assessing Estimates of 20th Century Sea Level Rise

We have condensed the full PSMSL RLR dataset down to a set of high-quality tide gauge records.

What constitutes a high-quality tide gauge record?

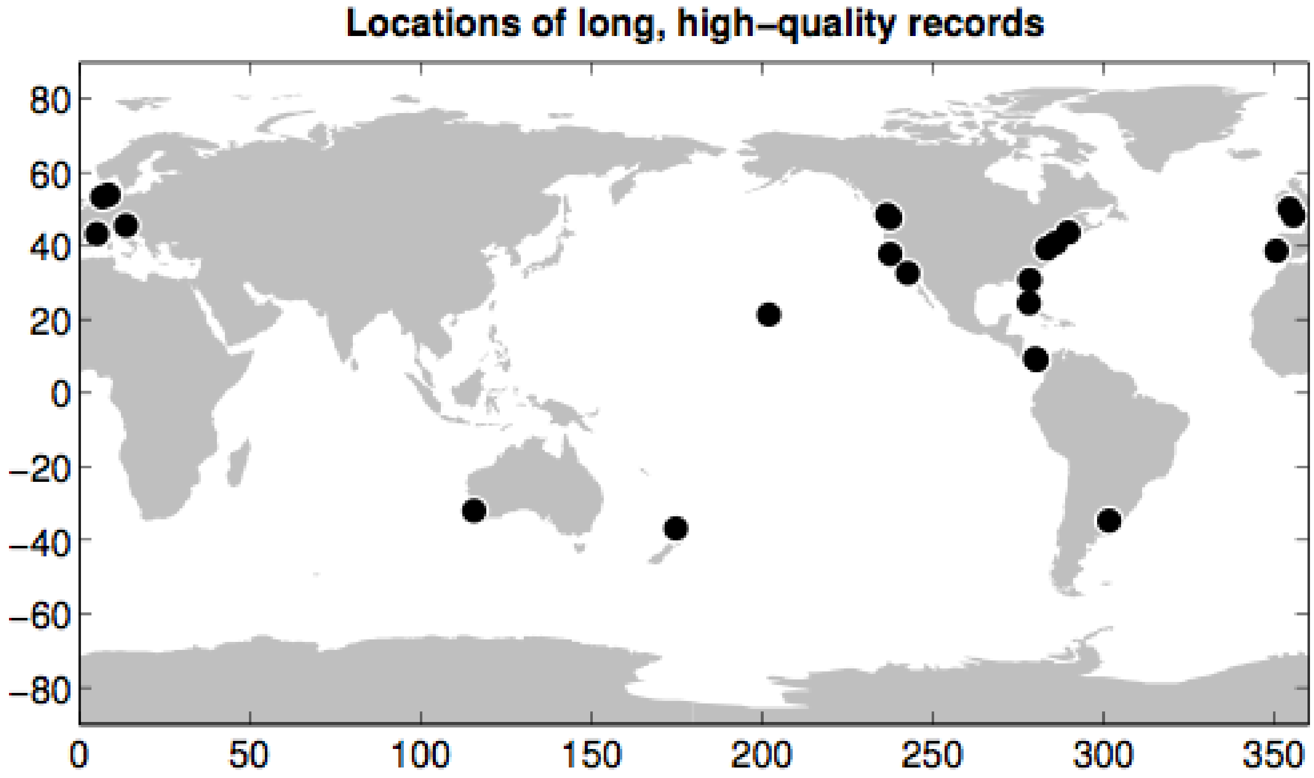
(1) >70 valid annual values during 1900-1990 (75 gauges).

(2) The glacial isostatic correction (GIA) correction must be less than half the magnitude of the sea level trend in the record itself (45 gauges).

