"Comparison of Comprehensive Tide Gauge and Satellite Data Sets"

12th International Workshop on Wave Hindcasting and Forecasting and 3rd Coastal Hazards Symposium

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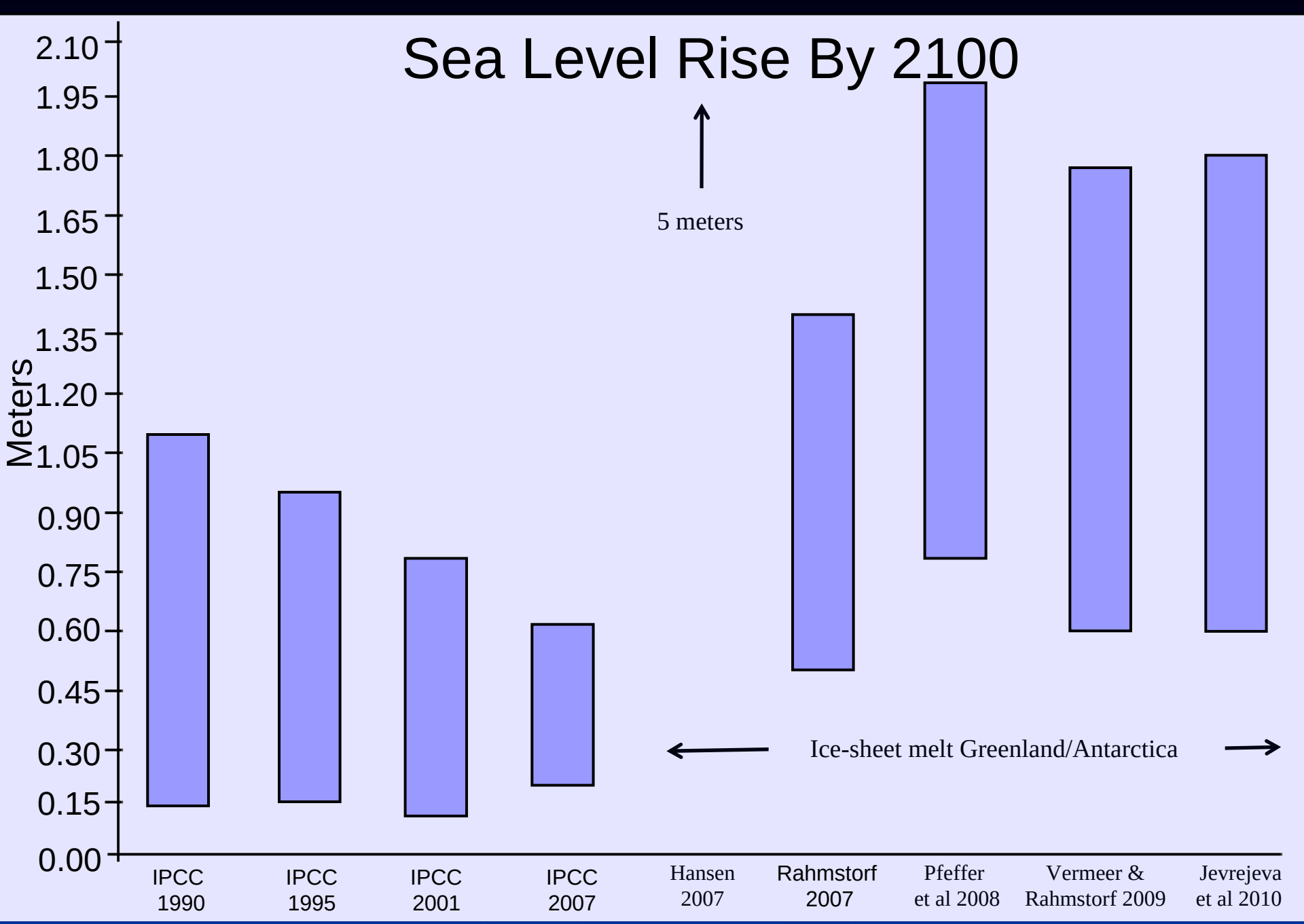
Resources for Sea Level Analysis

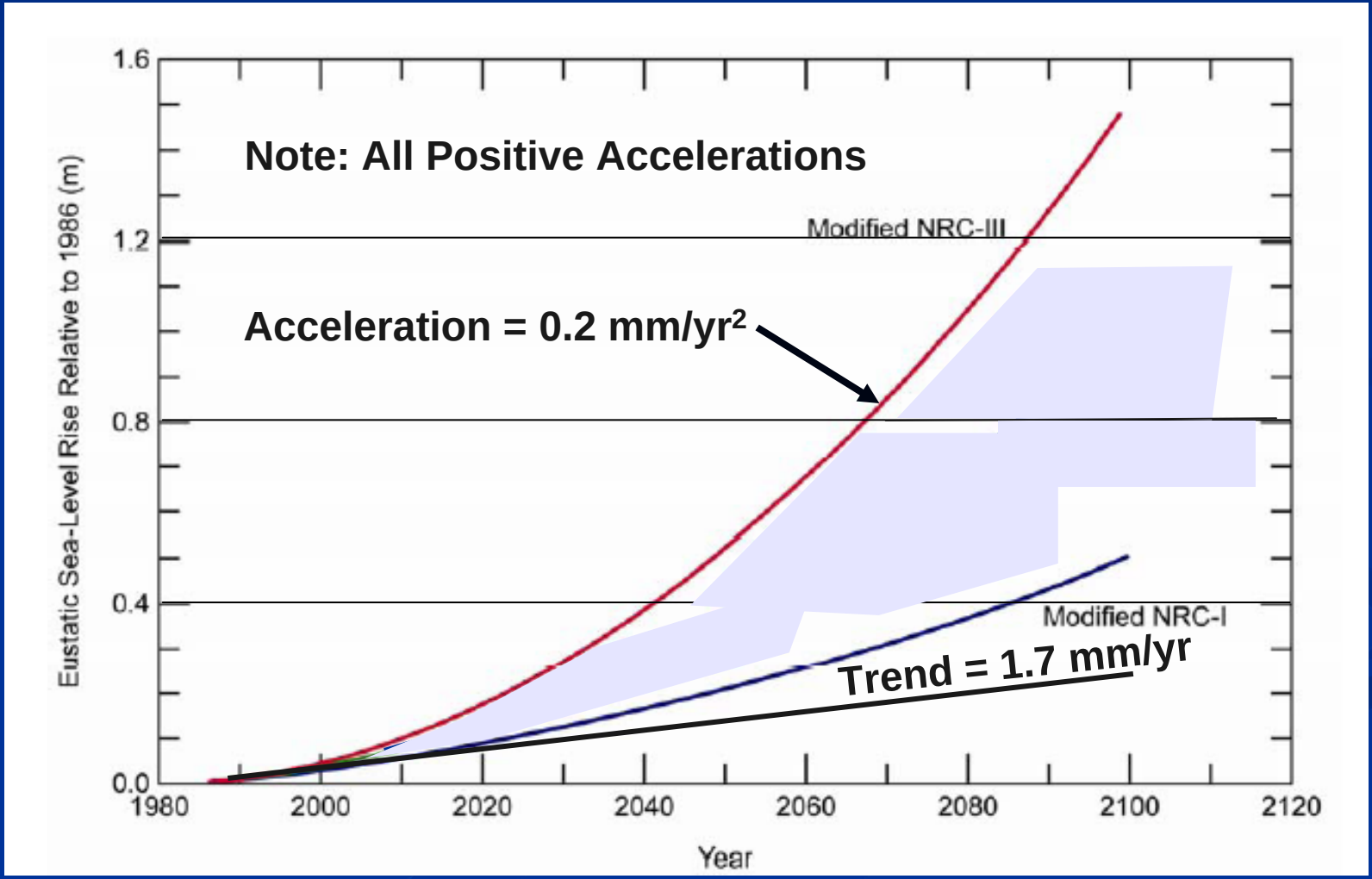
- **Permanent Service for Mean Sea Level (More than 2,000 gauges): http://www.psmsl.org/**
- University of Colorado Satellite Altimetry Website: http://sealevel.colorado.edu/
- SONEL GPS Website: http://www.sonel.org/-GPS,28-.html.

