# Sea-Level Rise in the Columbia River Estuary, past, present, and future

**Photo Credit**: The Wetlands Conservancy

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# Big Picture Questions

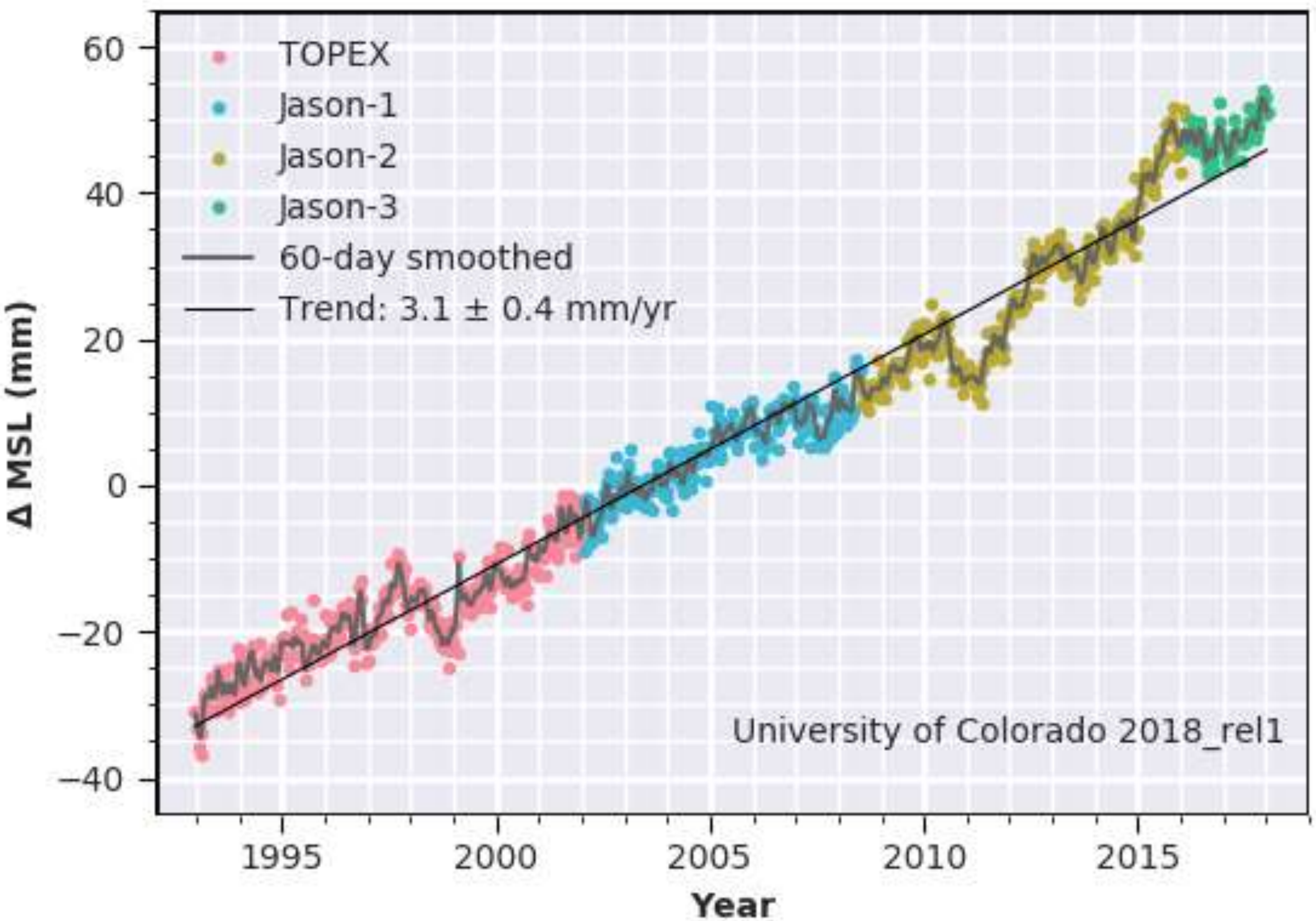
1. Water Levels in Columbia River were different in the past. But how different?

2. Are local factors, climate change, or both causing trends?

3. Based on the past, what can we learn for the future?

4. Today's focus: An empirical look at sea level

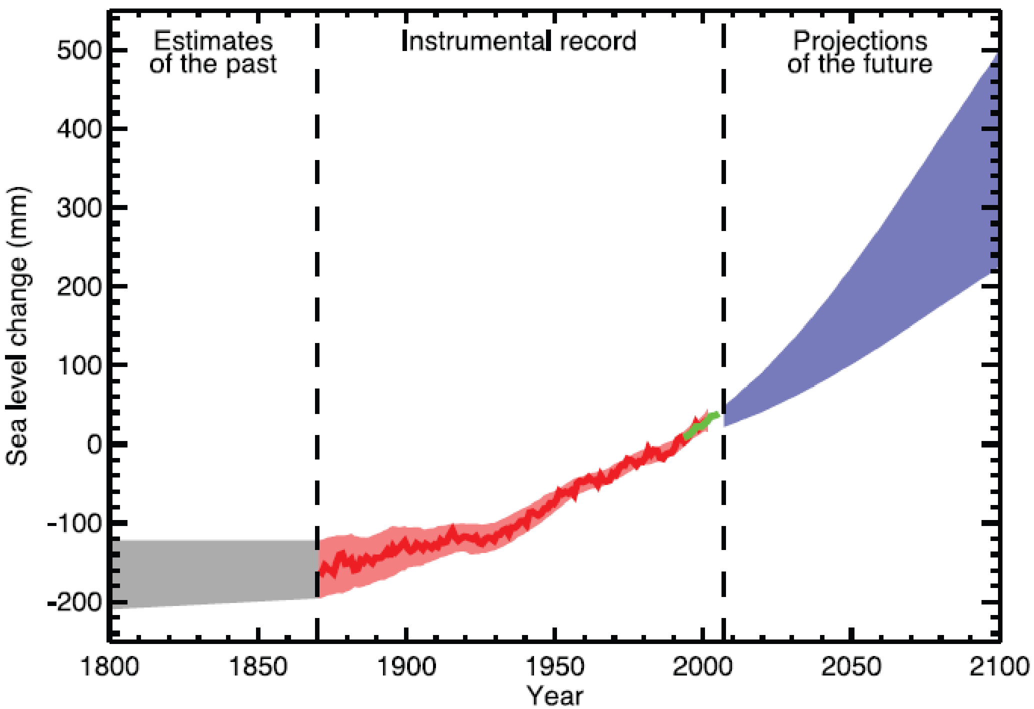
# Sea-Level rise




Current Rates of Global Sea Level Rise (from satellite)

https://www.washingtonpost.com/news/capital-weather-gang/wp/2016/05/20/10-things-you-should-know-about-sea-level-rise-and-how-bad-it-could-be/?utm_term=.a5df1de0a6b5

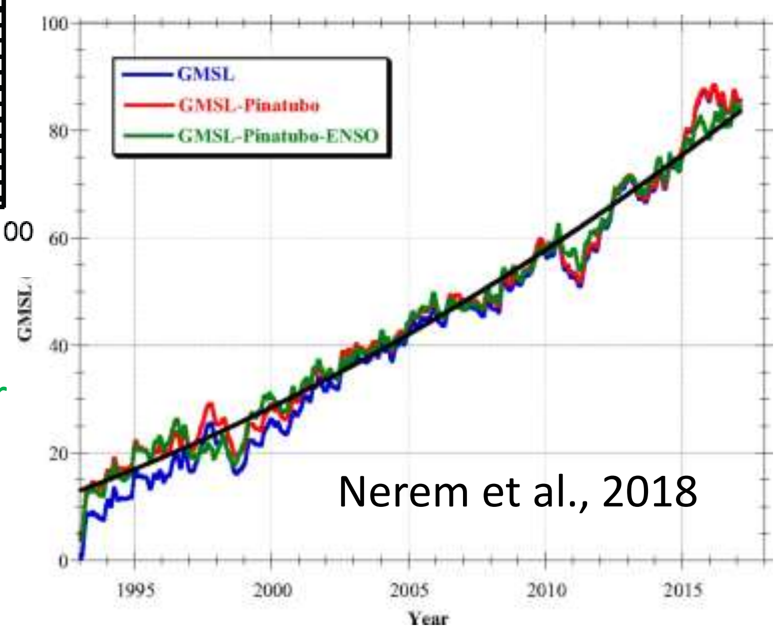
# The problem




IPCC projections, historical data, and adjusted satellite data suggest that the rate of increase in sea-level is not linear.