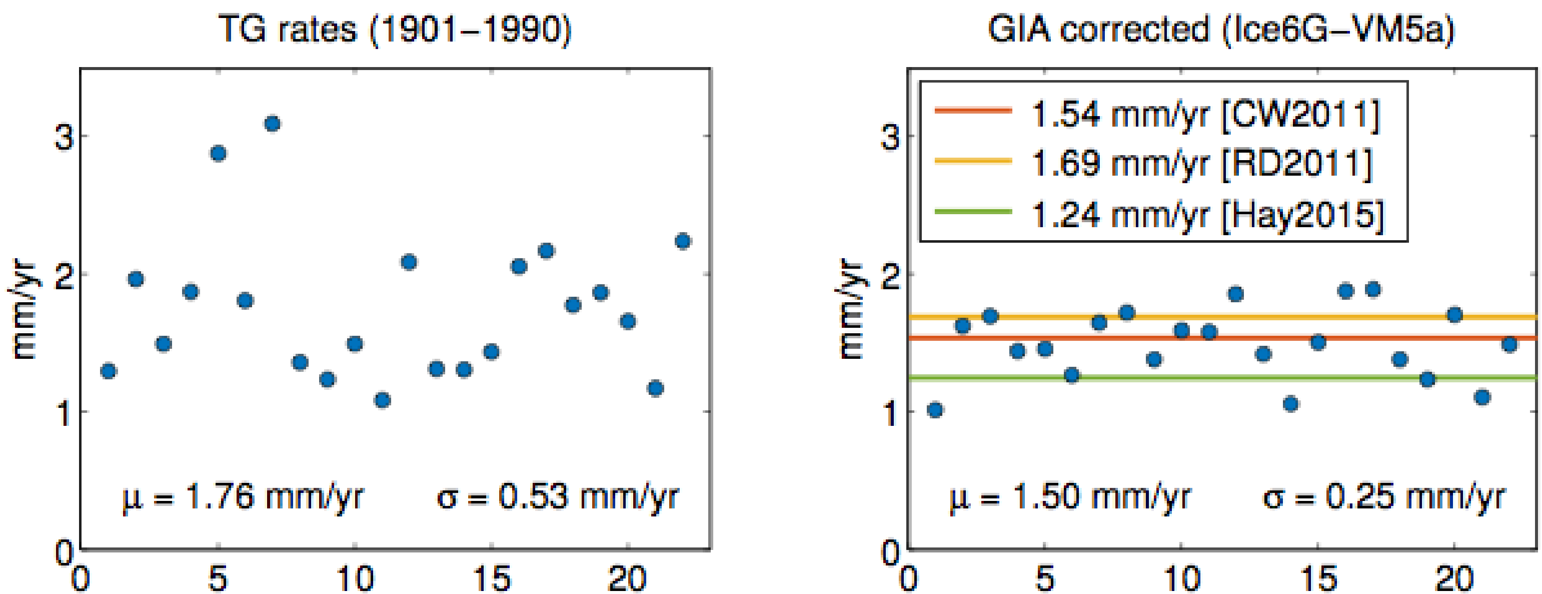
(3) No gaps longer than 5 years (43 gauges).

(4) No documented evidence of **large** vertical land motion signals from 1900 to 1990 – e.g., due to groundwater extraction, tectonics, mining, etc. (22 gauges).

Assessing Estimates of 20th Century Sea Level Rise



Assessing Estimates of 20th Century Sea Level Rise



- The Hay et al. (2015) estimate is much lower than the average of these long records à only 3 of the 22 gauges have trends lower than 1.24 mm/year.

- Are these tide gauges simply in the “wrong place” to estimate true GMSL?
  - **Is there a sampling bias associated with tide gauges?**

Assessing Estimates of 20th Century Sea Level Rise

- Even when focusing on long records relatively unaffected by VLM, trends estimated at the 22 tide gauges range from 1 to 2 mm/year – can we account for this trend variability?
- Having filtered out gauges significantly affected by non-GIA VLM, there are two main processes that lead to differences in the long-term trends from one location to the next:
    1. Changes in gravity due to ice melt (aka, melt fingerprints)
    2. Regional/local changes in the density of the ocean (steric sea level change)

- Based on their location, do these tide gauges systematically under/overestimate the rate of sea level change due to these processes?
    - For Hay et al. (2015) to be correct, these gauges must overestimate the rate of sea level change due to these processes.

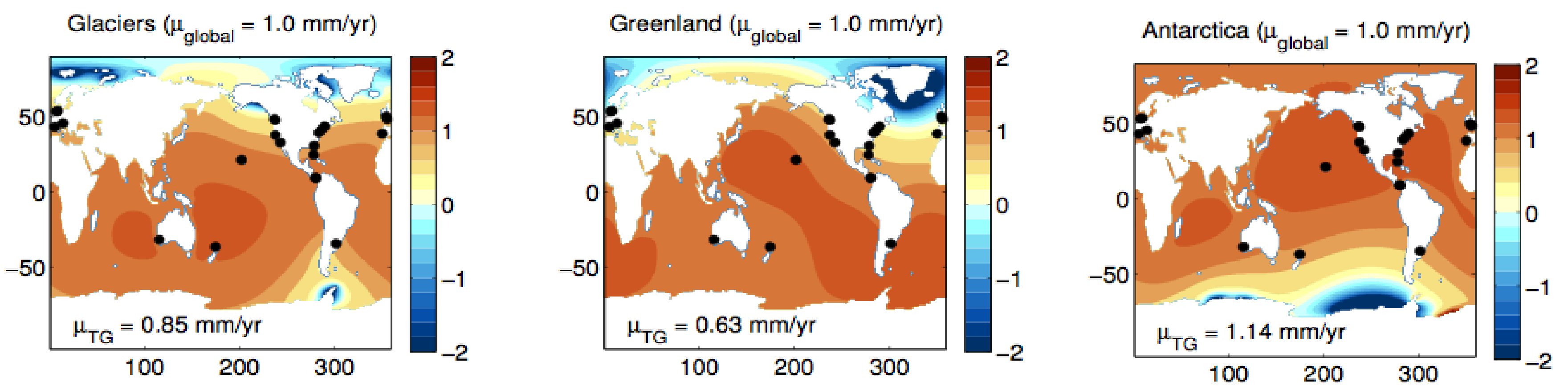
- We will try to account for the spatial trend variability arising from these two processes and provide a plausible range of 20th century GMSL estimates based on the tide gauges.

Assessing Estimates of 20th Century Sea Level Rise

- To reiterate, our test has two assumptions:
- (1) The longest (“high-quality) tide gauge records are the most representative of the long-term trend in GMSL.
- (2) These gauges are in the “wrong place” to actually measure true GMSL and thus introduce a sampling bias into the estimate of the long-term trend.
- After collecting the longest gauges, we then try to estimate the sampling bias and obtain a more realistic estimate of GMSL over the 20th century.