Outline

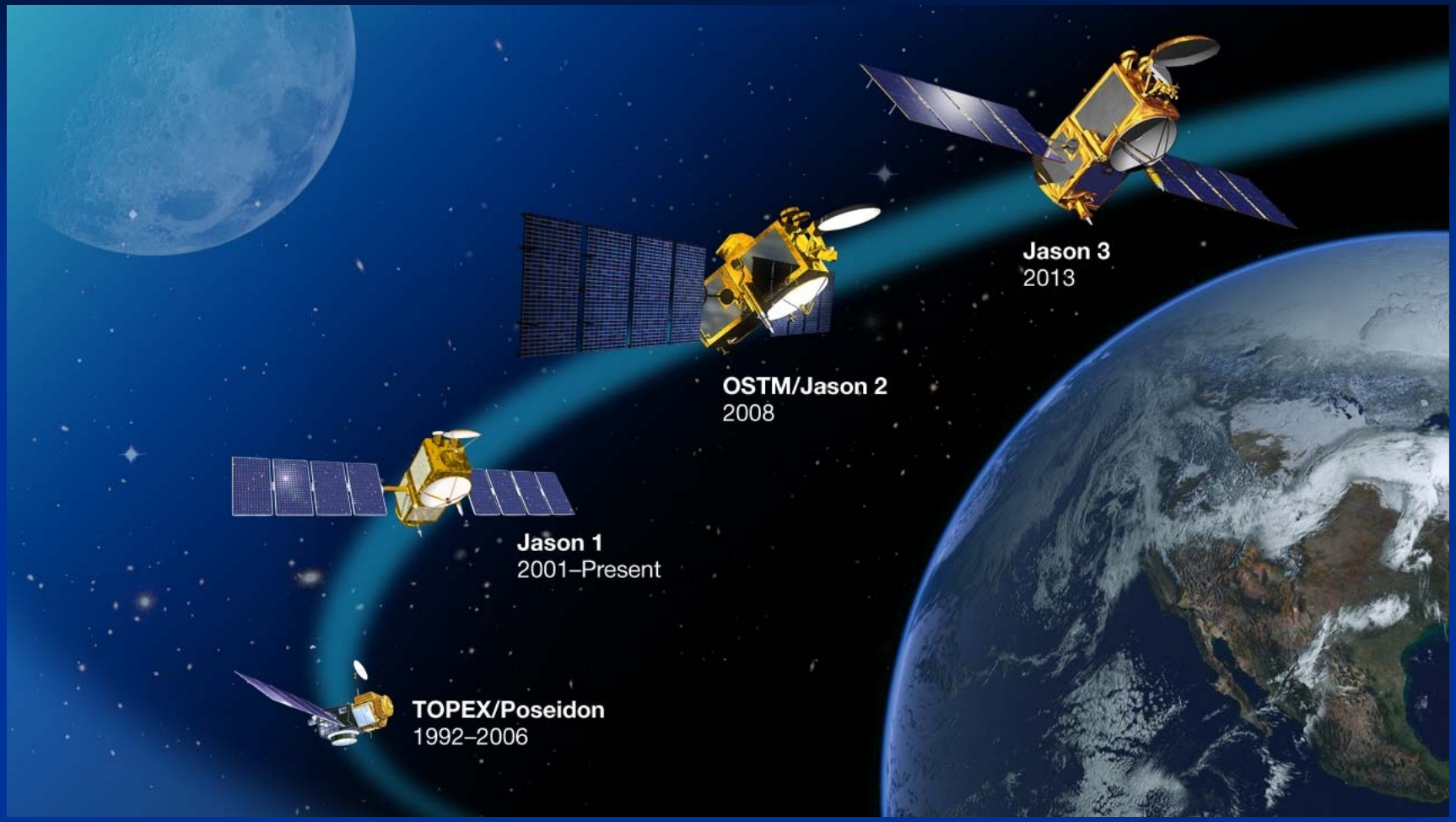
- Significance of Sea Level Acceleration
- Description of Tide Gauge Records
- Description of Satellite Data
- Three Studies That Jim and I have Conducted
  - Analysis of long-term U. S. Gauges
  - Analysis of many world-wide tide gauge records
  - Comparison of Tide Gauge and Satellite Data (Discussed Here)
- Summary and Conclusions


Sea Level Rise By 2100
Meters
2.10
1.95
1.80
1.65
1.50
1.35
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15
0.00
5 meters
Ice-sheet melt Greenland/Antarctica
IPCC 1990
IPCC 1995
IPCC 2001
IPCC 2007
Hansen 2007
Rahmstorf 2007
Pfeffer et al 2008
Vermeer & Rahmstorf 2009
Jevrejeva et al 2010

Corps of Engineers Guidance for Global Sea Level Rise (2009)



Satellite Altimetry Series



- 1,330 km above Earth, can measure ocean surface within 3.3 cm.
- Measures ocean surface between - 66 degrees and + 66 degrees latitude

Sea Level Rise Components as Measured by a Tide Gauge

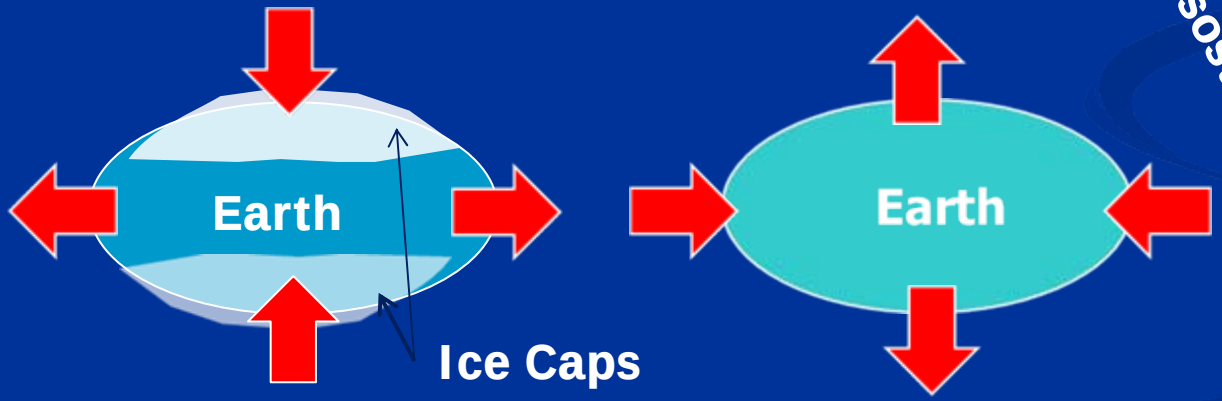
Sea Level Rise Components as Measured by a Tide Gauge

Sea Level = World Wide Sea Level + GIA + Local Effects + Noise

Global Sea Level

Glacial Isostatic Adjustment

Can Be Natural or Anthropogenic



Last Ice Age
20,000 Years Ago

Presently

Glacial Isostatic Adjustment

Examples of Local Effects

Natural

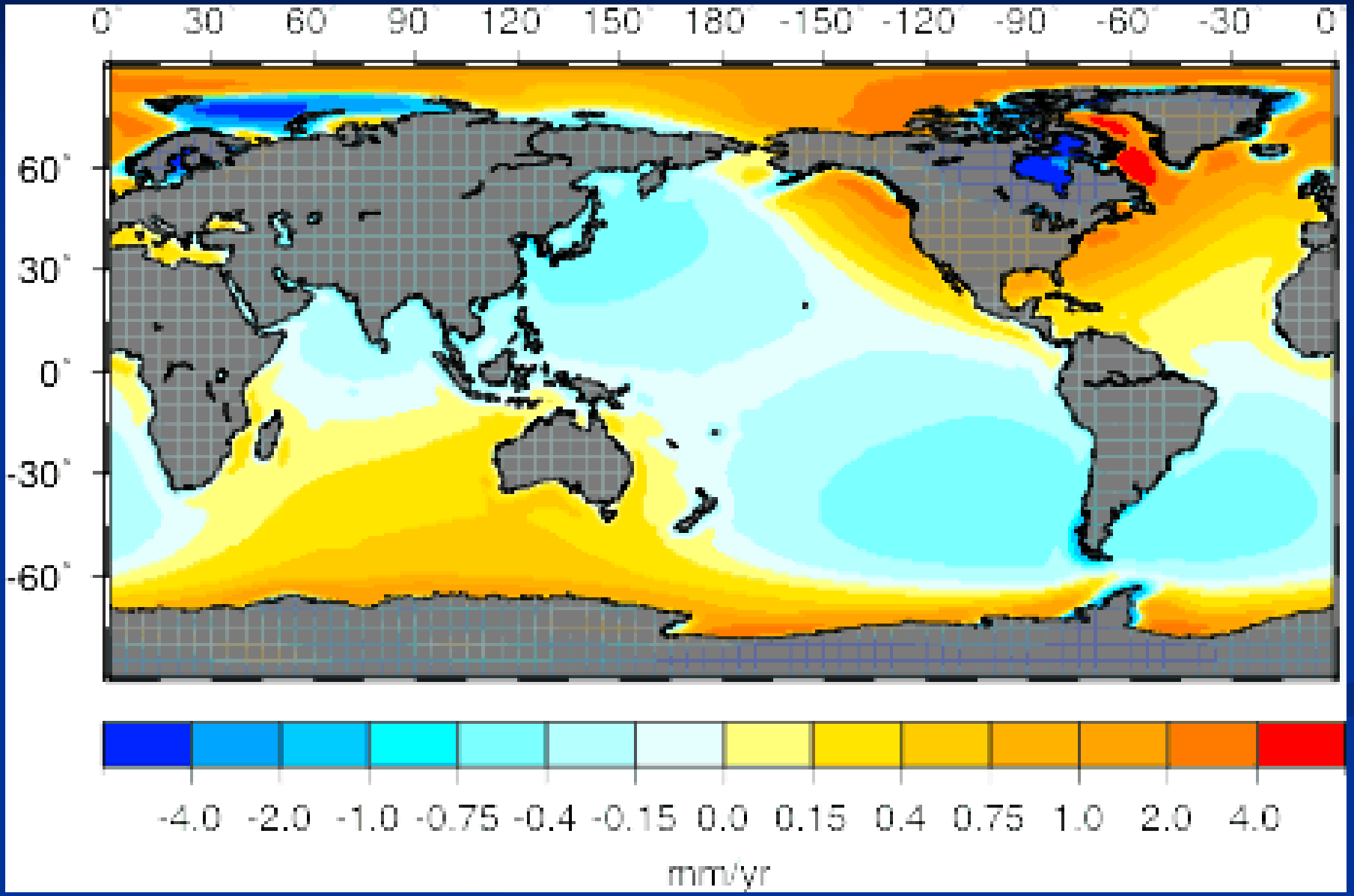
- **Compaction of Underlying Sediments**
- **Earthquakes**

Anthropogenically Induced

- **Withdrawal of Ground Fluids (Gas, Oil, Water)**
- **Building Heavy Structures on Weak Sediments**

It is noteworthy that almost all anthropogenic effects cause a lowering of land and thus a relative rise in sea level