In other words, sea-level rise is accelerating

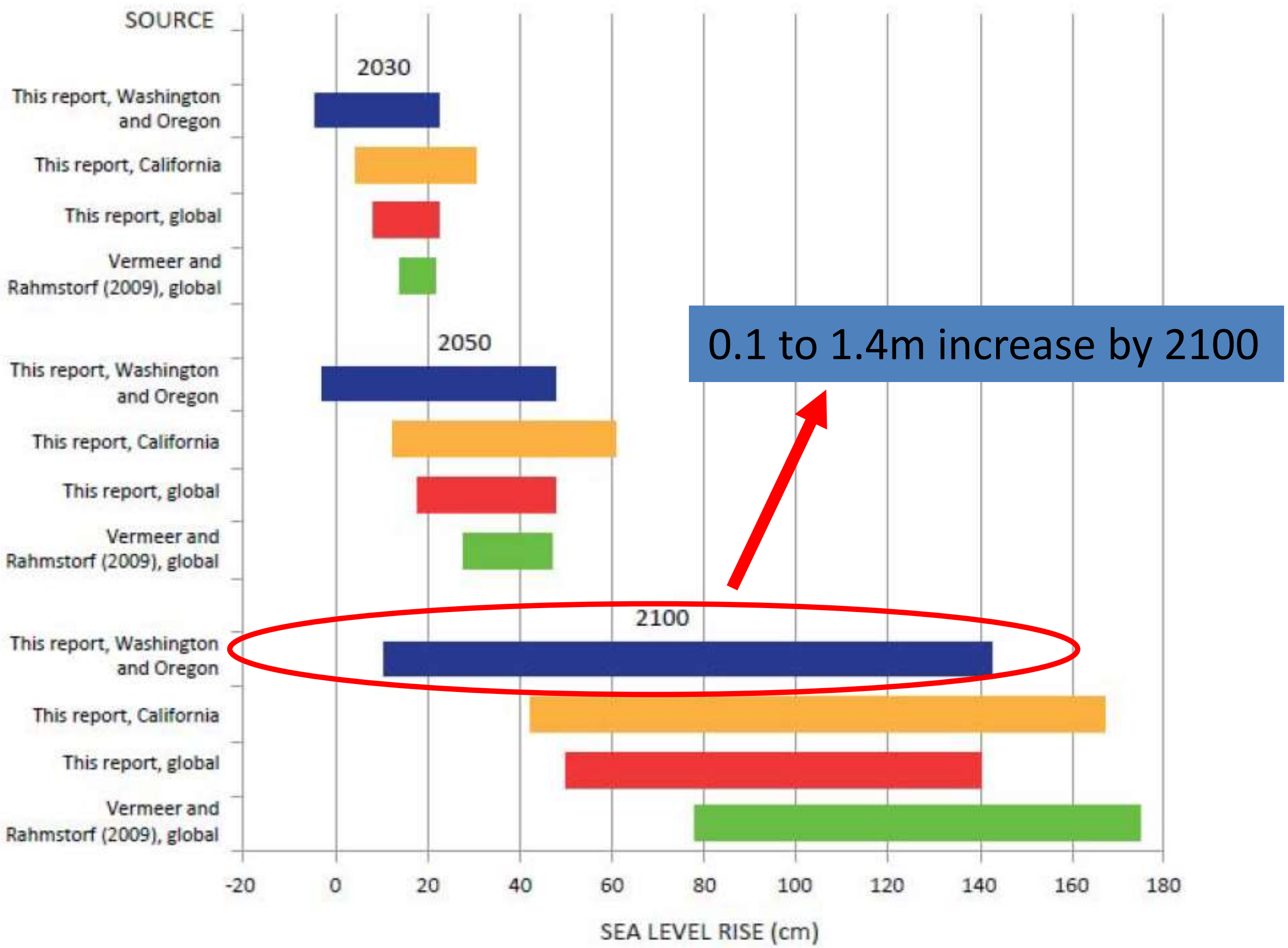
So…. How will the rate of rise in Columbia River evolve in the future?




Nerem et al., 2018

# Relative Sea Level (RSL) Projections

Relative sea-level change = Change in absolute sea level – Change in height of the solid earth surface,




NRC,2012

# Why the variance?

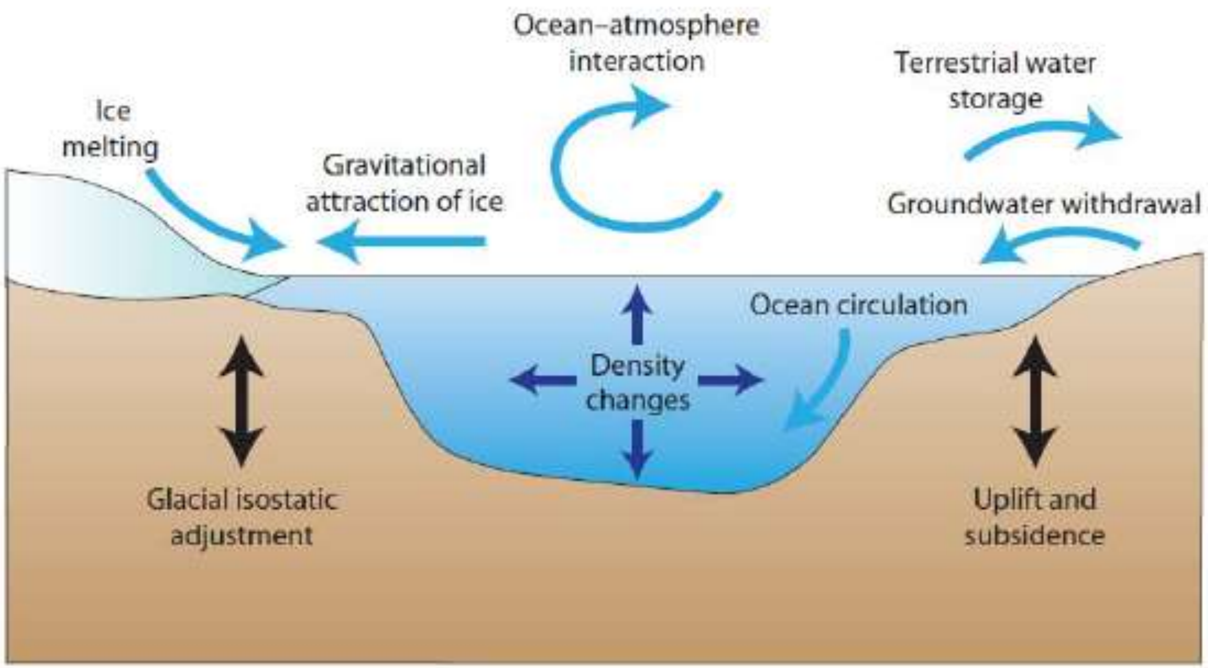



FIGURE 1.4 Processes that influence sea level on global to local scales. SOURCE: Modified from Milne et al. (2009).

NRC,2012

One cause: Many factors affect sea-level budget and relative sea-level rise

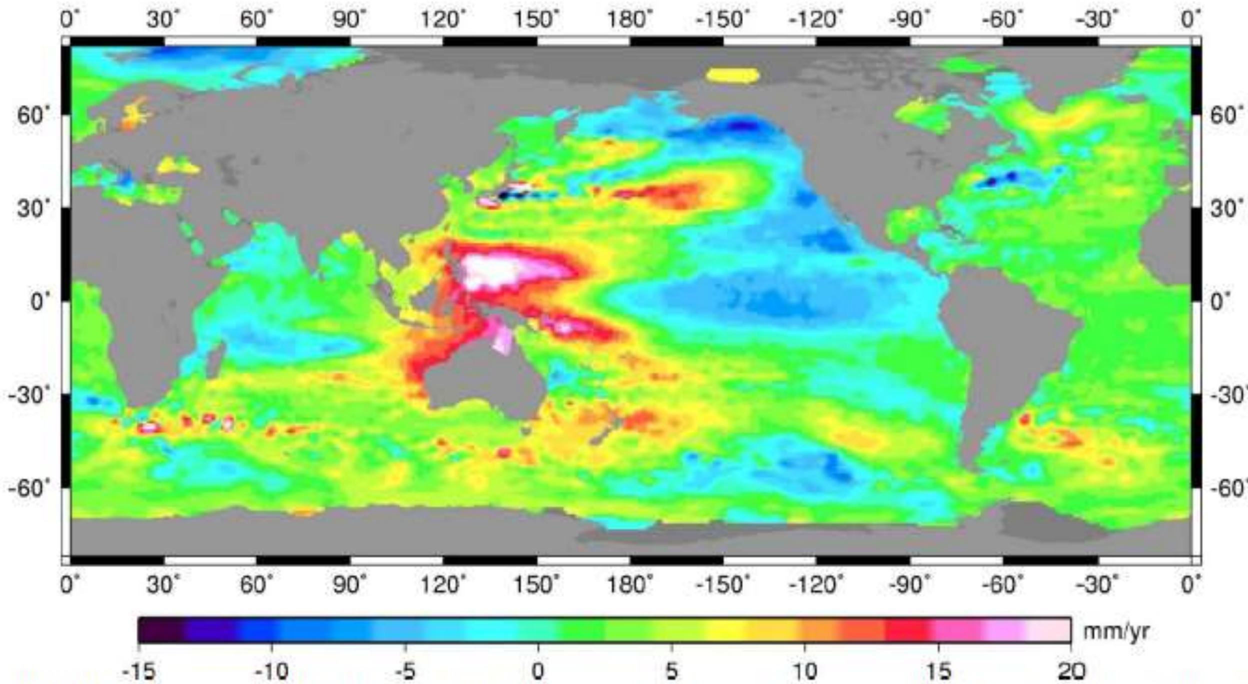
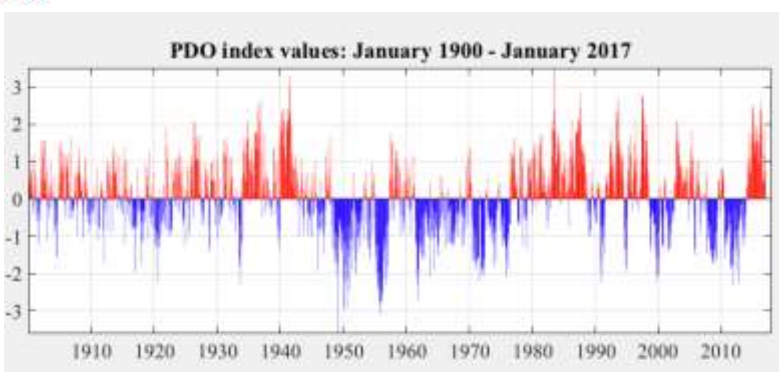



FIGURE 2.4 Regional variations in global sea-level rise based on observations from satellite altimetry from 1985 to 2010. The data were corrected for glacial isostatic adjustment, atmospheric barotropic pressure response, and various instrument, media, and geophysical effects. SOURCE: Updated from Shum and Kuo (2011).