Melt Fingerprints

- To account for the spatial differences arising from ice melt, we use the sea level fingerprints for melting of ice in Greenland, Antarctica, and glaciers.
- These patterns tell us how much of a difference there should be between trends at the tide gauge locations for different sources of melt.
- Based on the locations of the tide gauges, the mean of 1 mm/year is underestimated by 35% and 15% for Greenland and the glaciers, respectively, while the mean is overestimated by 15% for Antarctica.
- To draw a conclusion about possible over- or under-estimation, we still need to account for spatial differences arising from steric sea level change.

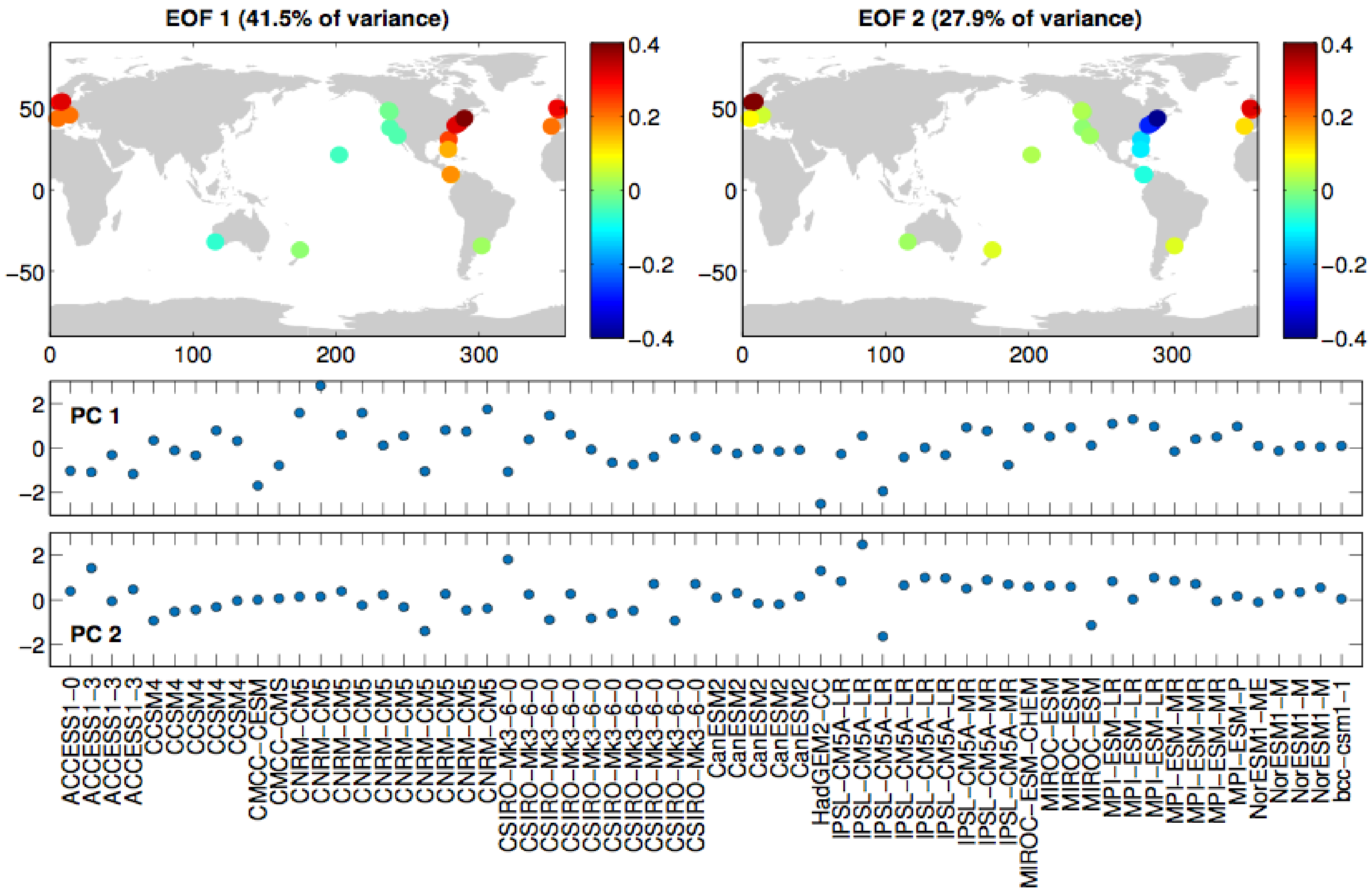


Courtesy of Riccardo Riva, Delft University, Riva et al. (2010), *GRL*, doi: 10.1029/2010GL044770

Steric Sea Level Trends

- The steric trend differences at the tide gauge locations primarily arise due to the phasing of decadal climate modes.
- What does the spatial pattern of steric sea level change look like during 1901-1990?
  - Observations are insufficient – cannot know the true pattern.
  - Climate models can provide an estimate of *possible* patterns that we can use in similar fashion to the melt fingerprints.
- To obtain these *possible* patterns, we rely on the CMIP5.
  - 66 historical runs forced by 20th century radiative forcing
  - Extract time series of steric sea level change for the 22 tide gauge locations, subtract GMSL from the steric time series for each model, calculate trends during 1901-1990.
  - The mean of the trends from any given model reflect the degree to which these locations under/overestimate the true global steric trend.
  - Finally, we compute EOFs to find the spatial patterns dominant in the ensemble of models.