Peltier Model Results for Glacial Isostatic Adjustment



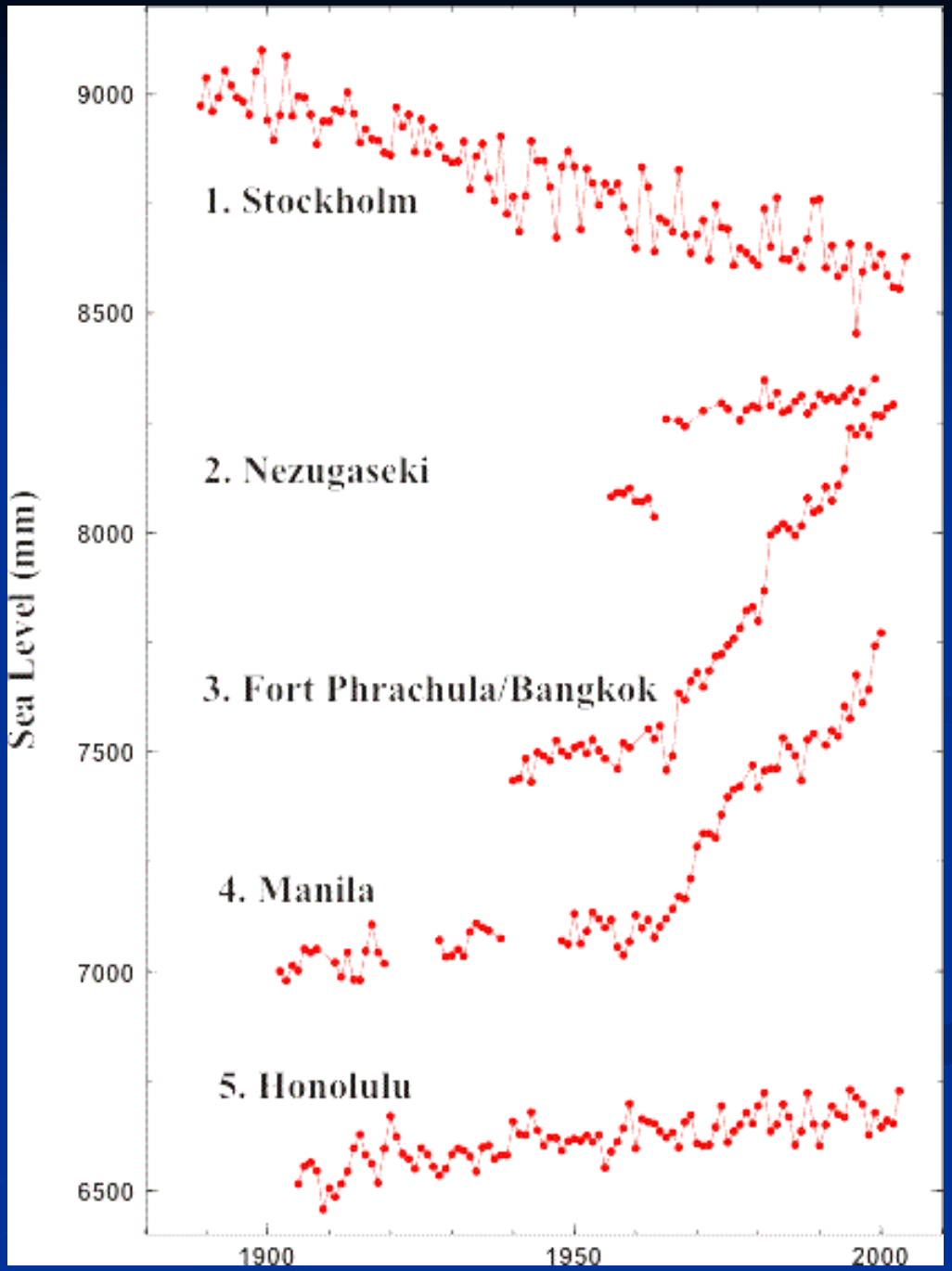
The Algebraic Relationship

$$y = a_0 + a_1 t + \frac{1}{2} a_2 t^2$$

- y: Sea Level
- a_0: Constant
- a_1: Initial Trend (mm/yr)
- t: Time (Years)
- a_2: Acceleration (mm/yr^2)

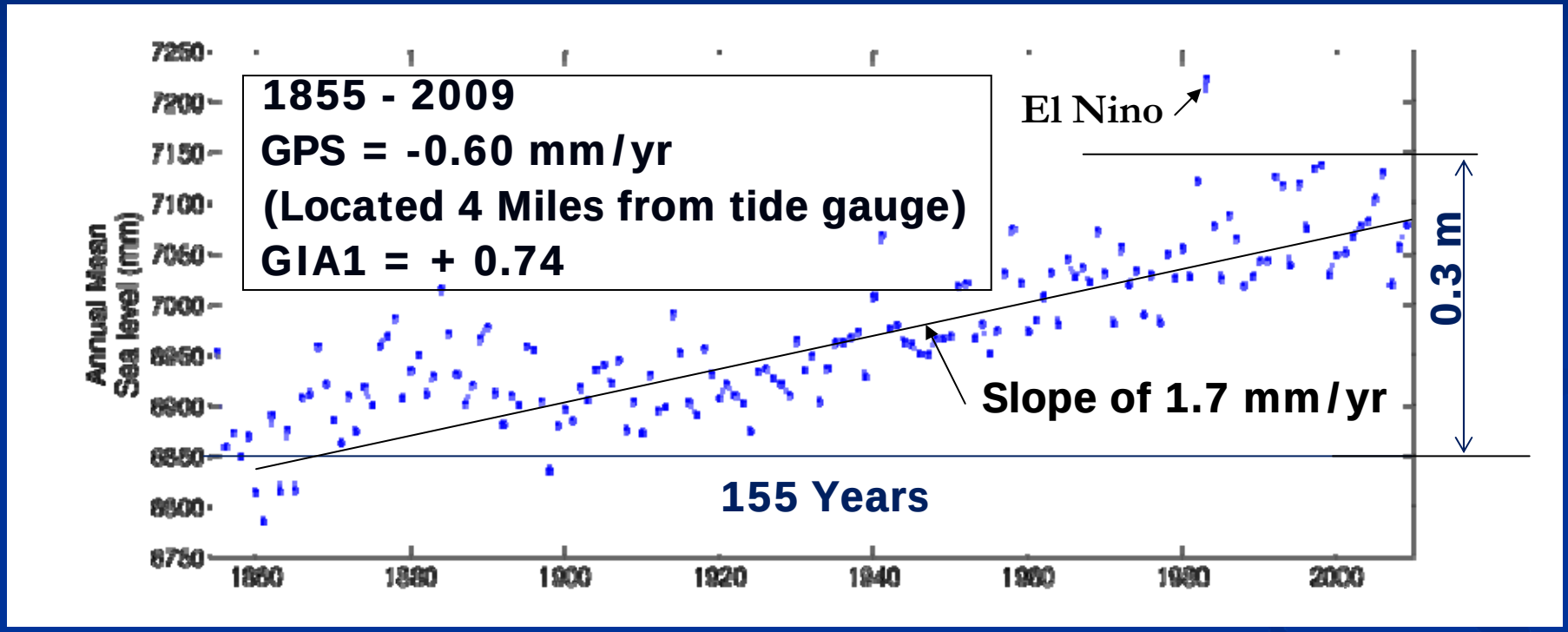
The accepted value of a_1 over the last century for the global trend is approximately 1.7 mm/yr

Tide Gauge Data Are Not Always Consistent With the Model



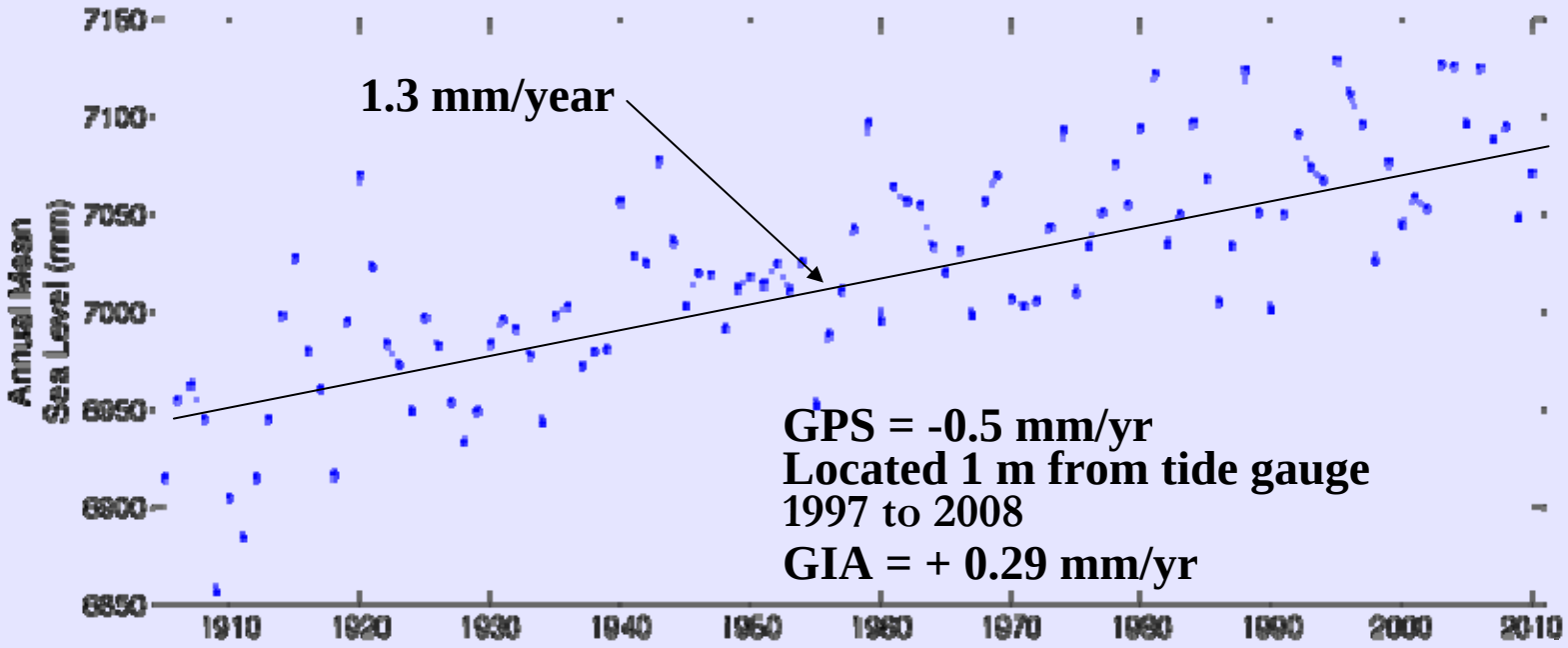
Example of Tide Gauge Record

(San Francisco: The Longest U.S. Gauge)