Seasonal, interannual (ENSO), and decadal (PDO) patterns in wind and water temperature can cause large trend differences




PDO (Pacific Decadal Oscillation)


# Glacial Isostatic Adjustment (GIA)

TABLE 4.3 GIA Predicted Relative Sea-Level Rise for ± 250 Years Relative to the Present Day Using an Ensemble of 16 GIA Models at 21 West Coast Tide Gage Locations

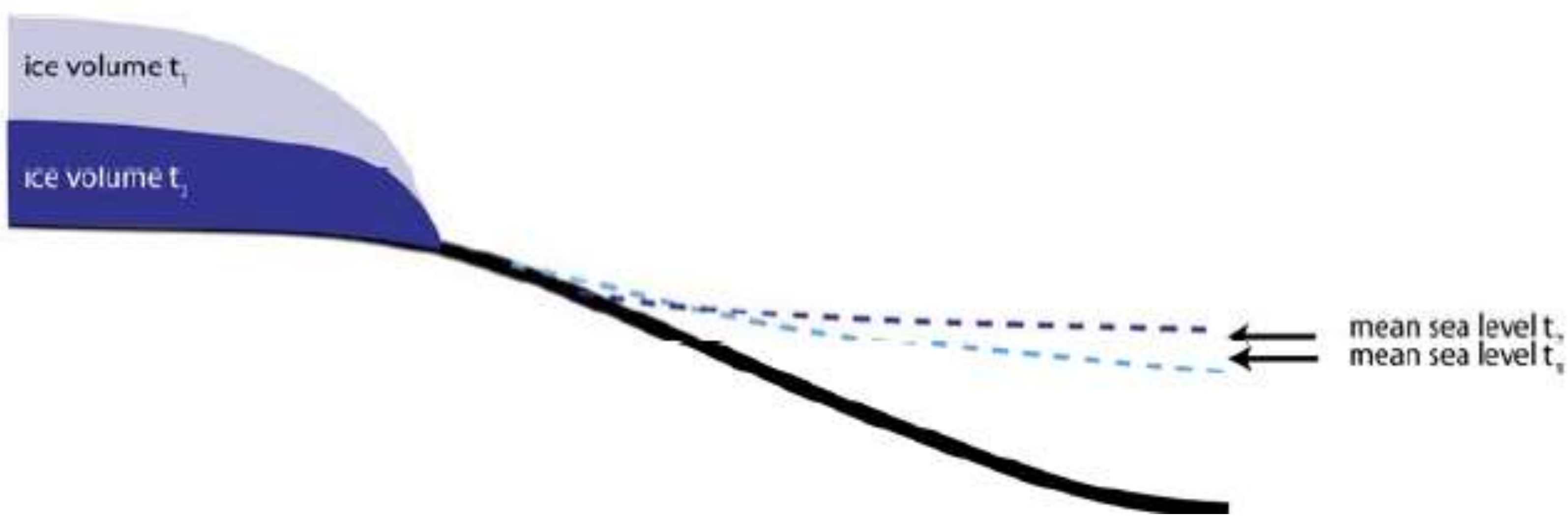
| | | | GIA Predicted Relative Sea-Level Rise ($mm\ yr^{-1}$) | |
|---|---|---|---|---|
| Location | Latitude | Longitude | Mean | Standard Deviation |
| Cherry Point, WA | 48.87 | -122.75 | -0.16 | 0.44 |
| Friday Harbor, WA | 48.55 | -123.00 | 0.14 | 0.46 |
| Neah Bay, WA | 48.37 | -124.62 | 0.58 | 0.64 |
| Port Townsend, WA | 48.12 | -122.75 | 0.40 | 0.48 |
| Seattle, WA | 47.60 | -122.33 | 0.53 | 0.44 |
| Toke Point, WA | 46.72 | -123.97 | 1.03 | 0.53 |
| Astoria, OR | 46.22 | -123.77 | 1.07 | 0.43 |
| South Beach, OR | 44.63 | -124.05 | 1.00 | 0.34 |
| Charleston II, OR | 43.35 | -124.32 | 0.86 | 0.32 |

NRC 2012

In Columbia Estuary, ~10 cm/century rise due to GIA. Large uncertainty in actual #.

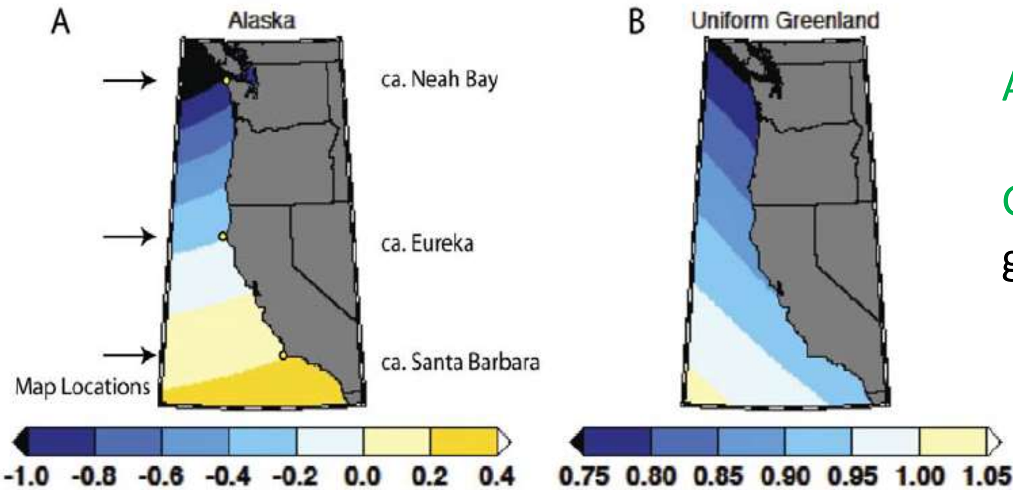
Location of maximum: 47 North

# Melting Ice also has a gravitational effect




NRC 2012

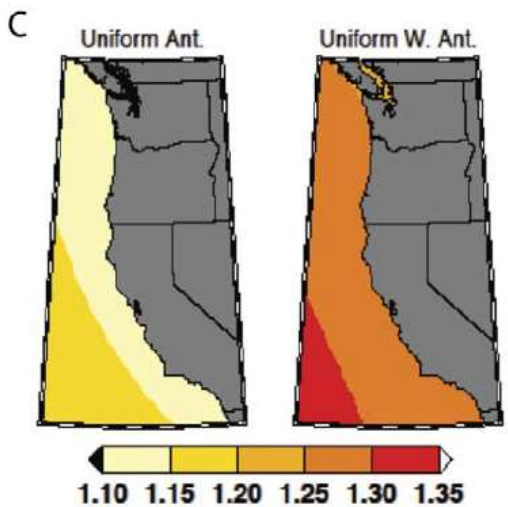
# Melting Ice also has a gravitational effect




Alaska melt reduces OR sea-level

Greenland melt causes less than global average rise

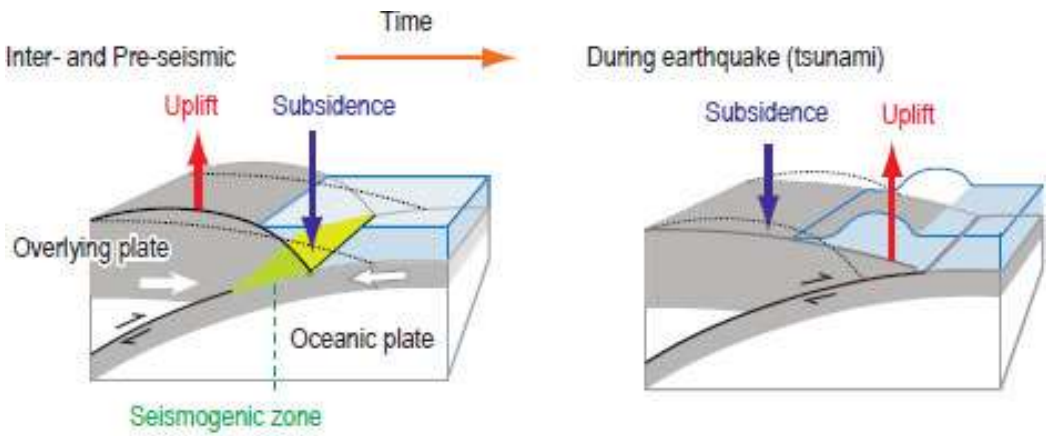
NRC 2012



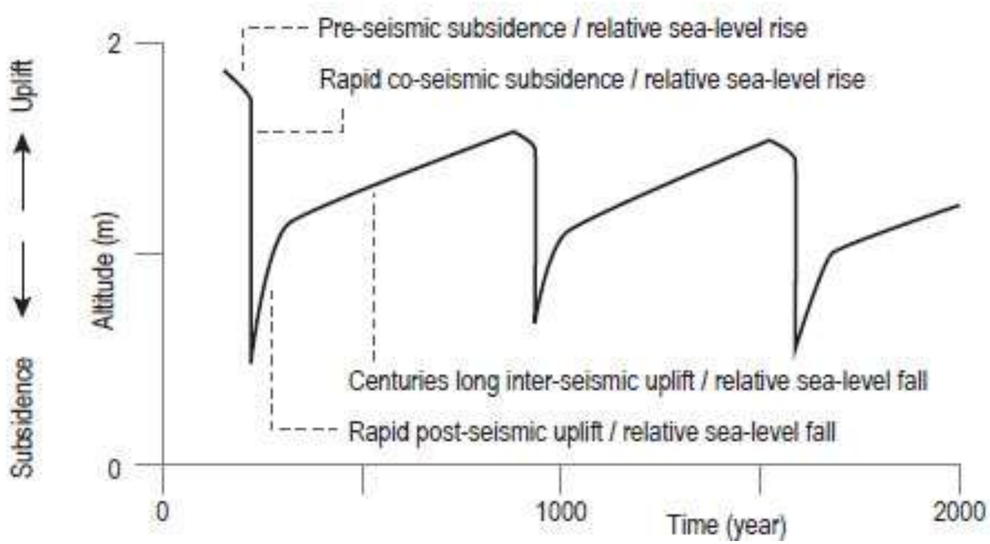

Antarctic melt causes greater than average rise in OR

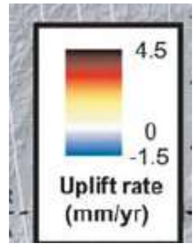
Unknowns in Antarctica drive significant uncertainty

# Plate Tectonics also in the mix




Diving plate causes regions of uplift and subsidence



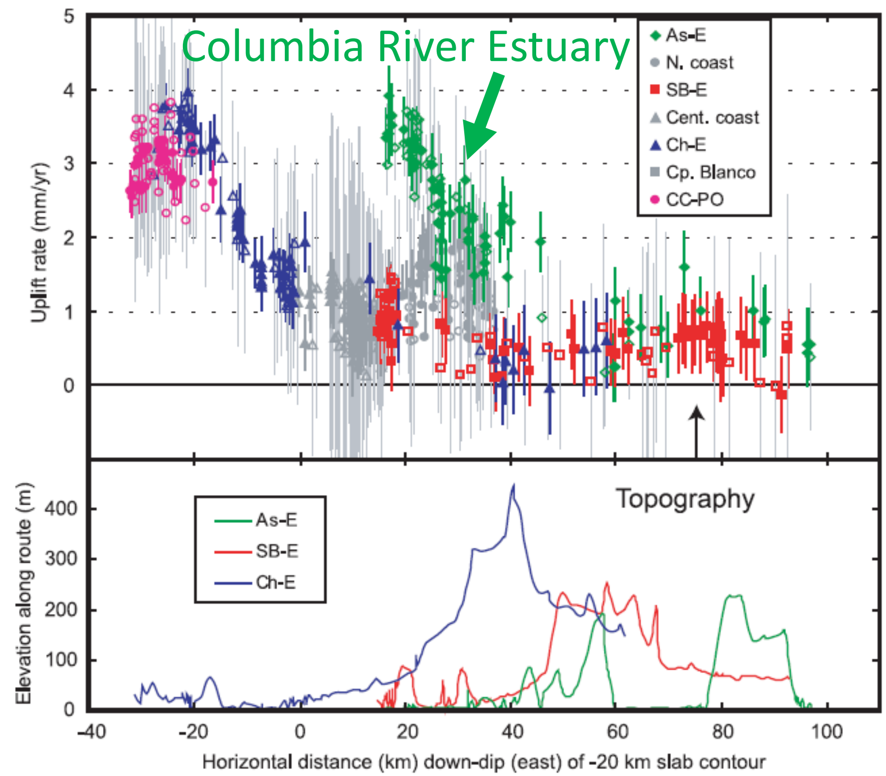




Burgette et al., 2009

At coast, huge uplift rates.