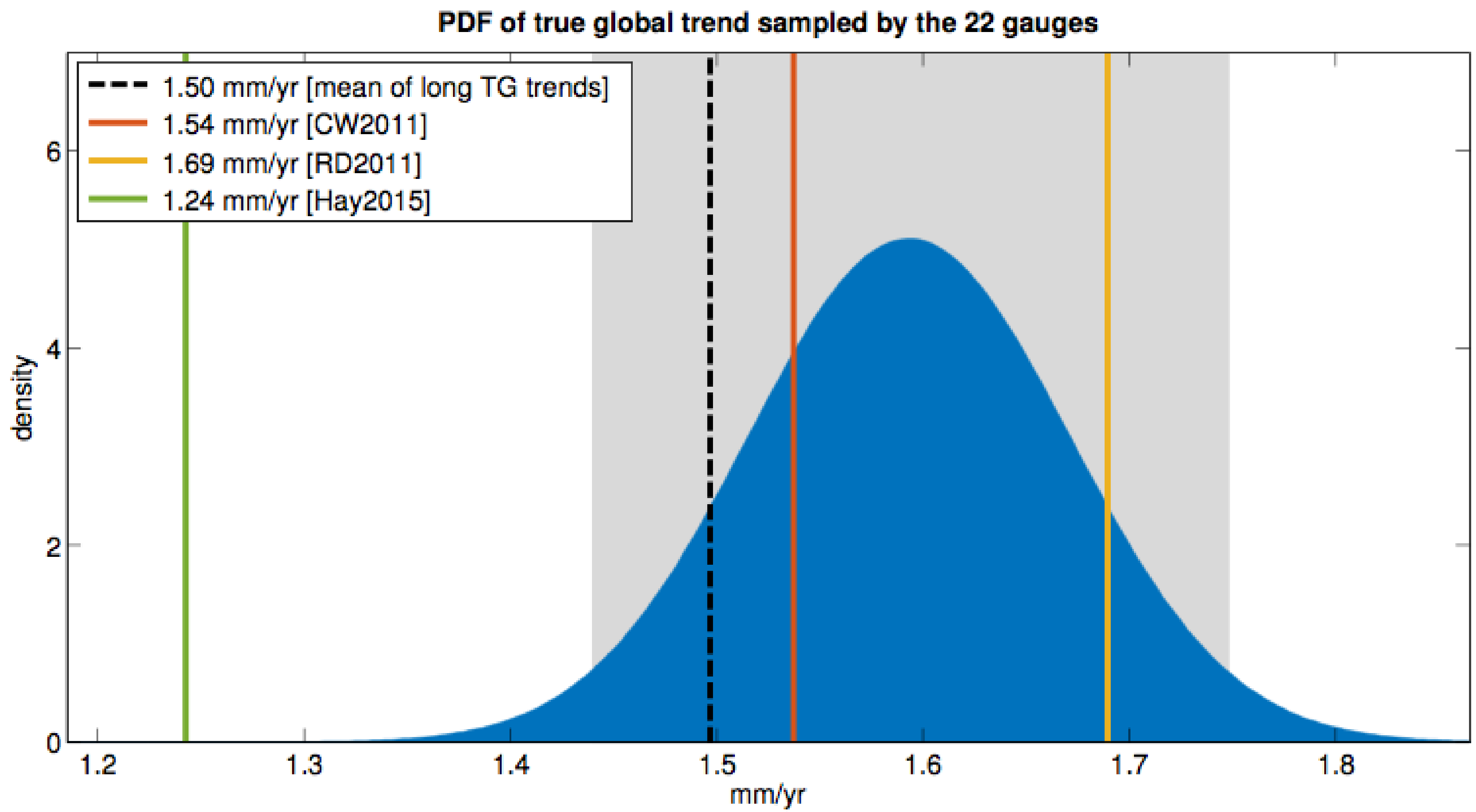
Steric Sea Level Trends



Using the Spatial Patterns

- Look for combinations of the melt and steric patterns that account for at least some fraction of the spatial differences in the tide gauge trends to get a distribution of the sampling biases that result from these various combinations.
- We cannot simply fit these patterns to the gauge trends.
  - The patterns are highly correlated at these small number of locations.
  - Choose random amplitudes of the patterns for which we have some information to apply as a constraint.
  - Glacial fingerprint: [0.3, 1.0] mm/yr (based on latest IPCC report)
  - EOFs 1-2: [-3.0, 3.0]; [-2.5, 2.5]
  - We scale the patterns according to their amplitude and subtract from the observed TG trends.
  - Finally, we fit the amplitude of the patterns for which we have no (few) constraints (Greenland and Antarctic fingerprints) to the remaining trend variability.
    - These two patterns are not significantly correlated at the gauge locations.
  - Two final constraints: (1) Subtracting the scaled melt and steric patterns must reduce the variance in the observed trends, and (2) Sum of the amplitudes applied to the melt fingerprints must be between 0 and 2 mm/yr.