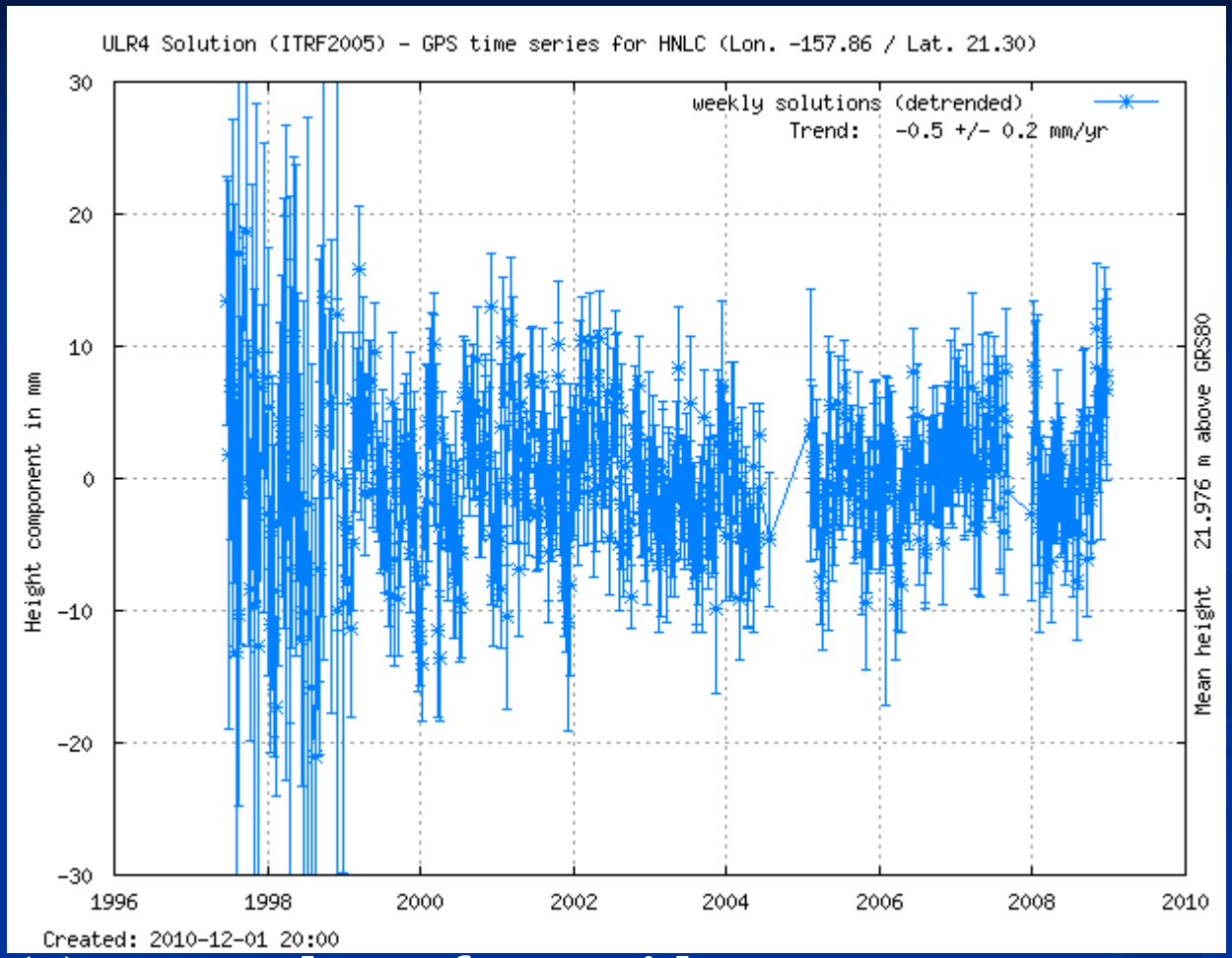


From PSMSL Web Site

Honolulu, HI Tide Gauge

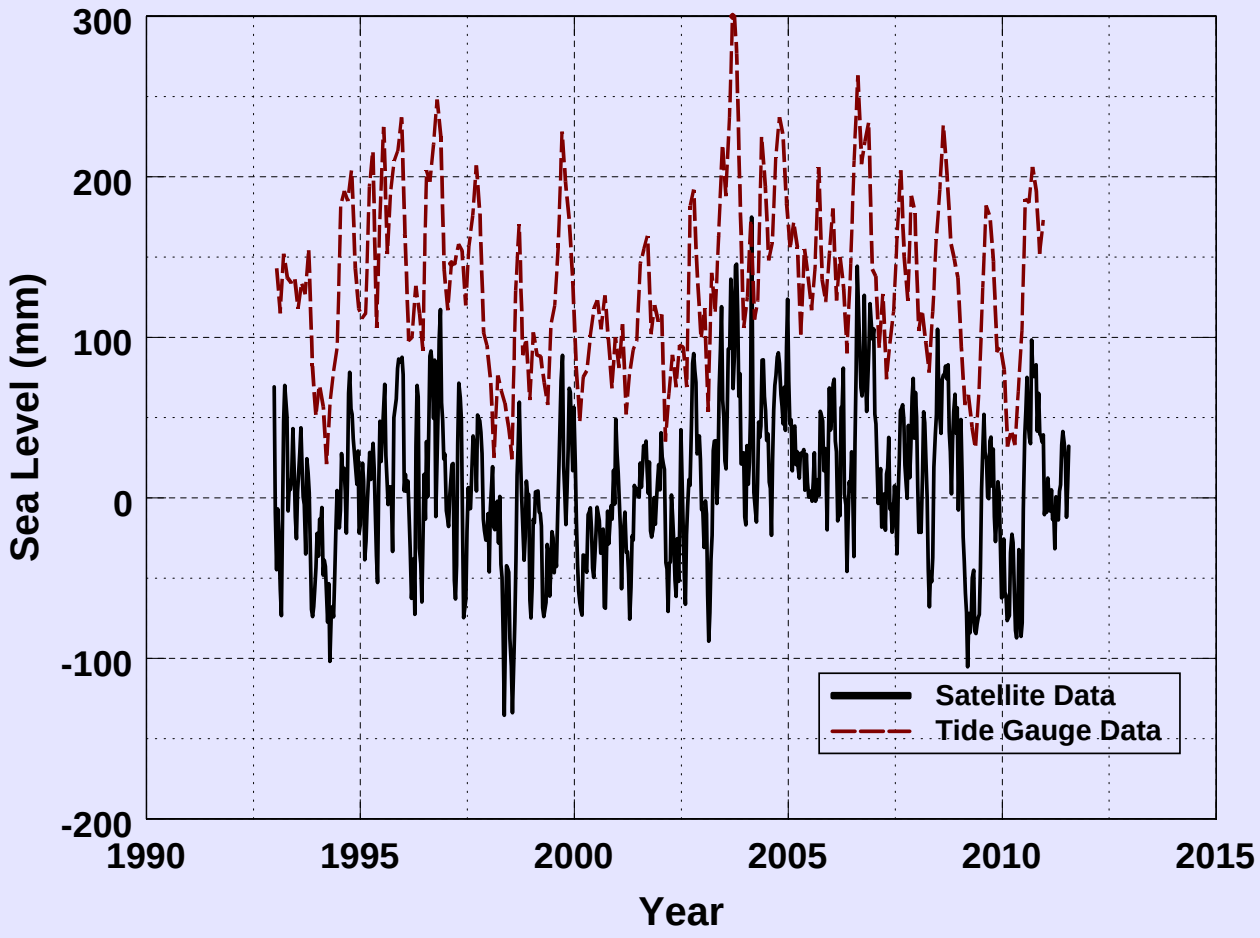


GPS Data For Honolulu, HI

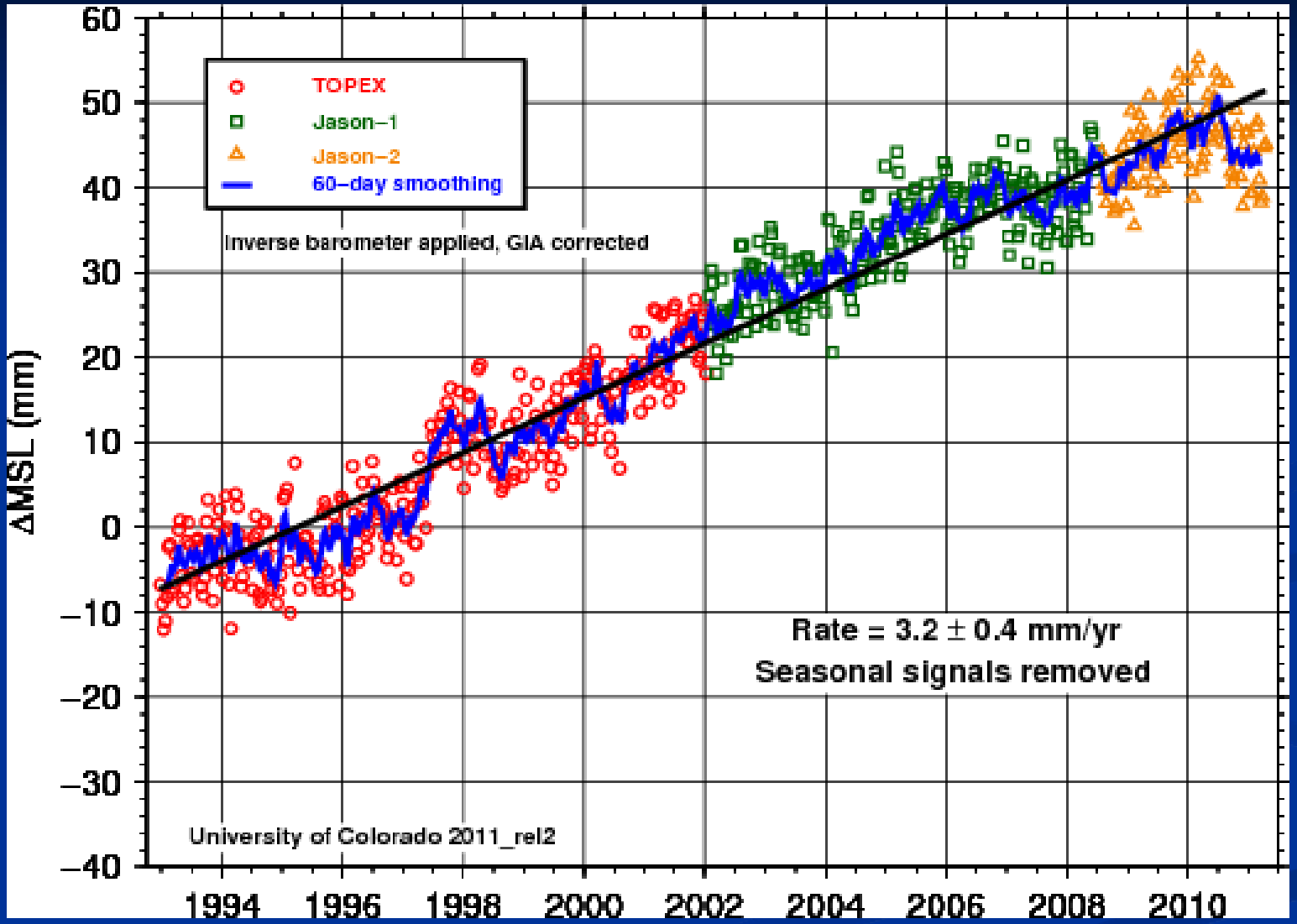


(1) Located 1 m from Tide Gauge
(2) 11 Years of Record
(3) Trend: -0.5 mm/yr (1997 to 2008)
(4) Above graph after trend removed