Fingerprint decreases rapidly inland

Uplift Rate from Leveling
(Burgette et al., 2009)



# Ultra-Local changes in vertical land motion

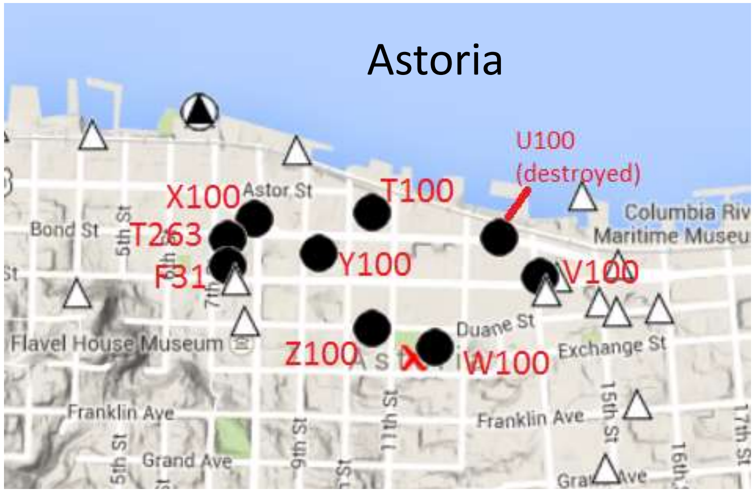



*Table S.2.4* *Benchmarks in Astoria, OR based on four datum. Benchmarks considered unstable by USC&GS or NGS are marked red. Benchmarks known to be located on piles over mudflats marked with blue. The change in BM height over time relative to the X100 benchmark (which is held fixed) is given in the rhs columns for two time periods: (a) the 1930 MSL datum and NAVD88 (modern height in 2015) and (b) the NGVD-29 datum (likely the 1947 update) and NAVD88. Units = feet.*

| BENCH MARK | 1920 MLLW (AVERS 1926) | 1930 MSL (RAPPLEYE 1932) | 1947 NGVD-29 | 2015 (NAVD-88) | 2015-1930 - X100 | 2015-NGVD29 -X100 |
|---|---|---|---|---|---|---|
| U31 | 20.77 | 16.844 | NA | NA | NA | NA |
| A32 | 21.97 | 18.081 | NA | NA | NA | NA |
| F31 | 22.97 | 18.993 | 19.64 | 22.97 | -0.185 | -0.12 |
| X100 | | 17.428 | 18.14 | 21.59 | 0 | 0 |
| T100 | | 16.46 | 17.12 | 20.45 | -0.172 | -0.12 |
| T263 | | | 19.55 | 2S.2.04 | | 0.04 |
| Y100 | | 17.707 | 18.41 | 21.73 | -0.14 | -0.13 |
| Z100 | | 18.629 | 19.34 | 22.81 | 0.02 | 0.02 |
| W100 | | 19.423 | 20.09 | 2S.2.5 | -0.085 | -0.04 |
| V100 | | 17.877 | 18.58 | 22.03 | -0.01 | 0 |

T100: Going Down (on fill)

F31: Going Down (near landslide)

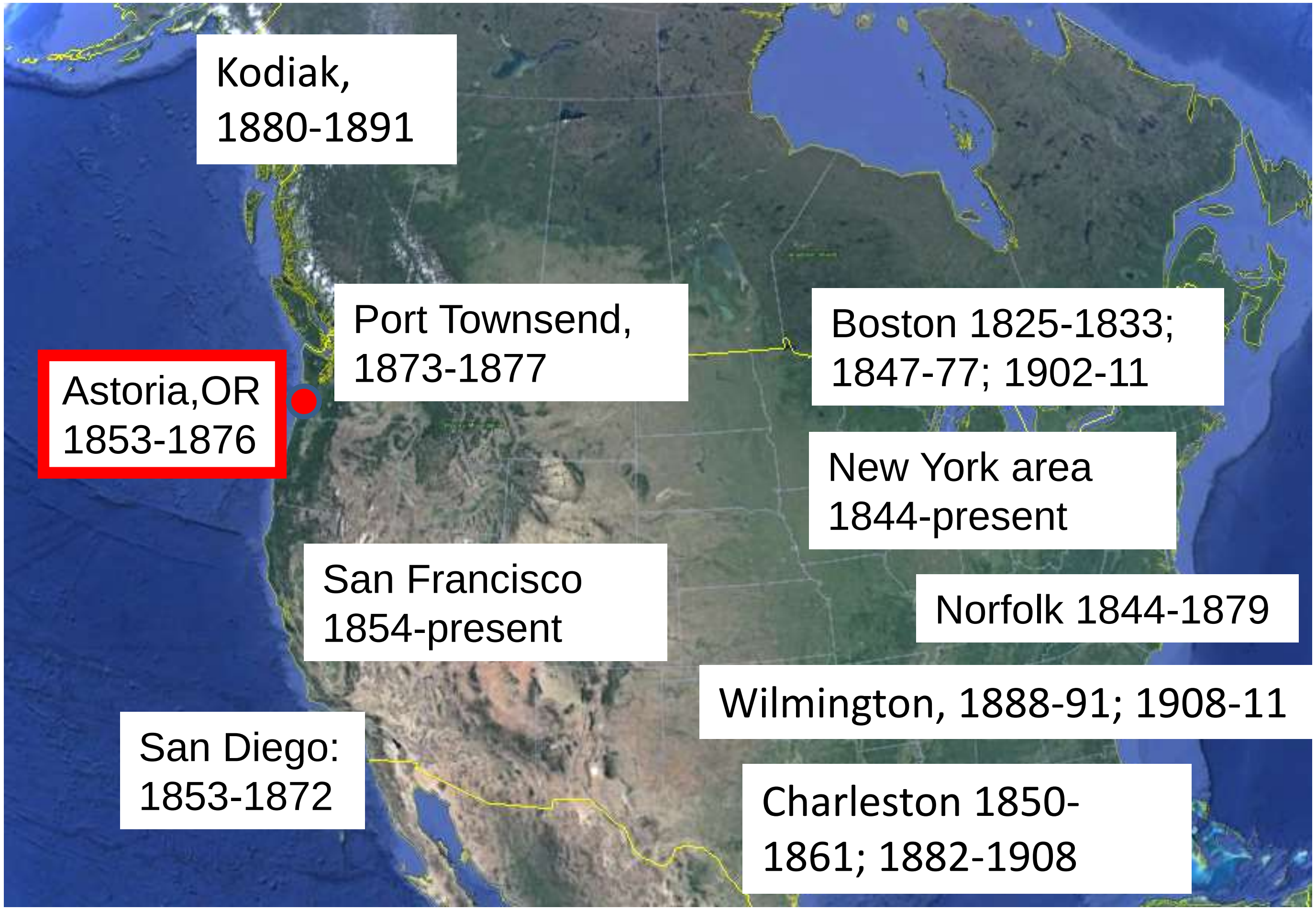
V100: More stable ground

In Astoria, approximately 6cm/century difference in long-term rates

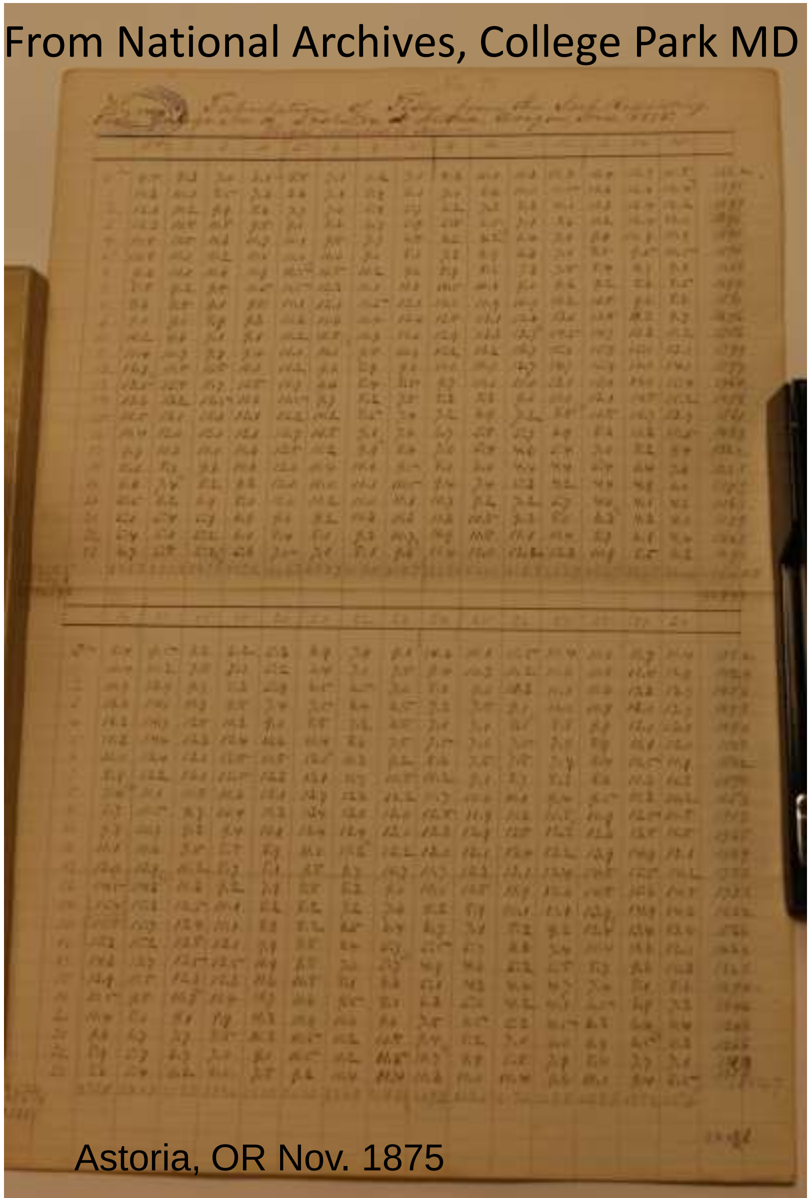
# What empirical data are available to assess actual trends?