Assessing Estimates of 20^{th} Century Sea Level Rise



Overview

- Question: What can the ***tide gauge record*** tell us about 20th century GMSL?

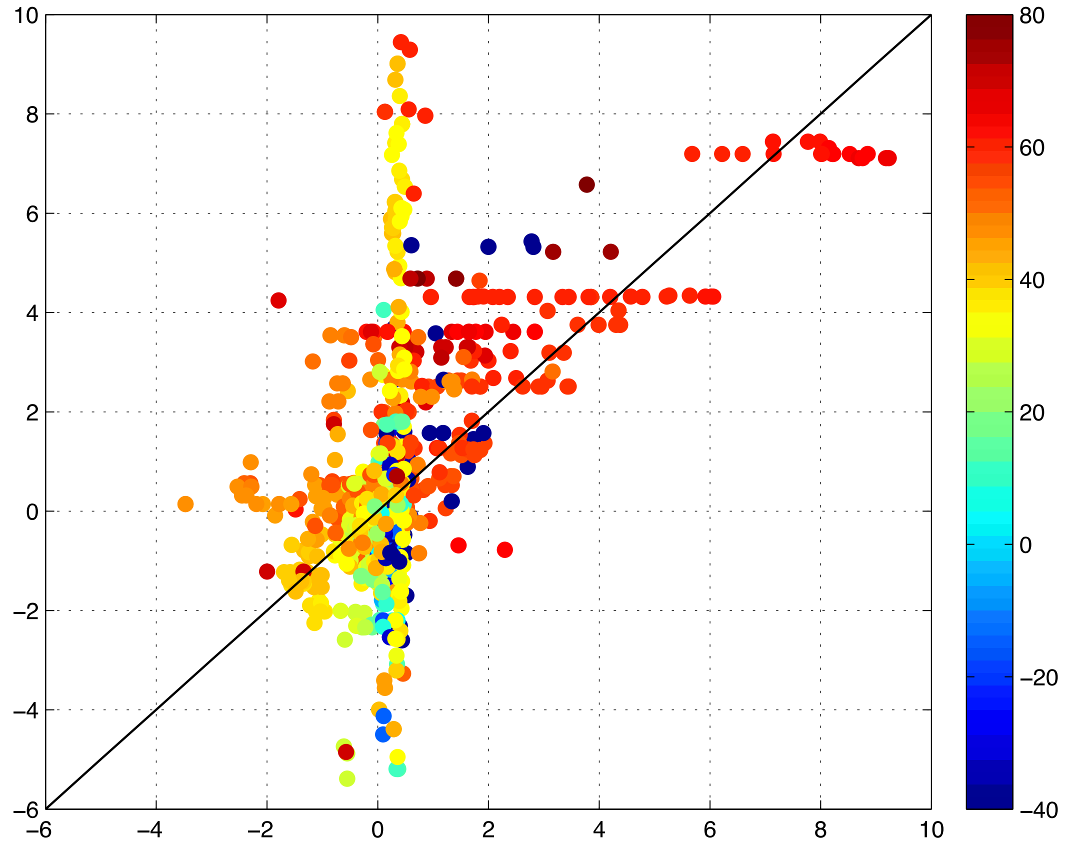
- Here, we will attempt to assess the impact of the following on our ability to estimate GMSL:

  1. *Tide gauge selection/distribution.*

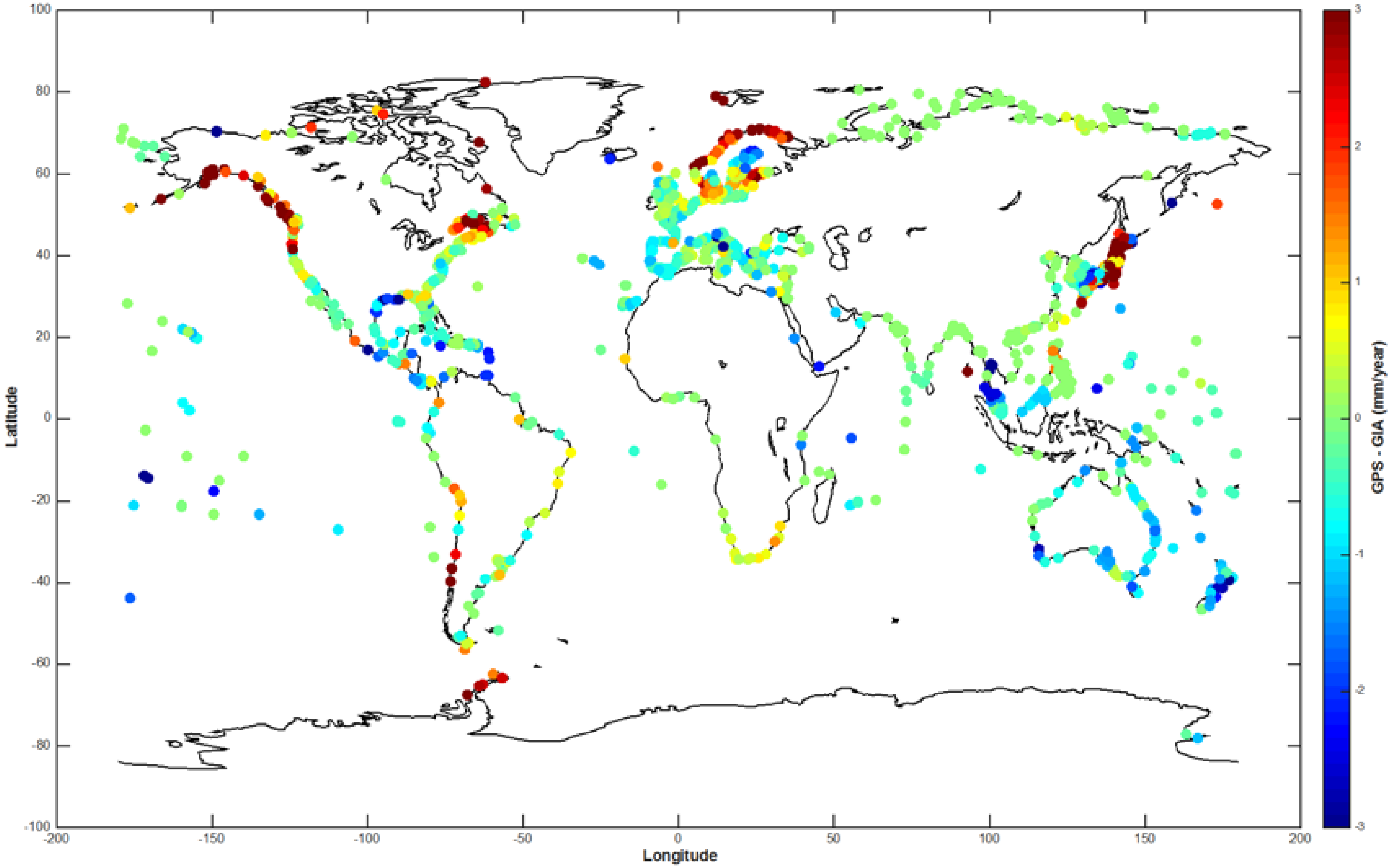
  1. **Vertical land motion.**

Vertical Land Motion

Comparison of GPS vertical land motion correction vs. GIA vertical land motion correction for 1420 tide gauges in the PSMSL RLR dataset, and GIA Correction is obtained from the ICE-6G_C (VM5a) postglacial rebound model. GPS correction is obtained from the MIDAS algorithm, synthesizing data from nearby GPS stations to produce an estimate of VLM at the tide gauge location. Color represents the latitude of each gauge.

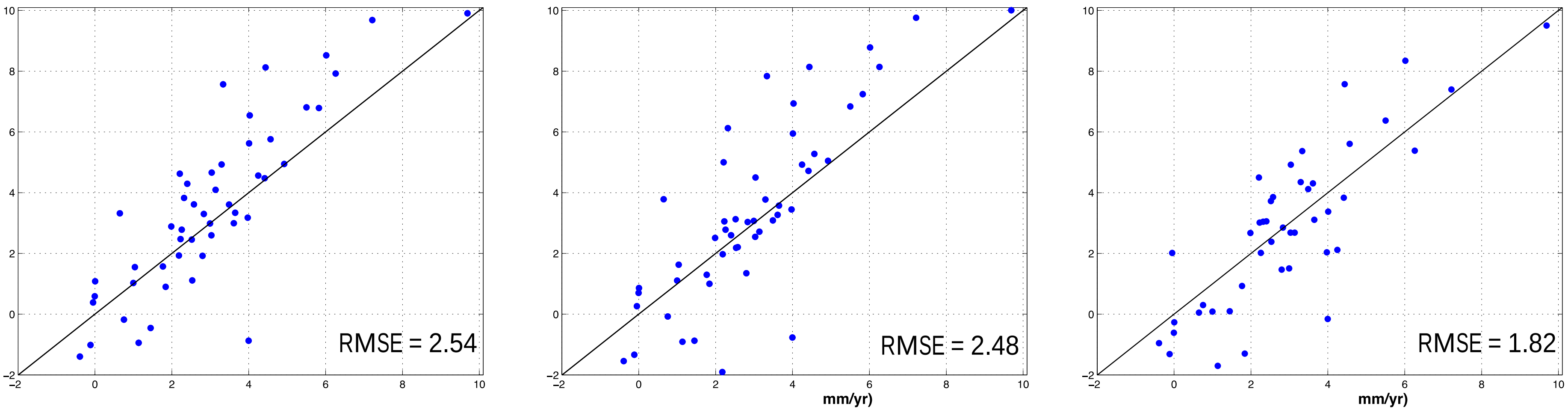


Vertical Land Motion



Vertical Land Motion

- To test the ability of the GPS VLM estimates to correct the long-term tide gauges, we start with the tide gauge dataset of Ray and Douglas (2011), totaling 89 gauges.
  - The GPS and GIA corrections are applied to each tide gauge, the trend is computed, and the result is compared to the trend of the nearest data point in the AVISO dataset.



  - Applying the GPS-correction improves the agreement with the satellite altimetry compared to applying no correction or applying the GIA correction.

Vertical Land Motion

- Can the GPS VLM estimates be used to correct the full tide gauge records?
- Expect long-term trends to agree better between gauges after accounting for VLM.