Comparison of Honolulu Tide Gauge and Satellite Data

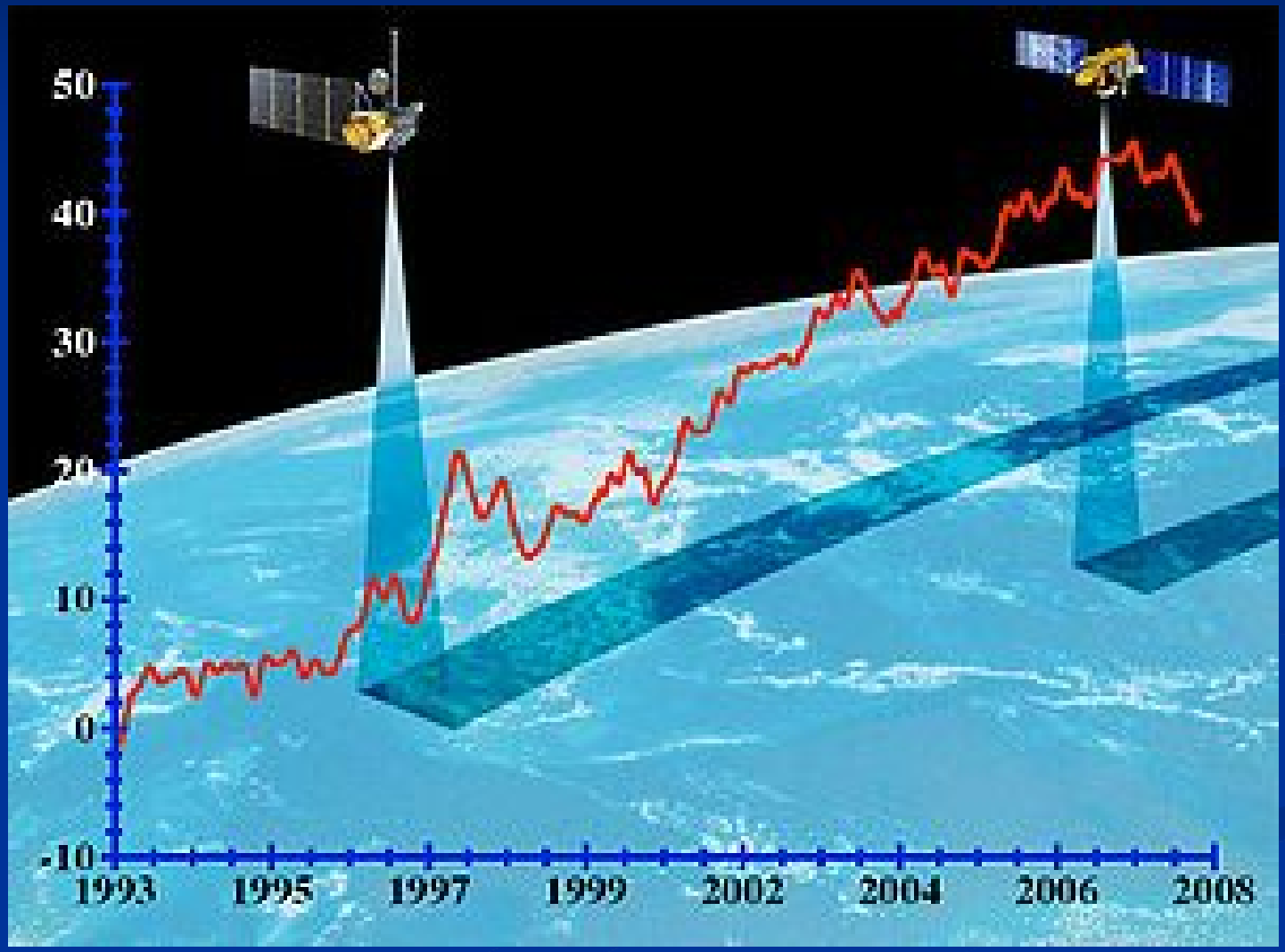


Average Sea Level Change From Satellites



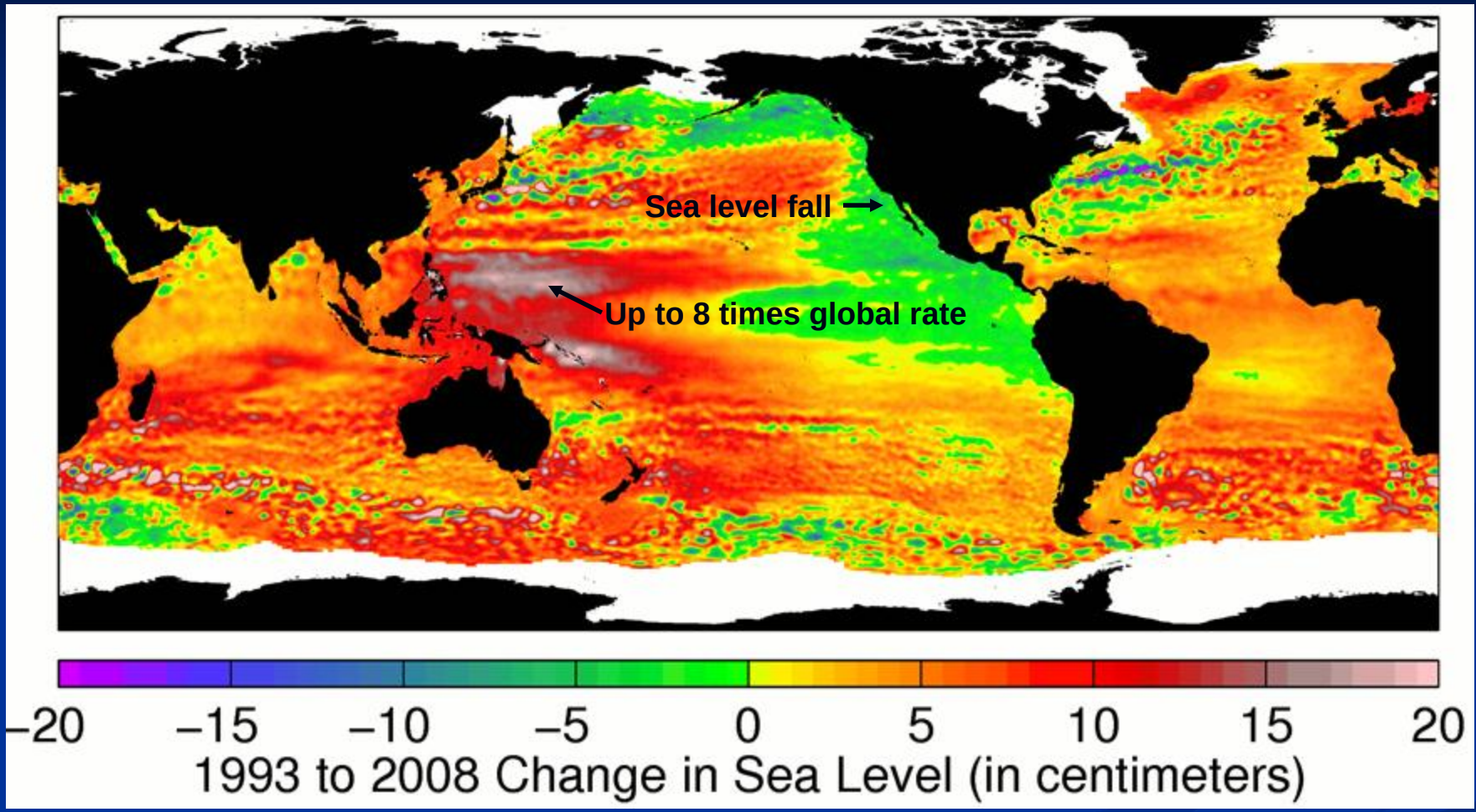
It is noteworthy that Satellite Data are calibrated against a fairly small set (64) of tide gauges!

Are Satellite Measurements 1993-2011 Leading Edge of Acceleration or Part of an Oscillation?