For the past 5 years, we've recovered and digitized tide records from the 19th century.

(along with many smaller time series not mentioned)



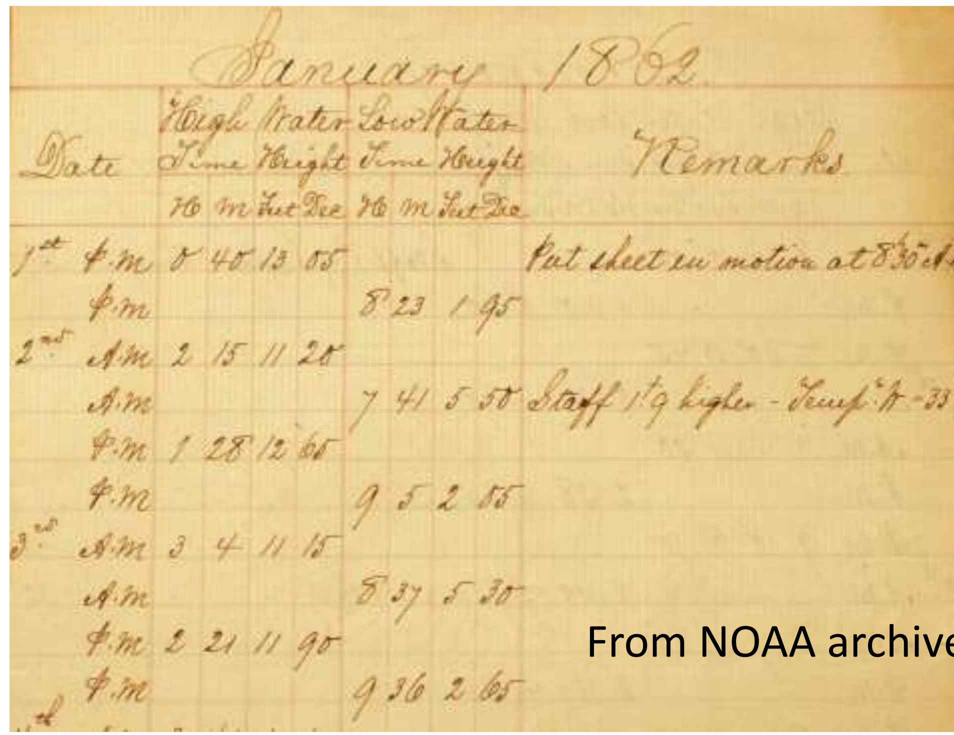

See *Talke & Jay, 2013, 2017*



From National Archives, College Park MD

Astoria, OR Nov. 1875

# Historic Data: Examples



January 1862

| Date | | High Water Time h | m | Height Feet | Dec | Low Water Time h | m | Height Feet | Dec | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1st | P.m | 8 | 40 | 13 | 05 | | | | | Put sheet in motion at 8 30 A.M |
| | P.m | | | | | 8 | 23 | 1 | 95 | |
| 2nd | A.m | 2 | 15 | 11 | 20 | | | | | |
| | A.m | | | | | 7 | 41 | 5 | 50 | Staff 1.9 higher - Temp. Air - 33° |
| | P.m | 1 | 28 | 12 | 65 | | | | | |
| | P.m | | | | | 9 | 5 | 2 | 55 | |
| 3rd | A.m | 3 | 4 | 11 | 15 | | | | | |
| | A.m | | | | | 8 | 37 | 5 | 30 | |
| | P.m | 2 | 21 | 11 | 90 | | | | | |
| | P.m | | | | | 9 | 36 | 2 | 65 | |

From NOAA archives

And some is high/low data

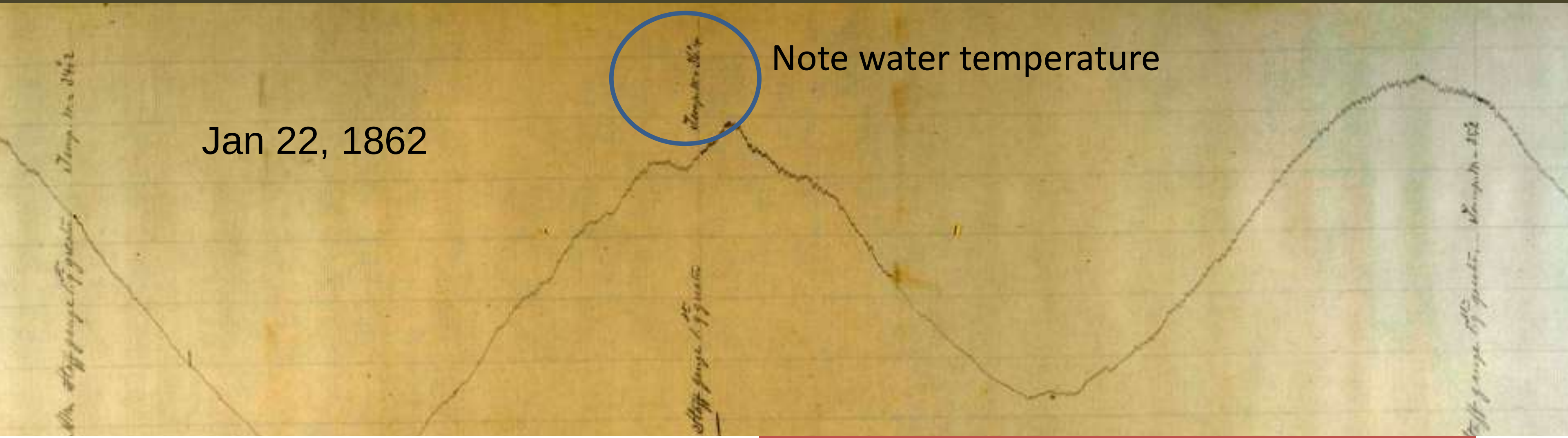
Marigrams—scrolls of paper with tide

--Automatic gauge
--Each month is a 60-70 foot scroll
--Gauge checked twice daily

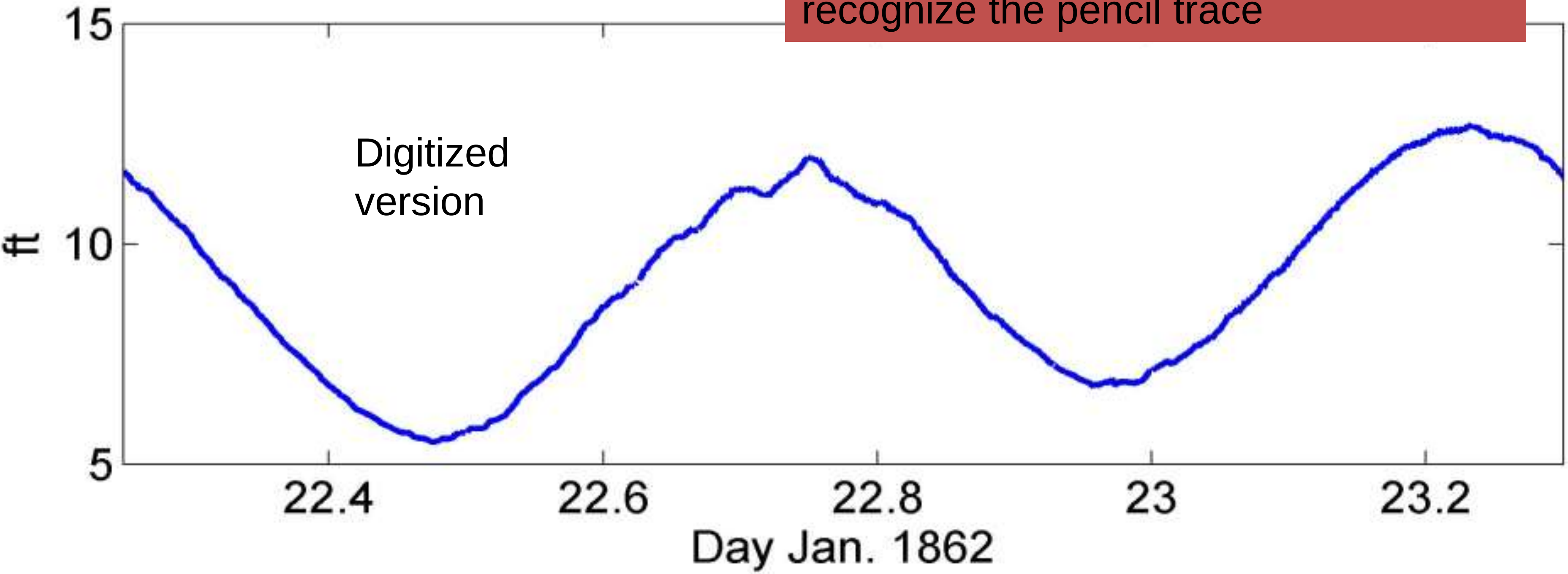
We have digitized these data from pictures, 1855-1870.