<u>**STD of trends over full record:**</u>

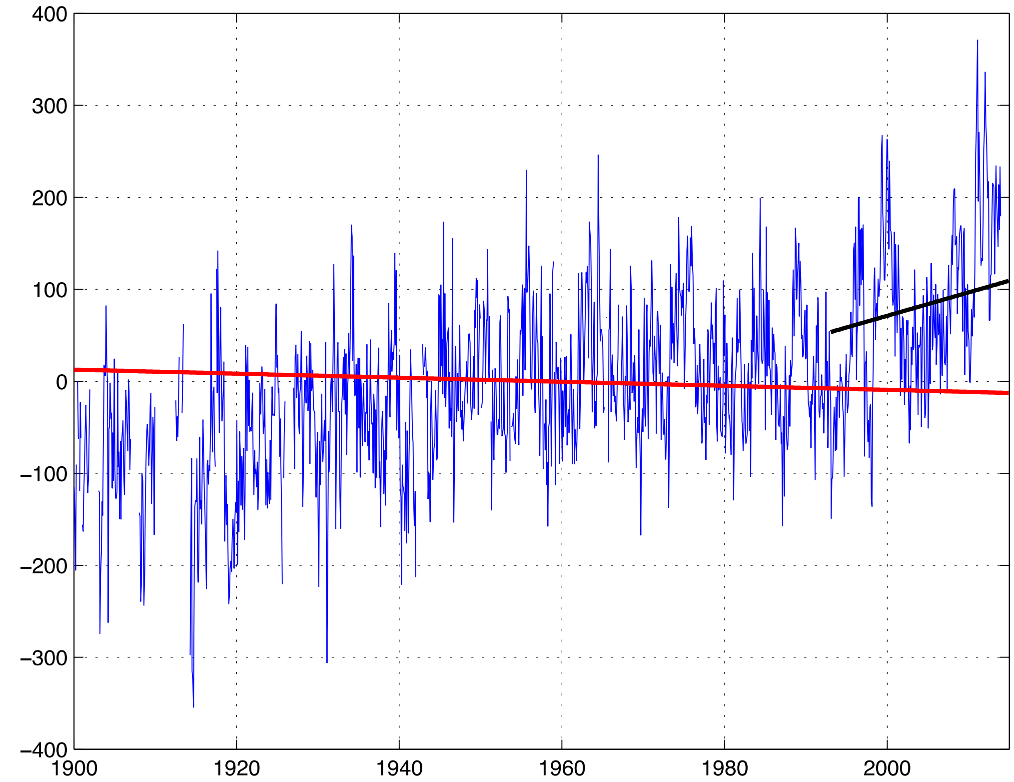
No Correction: 1.67 mm/year

GIA Correction: 1.65 mm/year

GPS Correction: 2.37 mm/year

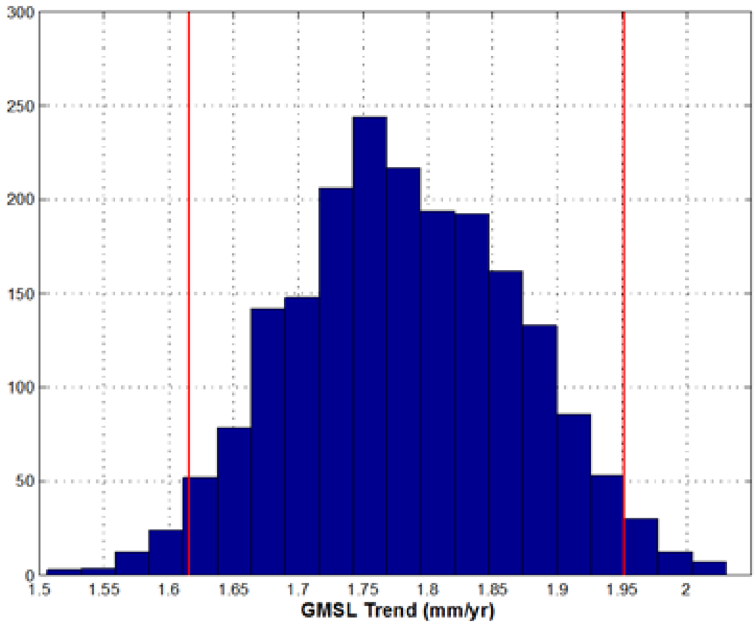
- GPS corrections improve TG estimates during altimeter time period, but are not necessarily applicable to full record (not surprising).

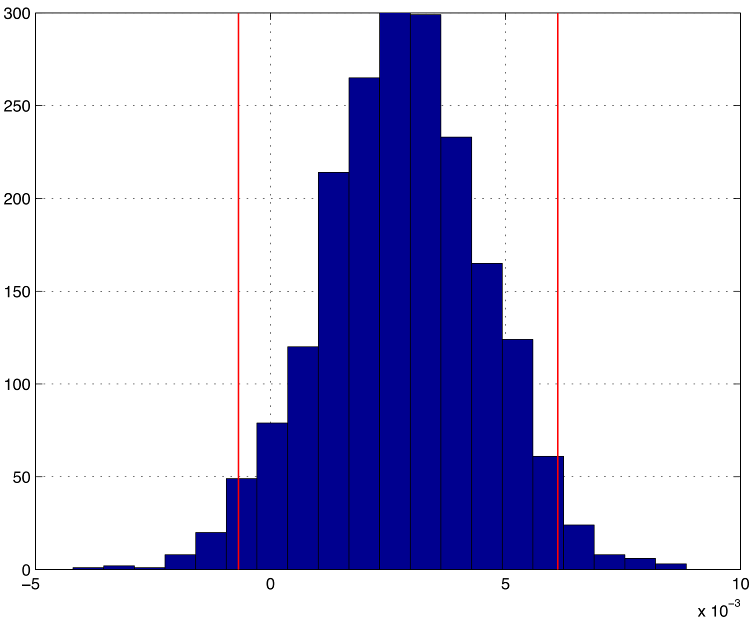
- Can we use the difference between the GPS correction and GIA correction to estimate the impact of unresolved VLM on estimates of GMSL?