3.2 mm/yr trend is greater than 20th Century trend of 1.7 mm/yr

Sea Level Rise Is Spatially Very Non-Uniform



Satellite altimeter measurements over 15 years

Our Findings to Present

- **Over the 20th Century Global Sea Level:**
  - **Increased at a Rate of Approximately 1.7 mm/yr**
  - **Experienced a Small Negative Deceleration**
- **Since the 1990's Satellites Indicate a Global Sea Level Increase at a Rate of Approximately 3.2 mm/year**

Effort Discussed Here

- Analyzed 459 tide gauges with > 50% data completeness over the period 1993 to present (Subset with 85% complete)
- Analyzed 73 gauge subset with GPS present
- Analyzed 313 Satellite records for locations in proximity with tide gauges
- Compared trends and accelerations for gauge and satellite results

Our Examination of Global Sea Level Rise 1993 to 2010

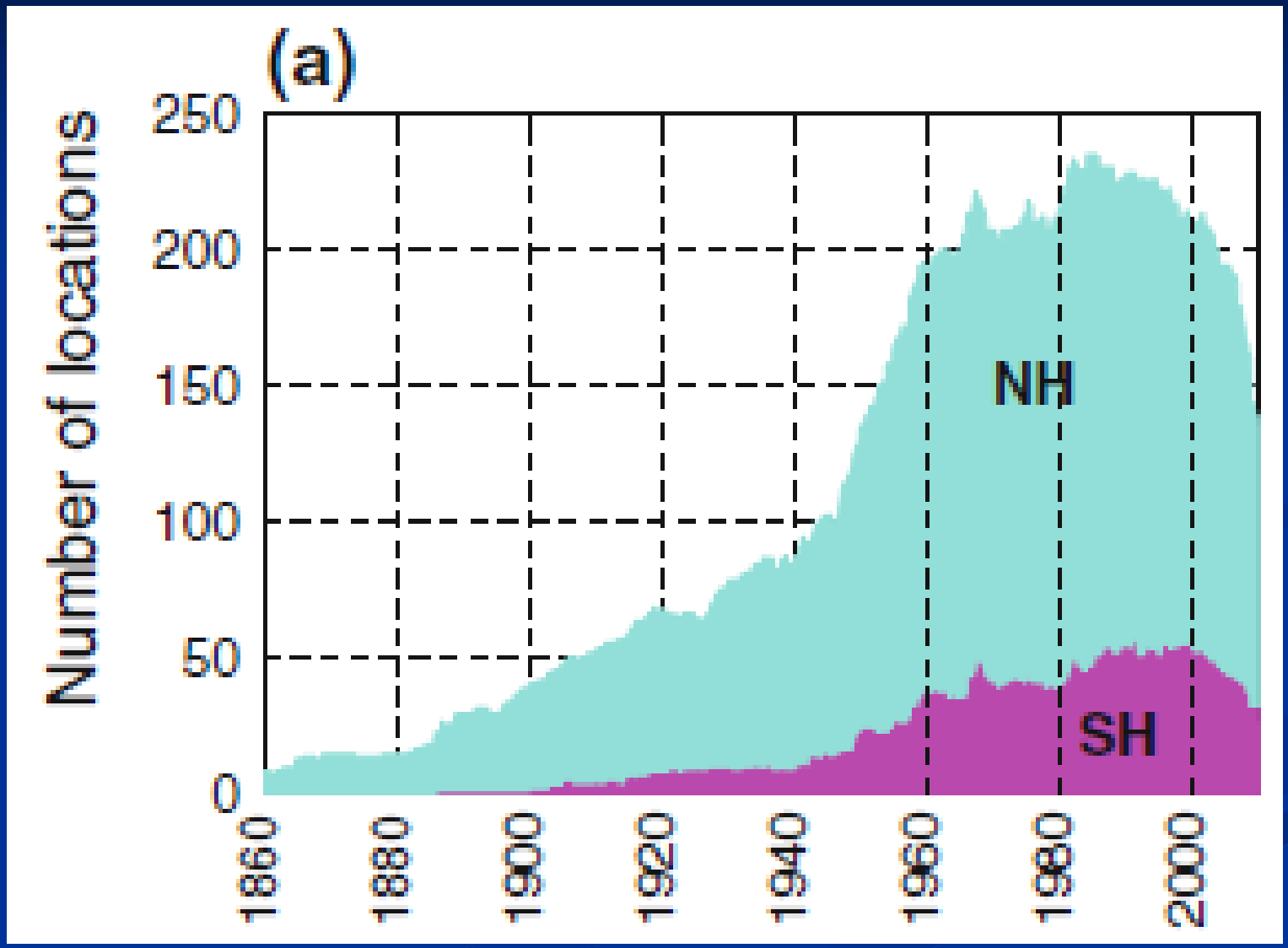
Examine 459 high quality tide gauge records

Analysis of Tide Gauges (1993 to 2011)

Data Description	No. of Gauges	Trend (mm/year)	Acceleration (mm/year^2)
50% Complete, Full Data Set	459	3.30± 0.81	- 0.191 ± 0.194
85% Complete, Full Data Set	370	3.42± 0.66	- 0.180 ± 0.201
50% Complete, GPS Data Set	73	2.58 ±1.07	- 0.153 ± 0.334
85% Complete, GPS Data Set	59	2.50 ±1.05	- 0.136 ± 0.233

These results have been weighted for 15^o by 15^o subarea size (Longitude line convergence toward Poles)

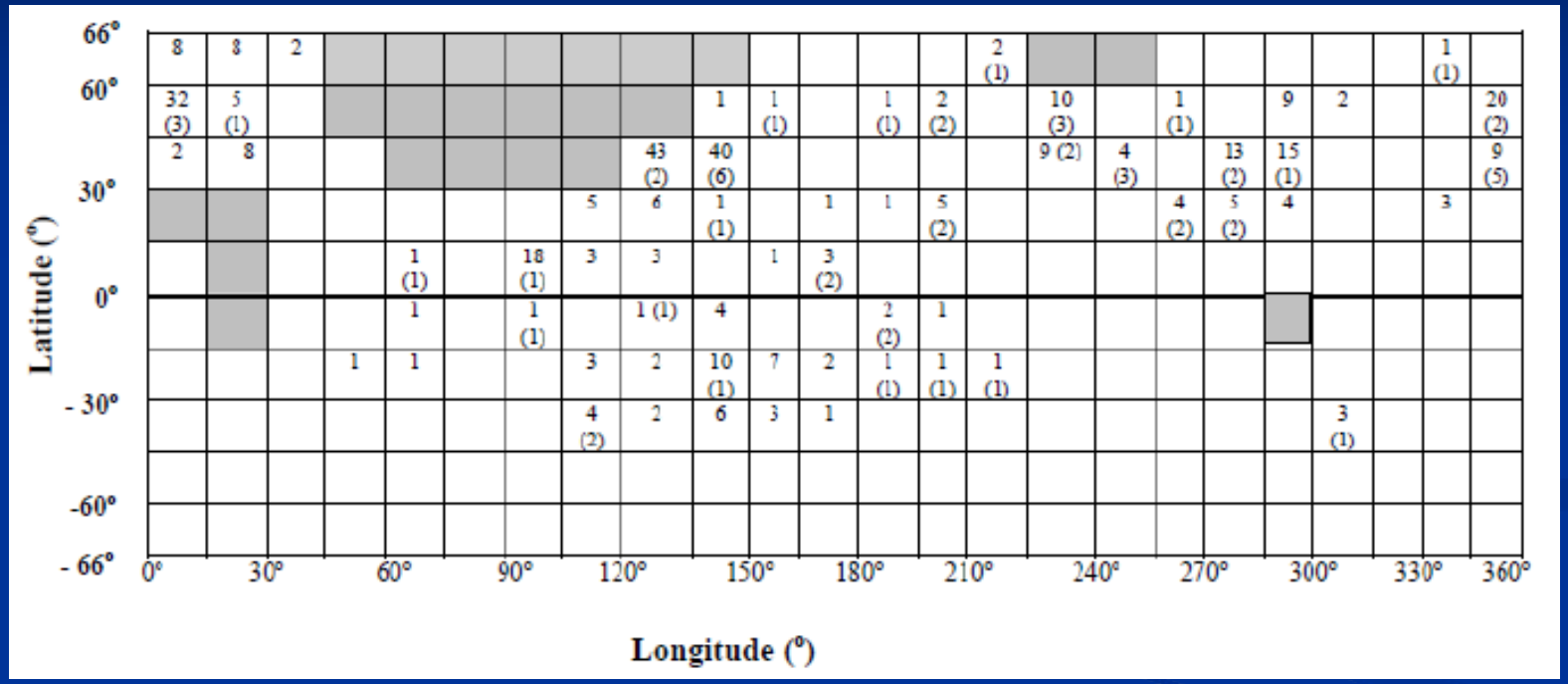
Uneven Distribution of Tide Gauges



Church and White (2011)

Distribution of 371 Tide Gauges Analyzed

(All 85% Complete Over the Period 1993 to Present)