The tides at Astoria about 150 years ago

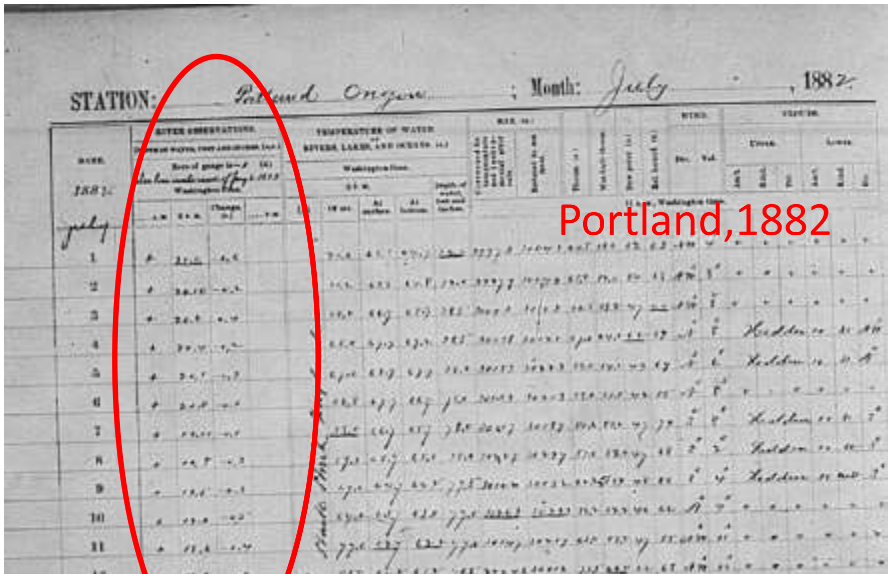
20 years of marigrams from Astoria, 1853-1876, have been photographed.
(approximately 2 miles worth, 1 foot at a time)



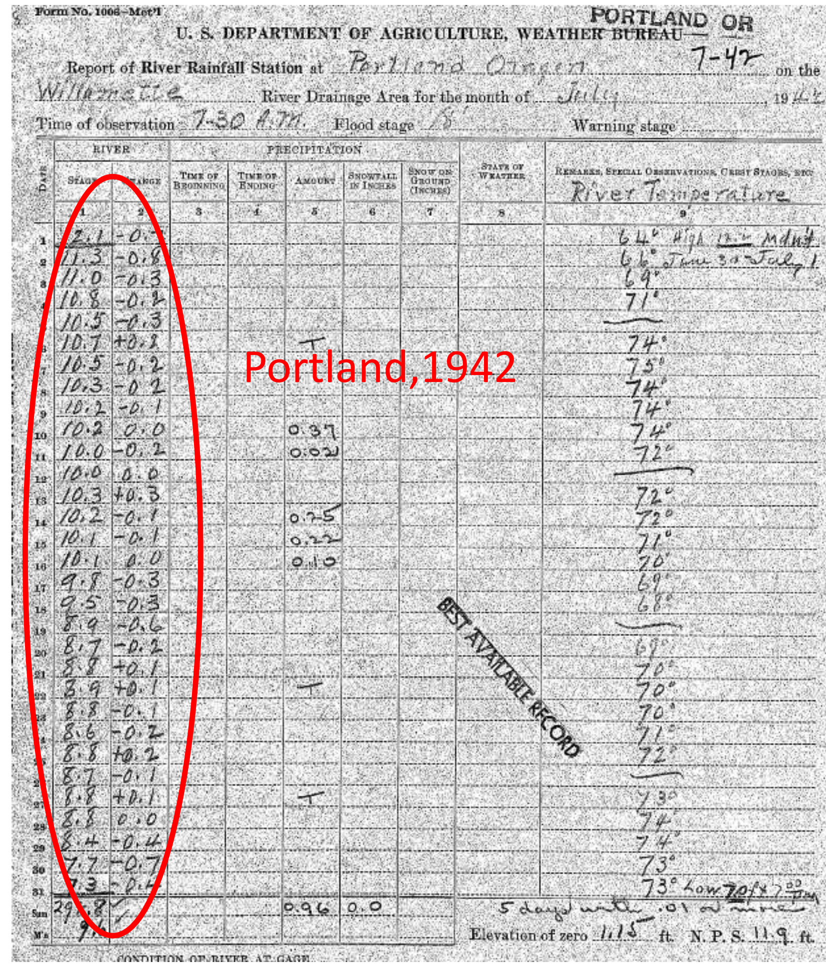

A Computer can be trained to recognize the pencil trace



# Lower Willamette Records (many never analyzed)




US Signal Service Records, 1879-1892

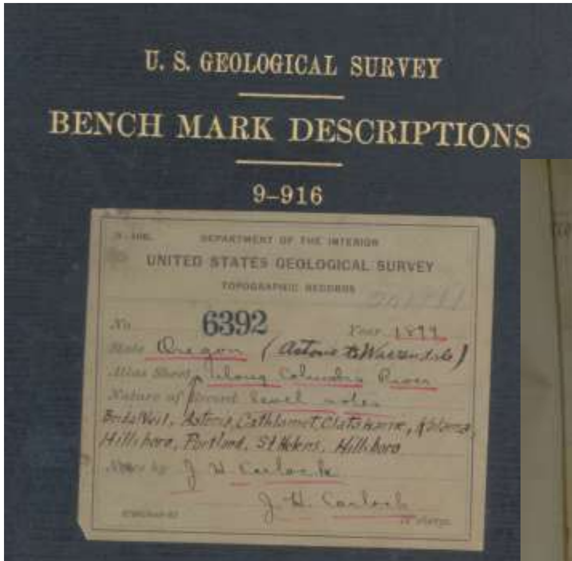


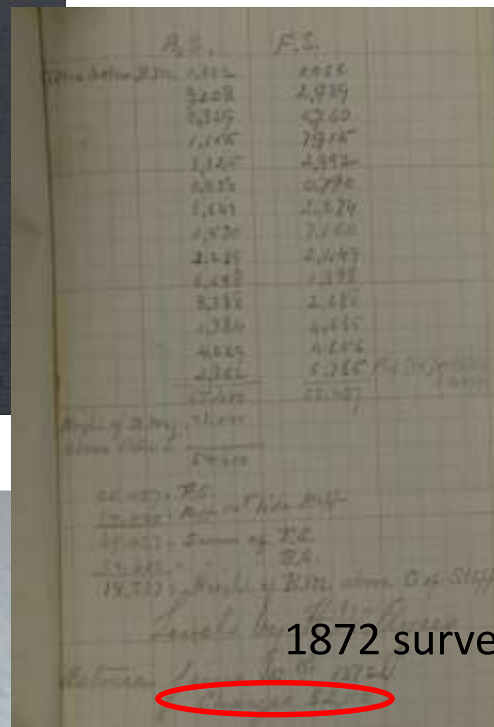

Weather Bureau Records (1893-1972)

Other Agencies with data:
USGS, NOAA, CMOP, OR DEQ, EPA Superfund, City of Portland, OR F&W