Vertical Land Motion

- Starting premise: The (GPS-GIA) VLM begins at some unknown point in the past.
  - GPS estimates are based on records with lengths of 5 to 20 years, and generally reflect VLM over this time period. What about prior to that time period?
  - The GIA correction is initially applied to the full record for each gauge in the RD dataset. The difference between the GPS correction and GIA correction is then applied to varying (random) lengths from 10 years to the full length of the record (starting in 2015 and extending back) for each gauge. GMSL is then computed for the corrected set of tide gauges.
  - This process is completed 1000 times to provide a (rough) estimate of the impact of unknown VLM on long-term GMSL.





Which tide gauges best represent long-term GMSL?

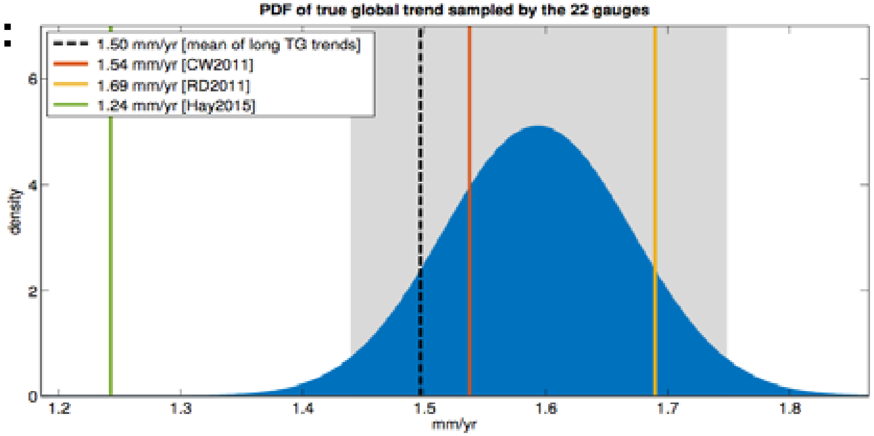
- Can one tide gauge – in the right place - be used to estimate long-term GMSL?
- Based on this work, we can search for a gauge(s) with the following criteria (similar to Holgate, 2007, but with a more quantitative approach):
  - *Record length > 70 years.*
  - *GPS VLM ~ GIA VLM ~ 0 mm/year*
  - *Melt fingerprint values ~ 1 for Greenland, Antarctica, and the Glaciers, meaning the melt-related trend is close to the global mean.*
  - *CMIP5 Steric EOF-1 and EOF-2 values ~ 0, meaning steric trends are close to the global mean.*
- Three tide gauges meet this criteria.

  <u>Trends from 1900 to 1990 (GIA corrected)</u>:

  San Francisco: 1.65 mm/yr.

  Honolulu: 1.65 mm/yr.

  Buenos Aires: 1.60 mm/yr.



- **Note, we are only using the Buenos Aires record up to 1982*

What does this mean for GMSL during the altimeter record?

- Improving the understanding of the historical record provides better context for sea level observed during the altimeter era.
  - Rely on tide gauges and reconstructions to estimate and remove decadal-scale variability from the altimeter record.
  - Allows us to determine if sea level change during altimeter record is different (and in what ways) when compared to sea level change over the past century à acceleration?
  - With comparisons being made between the altimetry and tide gauges, the limitations of the tide gauges must be understood.
- Semi-empirical projections rely heavily on the tide gauges and reconstructions.
- Obtaining an improved representation of past sea level, both regional and global, is important for model comparison and validation.

Summary

- Estimates of 20th century sea level rise disagree, varying from 1-2 mm/year.
  - While methodological differences contribute to the discrepancy in GMSL estimates, many of the problems are simply attributable to the subset of gauges selected for use (Hamlington and Thompson, 2015).
- The longest tide gauge records provide the best estimate of the long-term trend in GSML.
  - Based on the locations of these records and the spatial variability of sea level change over long time periods, we have determined that it is highly unlikely this set of gauges overestimates the long-term trend.
  - Reconstructions consistent with the best tide gauge data are those with trends from 1901-1990 near 1.6 mm/year, and within the range of 1.5 to 1.7 mm/year.
- Unresolved vertical land motion also contributes uncertainty to GMSL estimates, and needs to be accounted for either in the tide gauge selection process, or in the subsequent error analysis.
- Accounting for the spatial variability and vertical land motion, it is possible to identify gauges representative of long-term GMSL.

Thanks for your time!