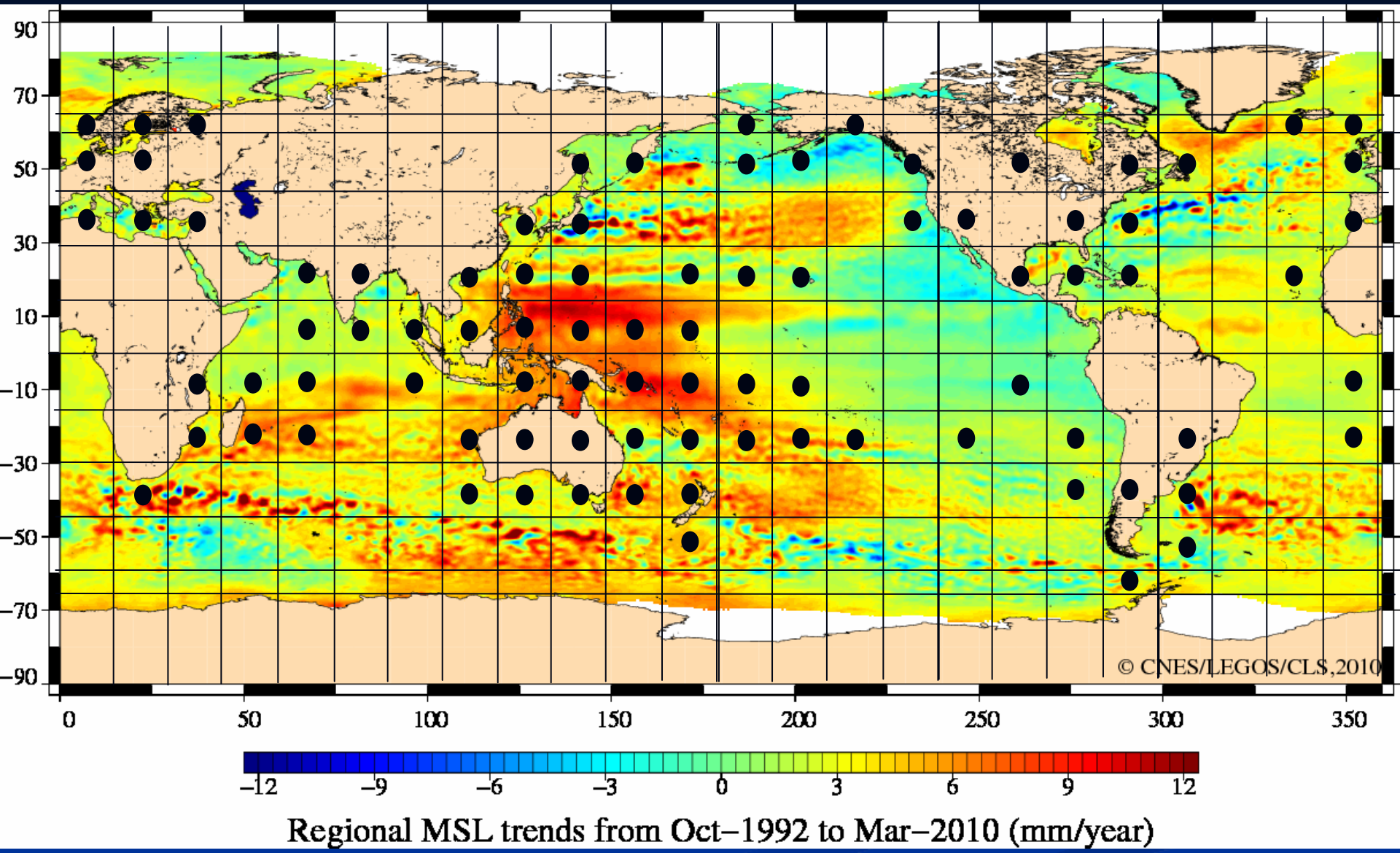


Notes:

(1) 18% of Tide Gauges in Southern Hemisphere

(2) 60% of Oceanic Waters in Southern Hemisphere

(3) Tide Gauge Trends and Accelerations in 15° Subareas Weighted for Subarea Size



15° by 15° Sub Areas Occupied by Tide Gauges Analyzed. Overlaid on Satellite Trend Chart

Adjustment of Tide Gauge Data for Spatial Bias Using Satellite Data (Adjusted for GIA and GPS Where Available)

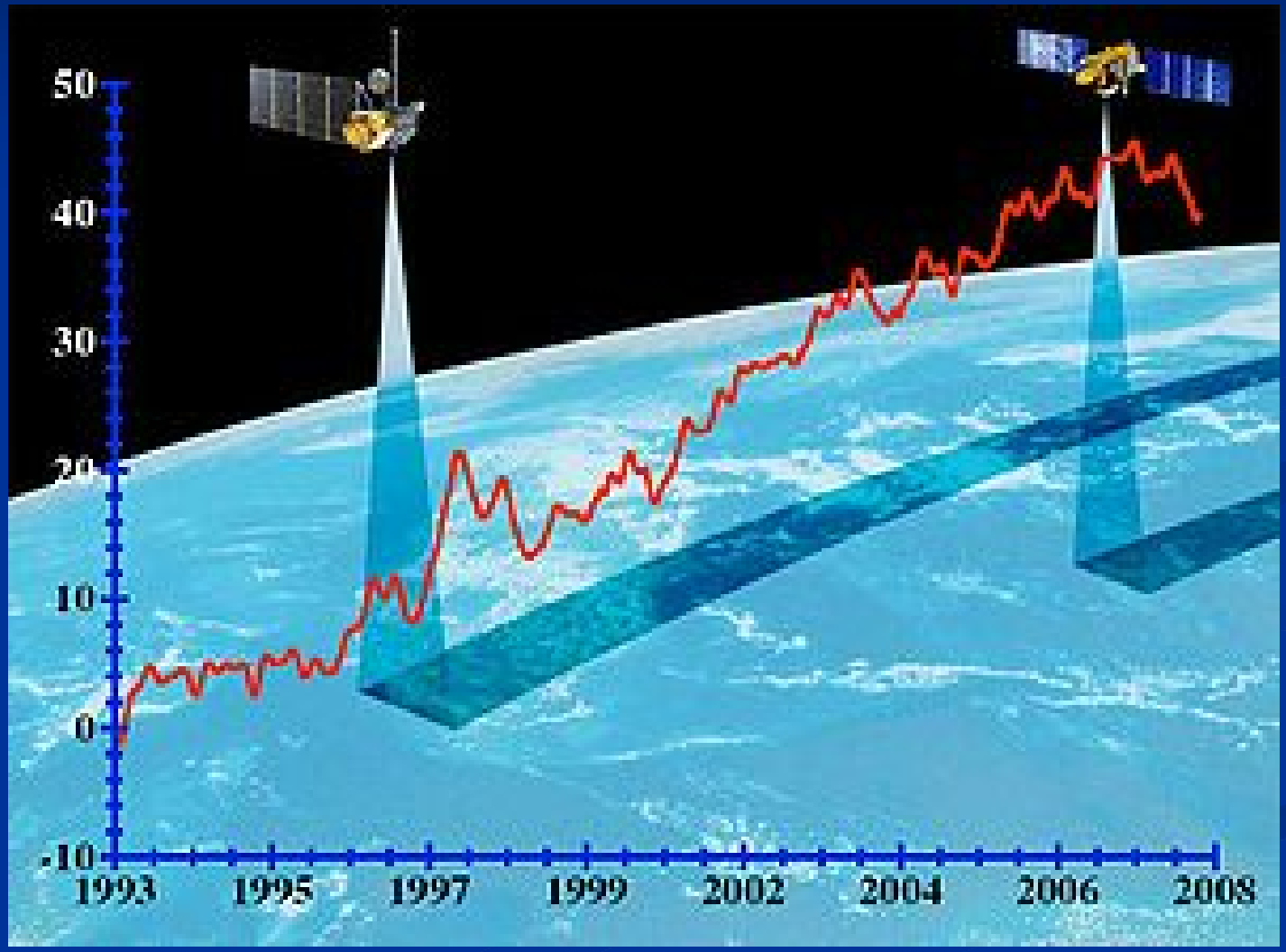
$$V_{Tide\ Gauge\ Adjusted} = \frac{V_{Satellite,\ All\ Active\ Subareas}}{V_{Satellite,\ Same\ Subareas\ as\ Gauges}} V_{Tide\ Gauge\ Unadjusted}$$

Adjustment of Tide Gauge Data for Spatial Bias Using Satellite Data
(Adjusted for GIA and GPS Where Available)

$$V_{Tide\ Gauge\ Adjusted} = \frac{V_{Satellite,\ All\ Active\ Subareas}}{V_{Satellite,\ Same\ Subareas\ as\ Gauges}} V_{Tide\ Gauge\ Unadjusted}$$

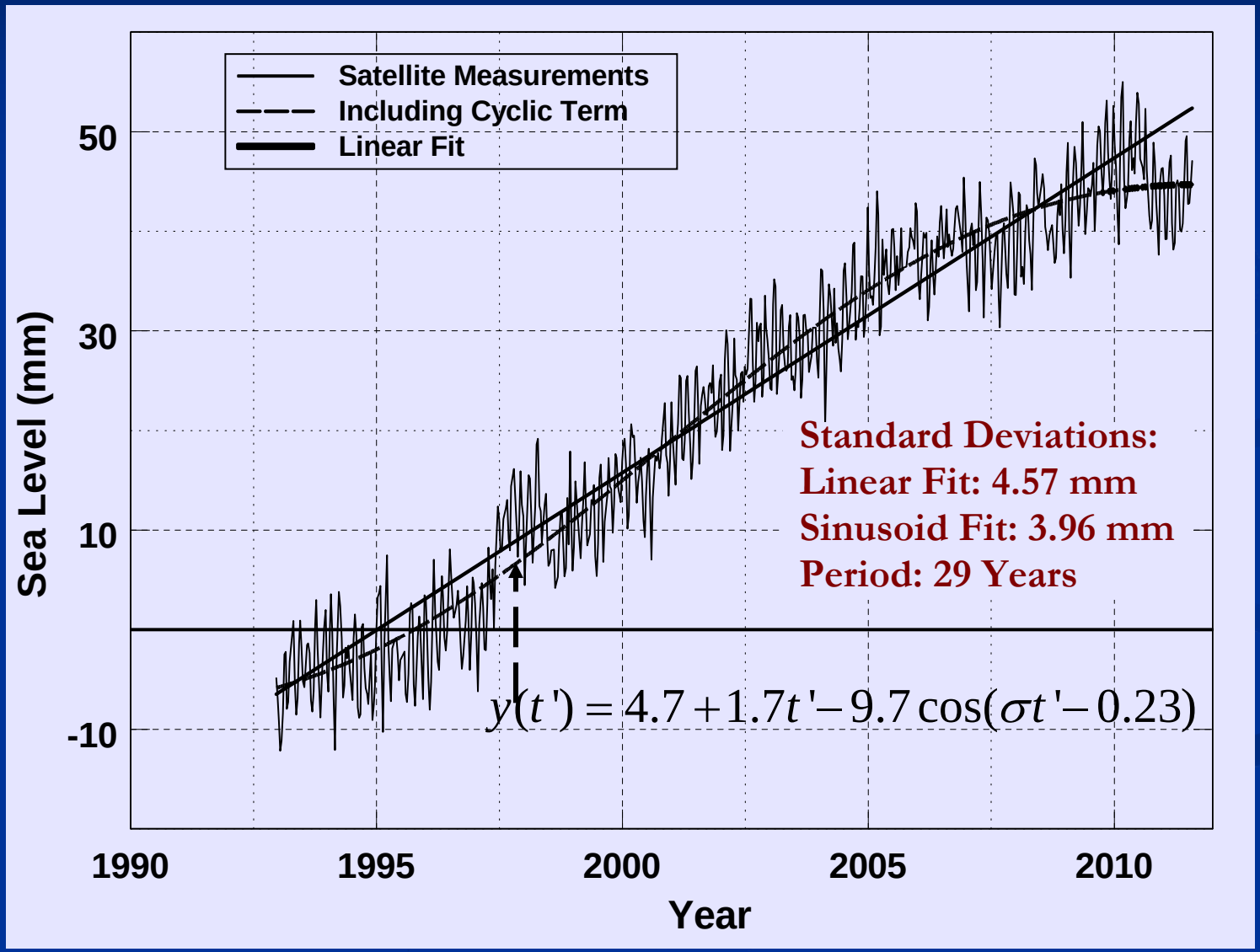
Data Set	Trend (mm/year)	Acceleration (mm/yr^2)
Full 85% (370 Gauges)	2.67 (vs 3.42 Unadjusted)	- 0.171 (vs - 0.180 Unadjusted)
GPS 85% (59 Gauges)	2.29 (vs 2.50 Unadjusted)	- 0.099 (vs – 0.136 Unadjusted)

Are Satellite Measurements 1993-2011 Leading Edge of Acceleration or Part of an Oscillation?