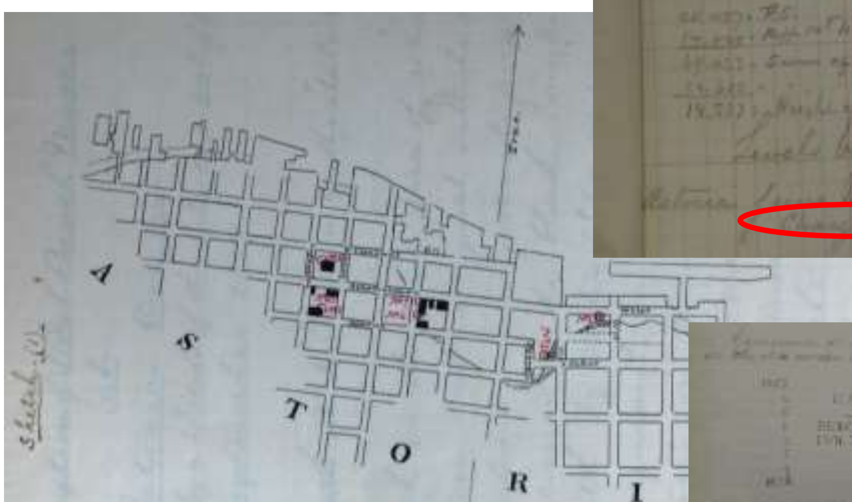
→ Big concatenation effort

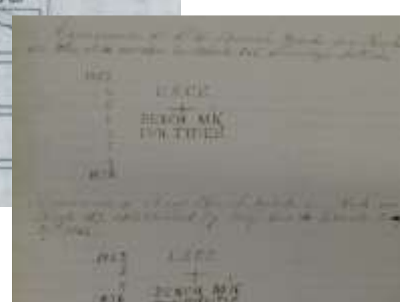
# Datum Recovery

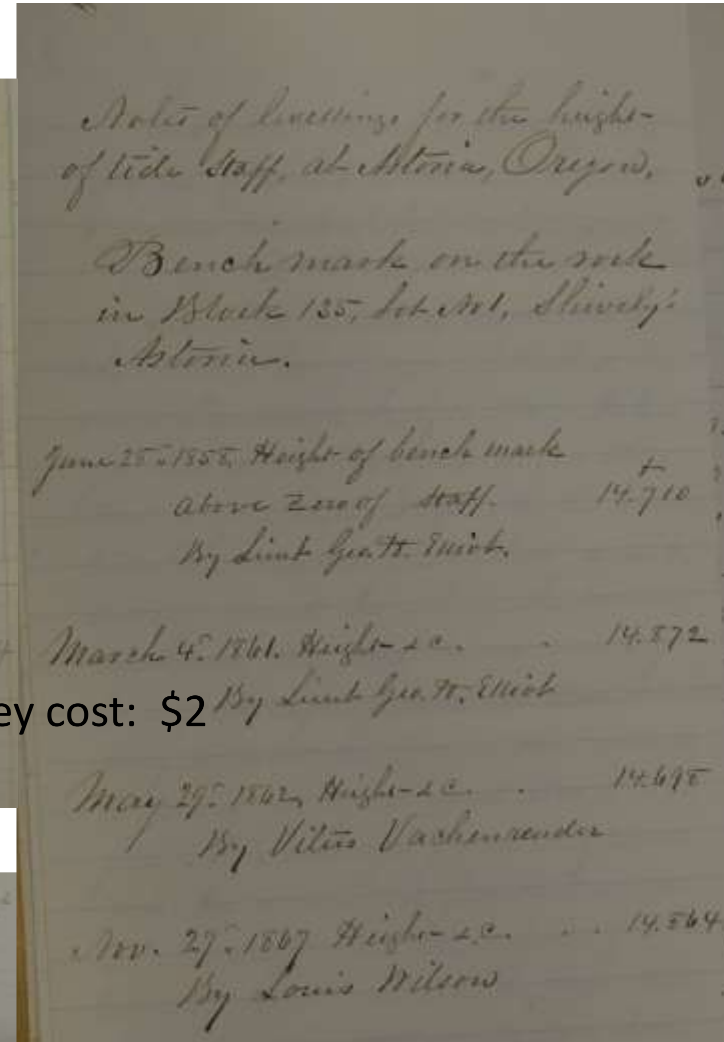



1872 survey cost: $2



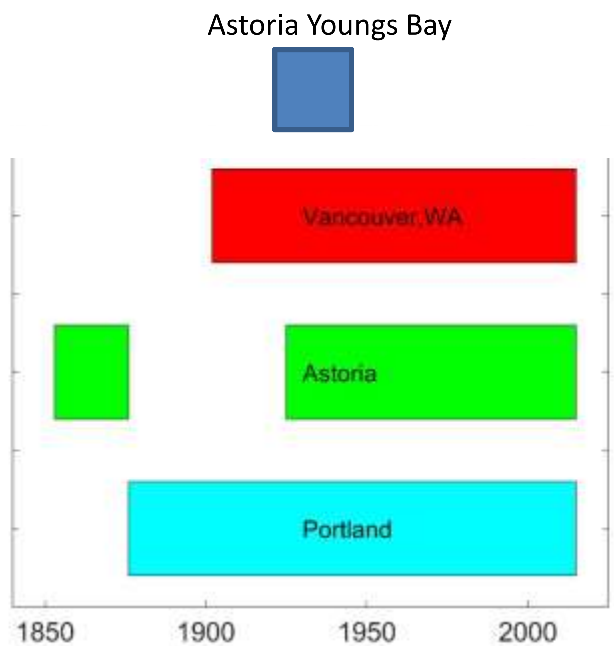


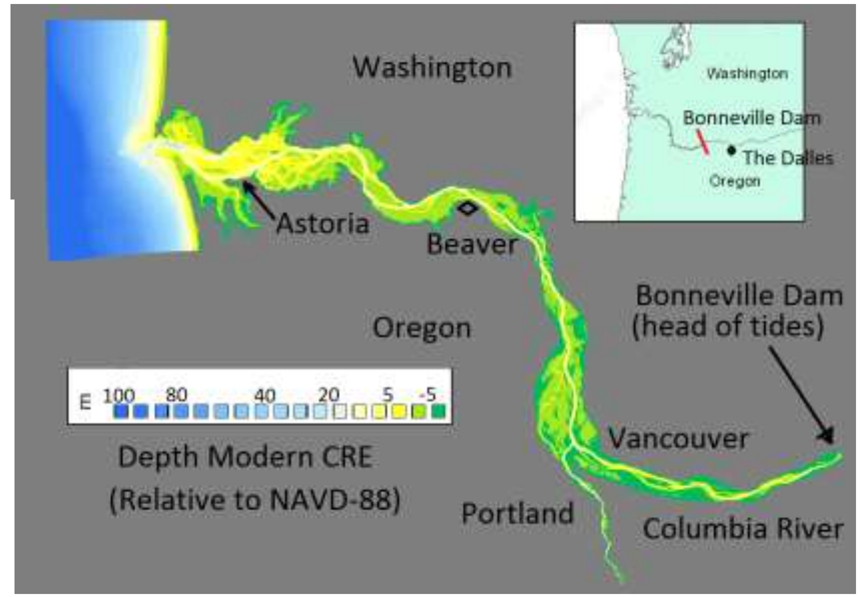

Benchmark Survey, 1887
US National Archives, MD

Leveling Synopsis
US National Archives, San Bruno

# Data Recovery Synopsis

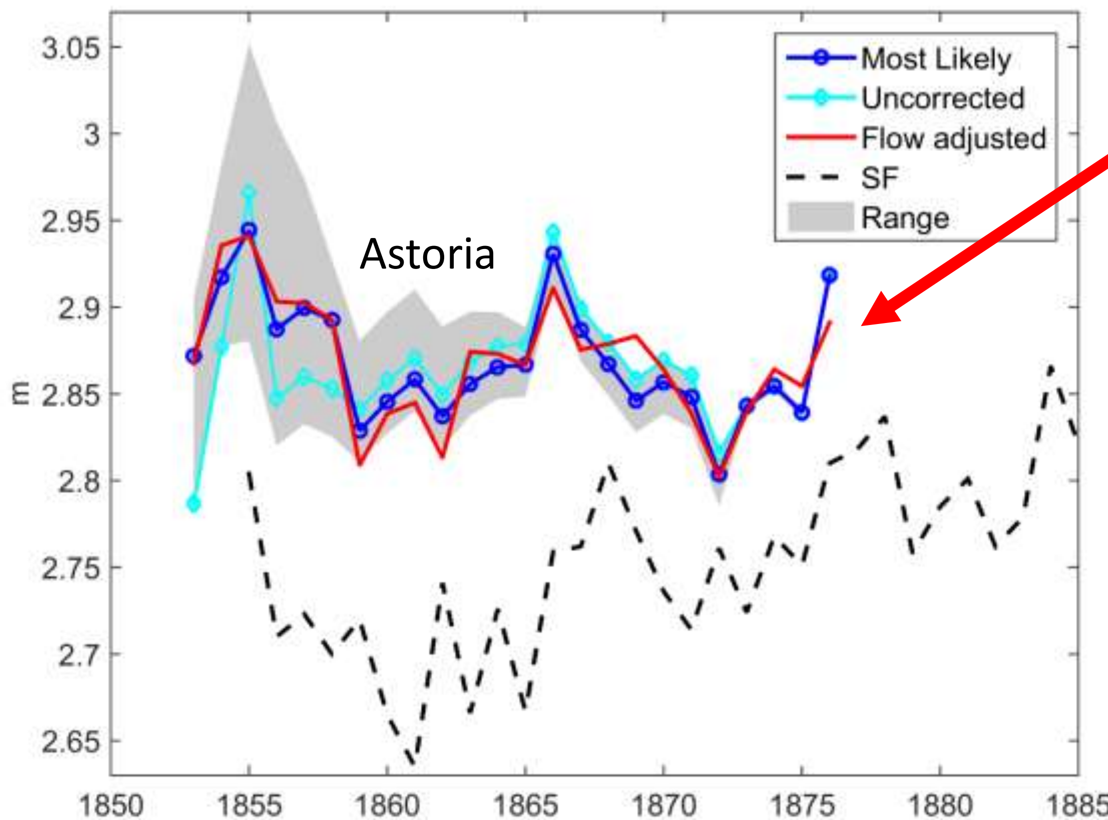
Water Level

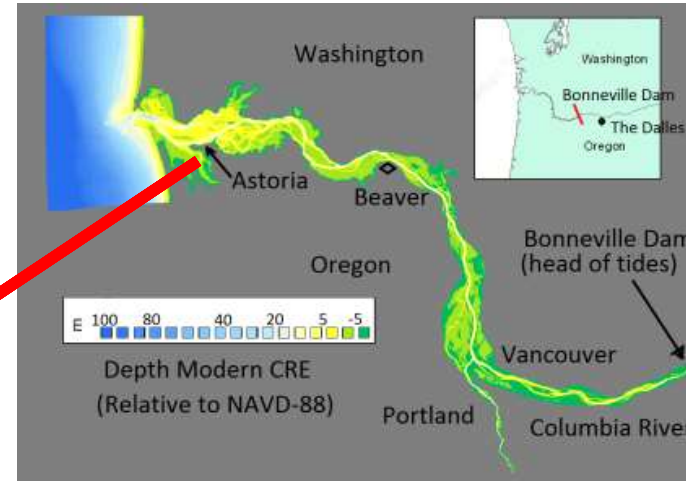



Original 1853 Astoria benchmark on backside

# MSL Results for Astoria, 19th century



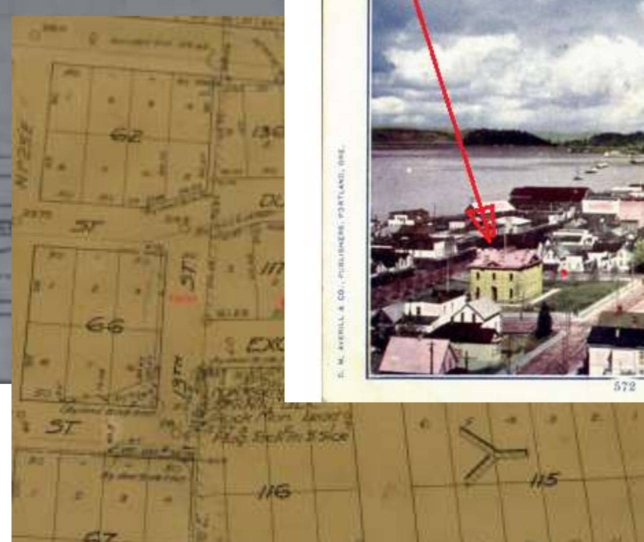

Sea Level flat or trending
Slightly downward

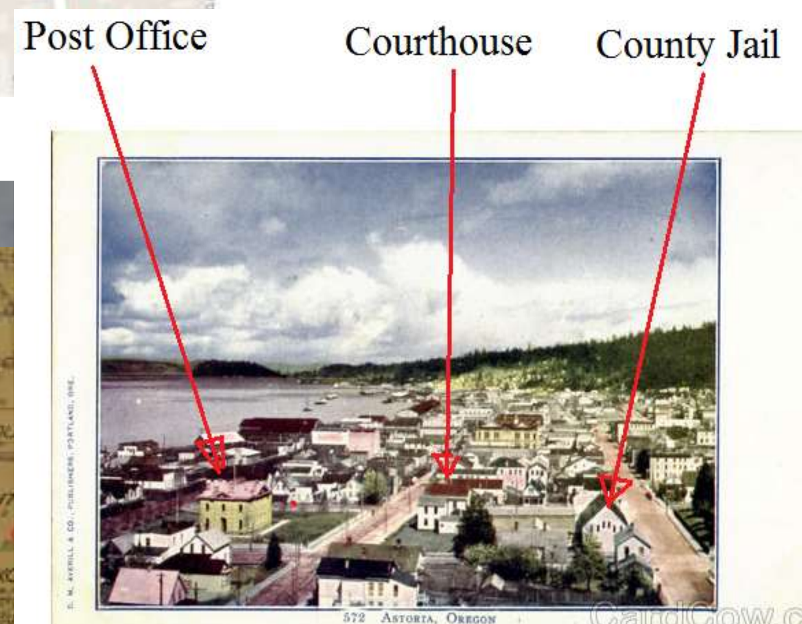
Results similar to SF

Major El Nino events
1866-68 and 1876-78

# Details: Tying datum to modern series

Old benchmarks were looked for; "chain of custody" from past to present developed