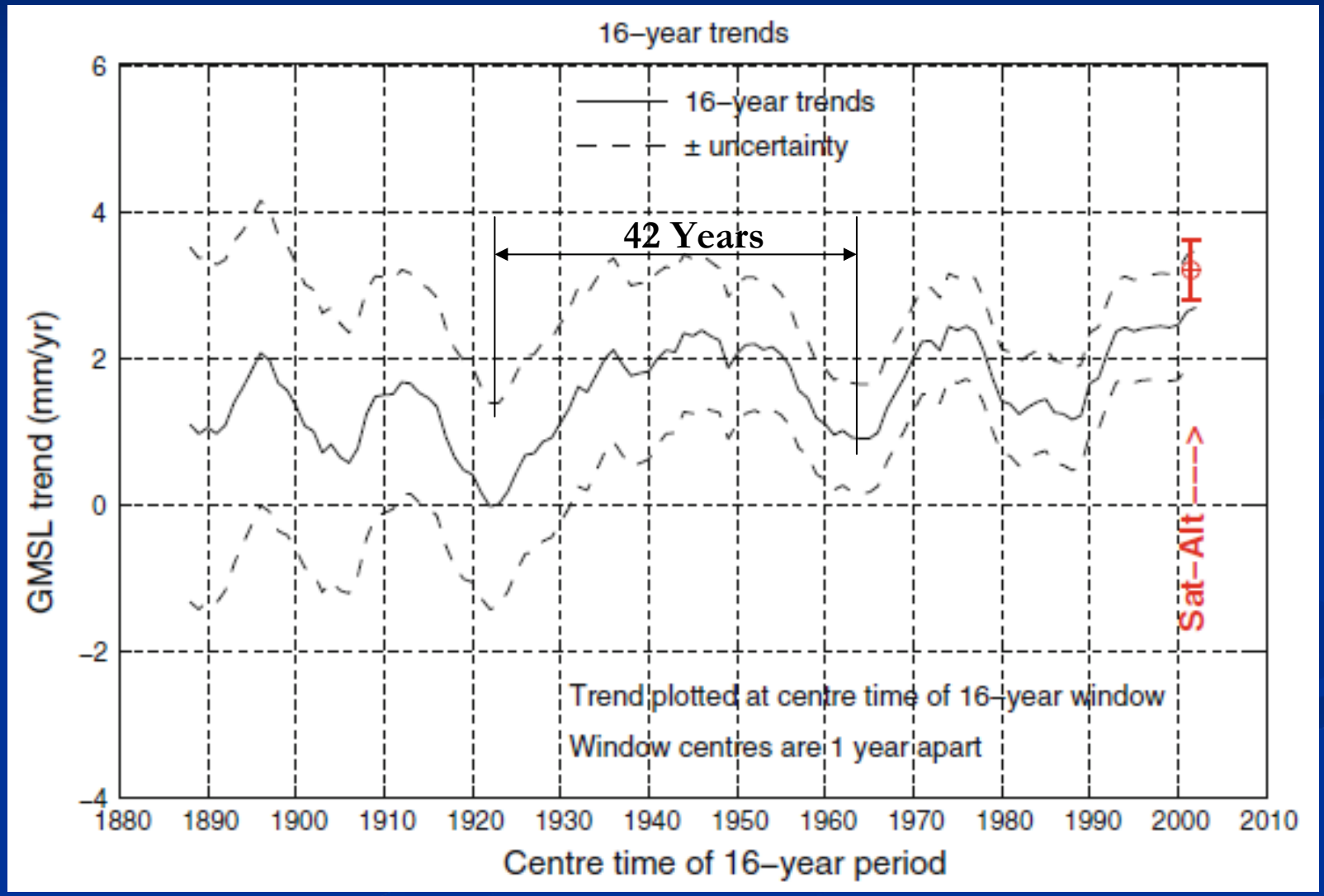


3.2 mm/yr trend is greater than 20th Century trend of 1.7 mm/yr

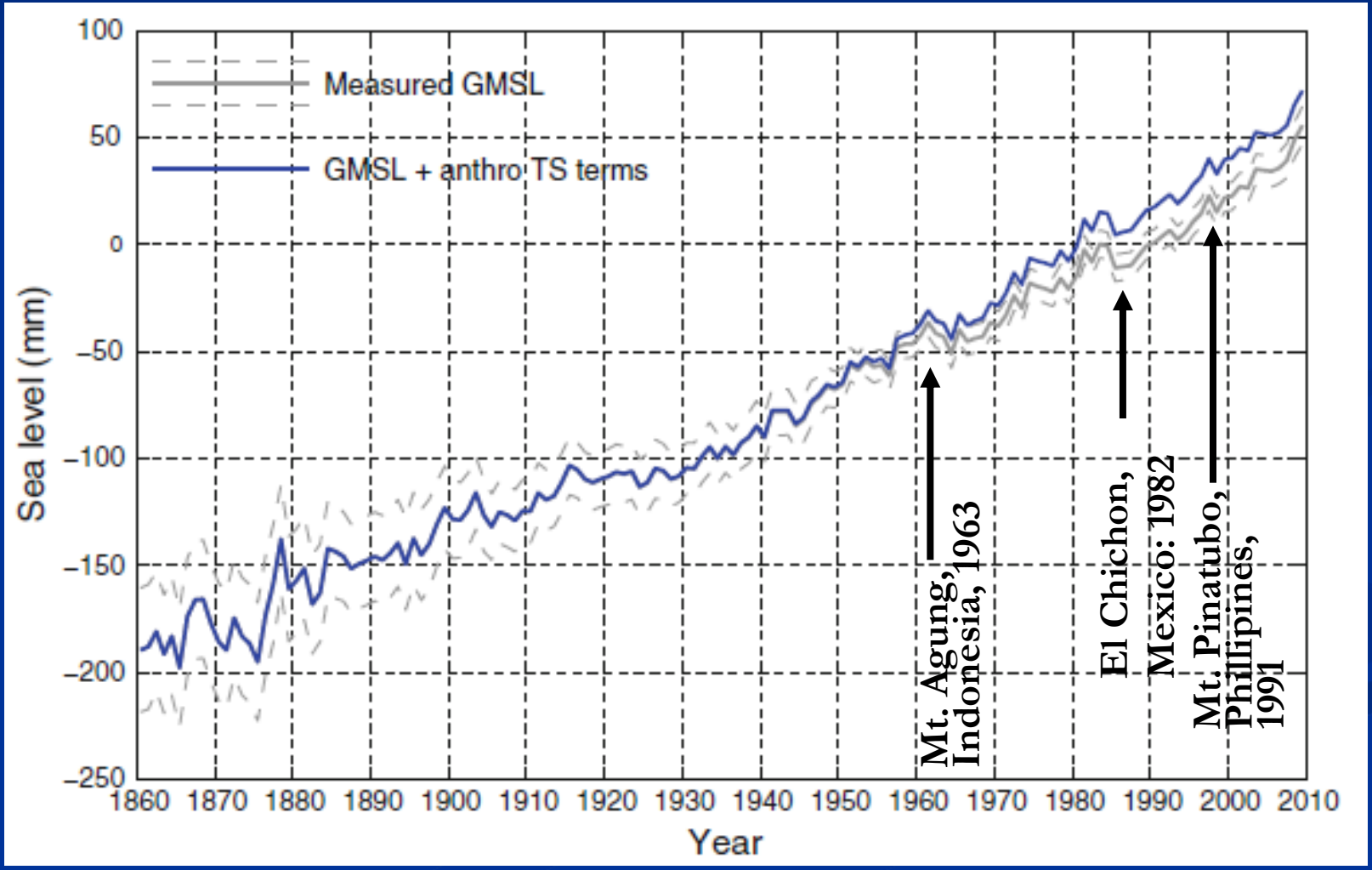
Satellite Data Compared With Best Linear and Sinusoid Fits



Past Oscillations (Church and White, 2011)



Possible Effects of Volcanic Eruptions (Church and White, 2011)



Summary

1. **Over the last year, we have conducted extensive analyses of quality tide gauge data including world wide and U. S. gauges.**
2. **Tide gauge data are "noisy" requiring analysis of many long-term records from areas of geological stability.**
3. **The results of all of our analyses are consistent - There is no indication of an overall world-wide sea level acceleration in the 20th Century data. Rather, it appears that a weak deceleration was present.**
4. **We have also conducted an extensive comparison of satellite and tide gauge data.**

Summary (Continued)

5. Our preliminary examination of large numbers (370) of tide gauge records over the period 1993 through 2010 suggest a trend of approximately 2.7 mm/yr, somewhat lower than satellite data for this period (3.2 mm/yr) with the following caveats:

- **An eighteen year period is relatively short**
- **Satellite altimetry is calibrated with tide gauges due to drift problems.**
- **Mount Pinatubo (Philippines) eruption in 1991 caused a lowering of sea level, so part of the higher trend is believed to be a "rebound".**

6. The relative dearth of tide gages in the Southern Hemisphere is a serious drawback in determining global sea level characteristics

Recommendations

1. Continue collecting tide gauge data.
2. In view of the significant differences in the model-produced GIA values, install more GPS units adjacent to longer term tide gauges.
3. Only apply GIA results in areas of high glacial rebound where GPS data are not available.
4. Continue to monitor the satellite altimetry results.

Thank You!