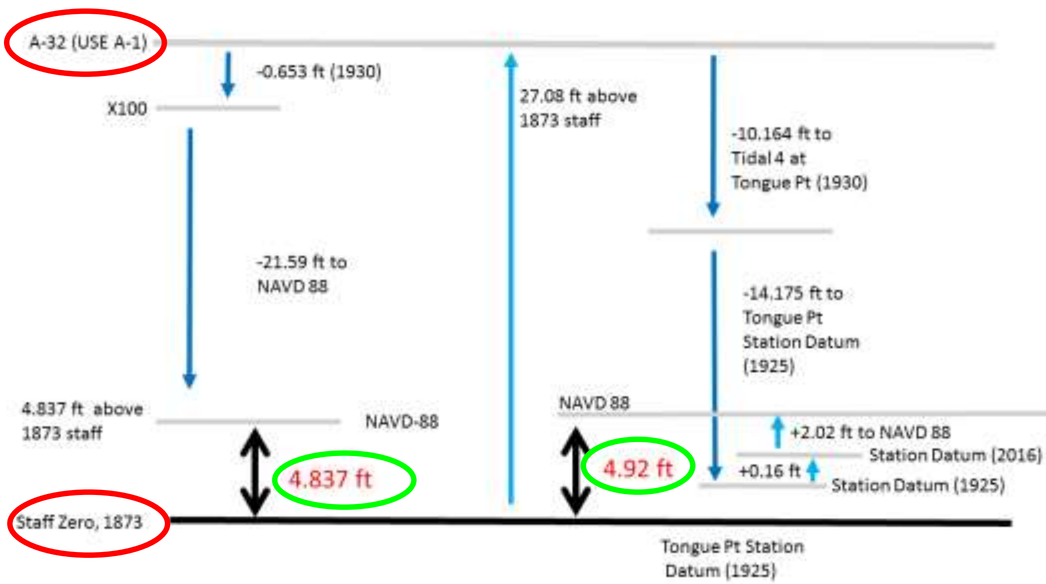



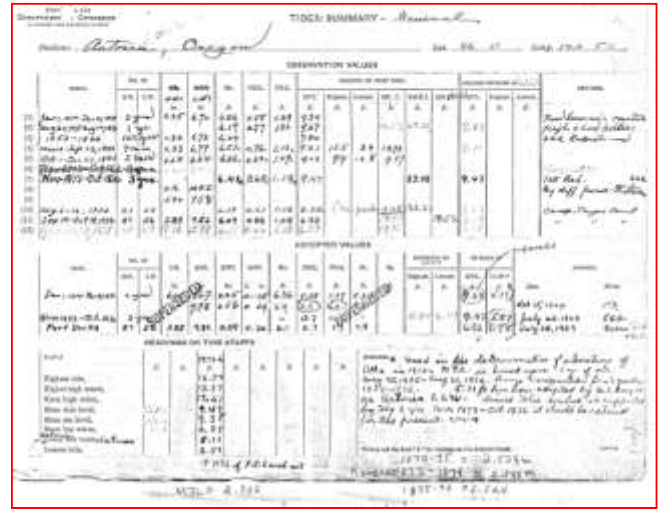




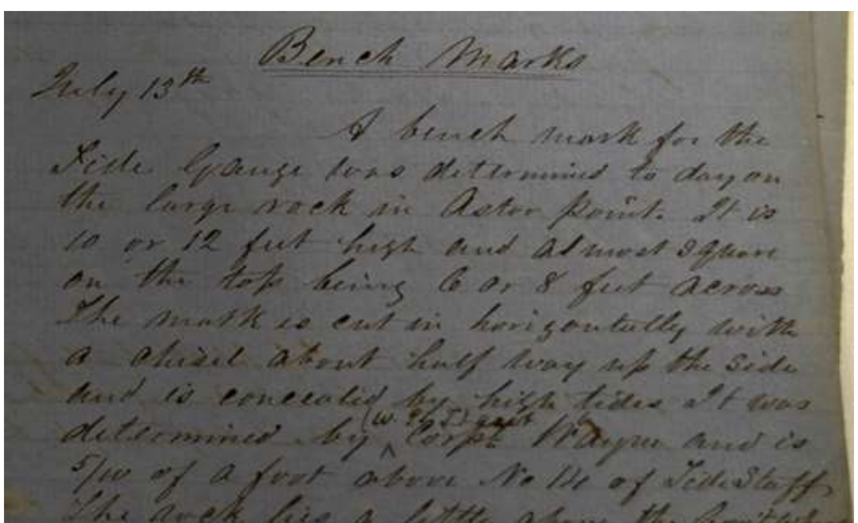


# Details: Tying datum to modern series




Main idea: relate historic staff zero and benchmarks to modern datum/benchmarks using multiple pathways, to estimate error



Bench Marks

July 13th

A bench mark for the Tide Gauge was determined to day on the large rock in Astor point. It is 10 or 12 feet high and almost square on the top being 6 or 8 feet across. The mark is cut in horizontally with a chisel about half way up the side and is concealed by high tides. It was determined by Capt. Wagner and is 5/10 of a foot above No 14 of Tide Staff.

| | BM1 | BM2 | BM3 | BM4 | BM5 | A32 | U31 | Notes |
|---|---|---|---|---|---|---|---|---|
| 1876 | 14.83 | 14.81 | 18.691 | | | | | Rel. Staff zero |
| 1887 | 14.83 | 14.79 (-0.02) | 18.645 (-.046) | 2S.2.013 | 29.913 | | | BM#1 held constant; |
| 1898 | -- | 14.79 | -- | 22.97<br>(-0.046) | 29.87 (-0.046) | | | BM#2 held constant |
| 1911 | -- | ? | -- | ? | ? | 21.97 | | Rel. to MLLW |
| 1920 | ? | ? | Not found | Destroyed | Destroyed | 21.97 | 20.77 | Sp. Pub. 122 (Avers 1926) |
| ~1924 | 14.83 | | | | | 27.08 | | See Figure S.2.1 |





# Different Ties

| | F31 | X100 | T100 | Y100 | Z100 | W100 | V100 |
|---|---|---|---|---|---|---|---|
| Offset above A32 in 1930 (ft) | 0.912 | -0.6530 | -1.6210 | -0.3740 | 0.5480 | 1.3420 | -0.2040 |
| NAVD88 | 22.97 | 21.59 | 20.45 | 21.73 | 22.81 | 2S.2.500 0 | 22.03 |
| A32 estimate (NAVD-88) | 22.058 | 22.243 | 22.0710 | 22.104 | 22.262 | 22.158 | 22.234 |
| Estimated height NAVD 88 above 1873 staff zero | **5.022** | **4.837** | **5.009** | **4.976** | **4.818** | **4.922** | **4.846** |

DEPARTMENT OF COMMERCE
COAST AND GEODETIC SURVEY
Ed. Sept. 1929

## TIDES: COMPARATIVE READINGS

Station: Astoria (Tongue Point) Ore. Lat.
Party of Time meridian 120° W Long.
Obs. begin Obs. end Tabulated by gms Date
Tide gage No. Scale 1:16 Preliminary scale setting of datum line 7.00 feet

| DATE 19 48 (mo. / d.) | TIME OF STAFF READING (h. / m.) | STAFF A (feet) | SCALE B (feet) | DIFFERENCE A—B (feet) | PHASE OF TIDE* | REMARKS |
|---|---|---|---|---|---|---|
| Sept 1 | 10 40 | 8.50 | 8.70 | −0.20 | R | |
| 2 | 10 30 | 7.75 | 7.90 | −0.15 | R | |
| 3 | 10 31 | 6.55 | 6.80 | −0.25 | R | 1— Setting = 6.94 |
| 7 | 14 06 | 9.50 | 9.65 | −0.15 | R | |
| 8 | 10 21 | 4.00 | 4.20 | −0.20 | L | |
| 9 | 10 37 | 5.20 | 6.30 | −1.10 | F | |
| 9 | 12 31 | 5.70 | 6.55 | −0.85 | R | |
| 10 | 10 26 | 6.80 | 7.60 | −0.80 | F | |

Next, we connect 1853-1876 to modern Tongue Pt measurement, 1925-present

Scale setting for Sept 9 to Oct 1
Sum of differences 17 −14.25
Mean difference −0.84
Preliminary setting 7.00
Setting for reduction to tide staff 6.16
Constant for fixed datum 0.13
Setting for reduction to fixed datum 6.29

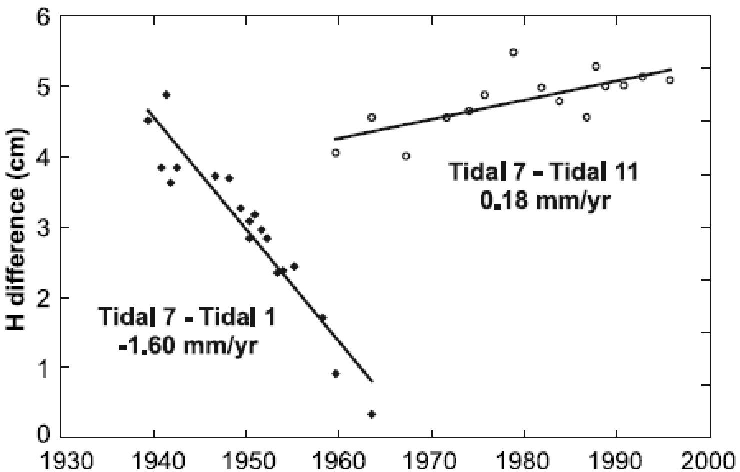
However, Tongue Pt gauge datum is wrong, 1925-1960 (Burgette et al., 2009)

This "constant" was changed every few years such that it kept a constant offset to a benchmark

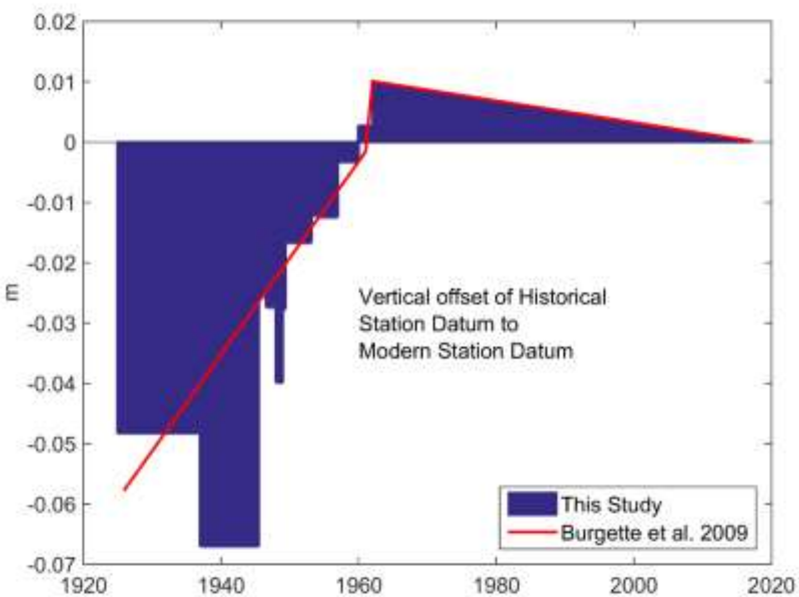




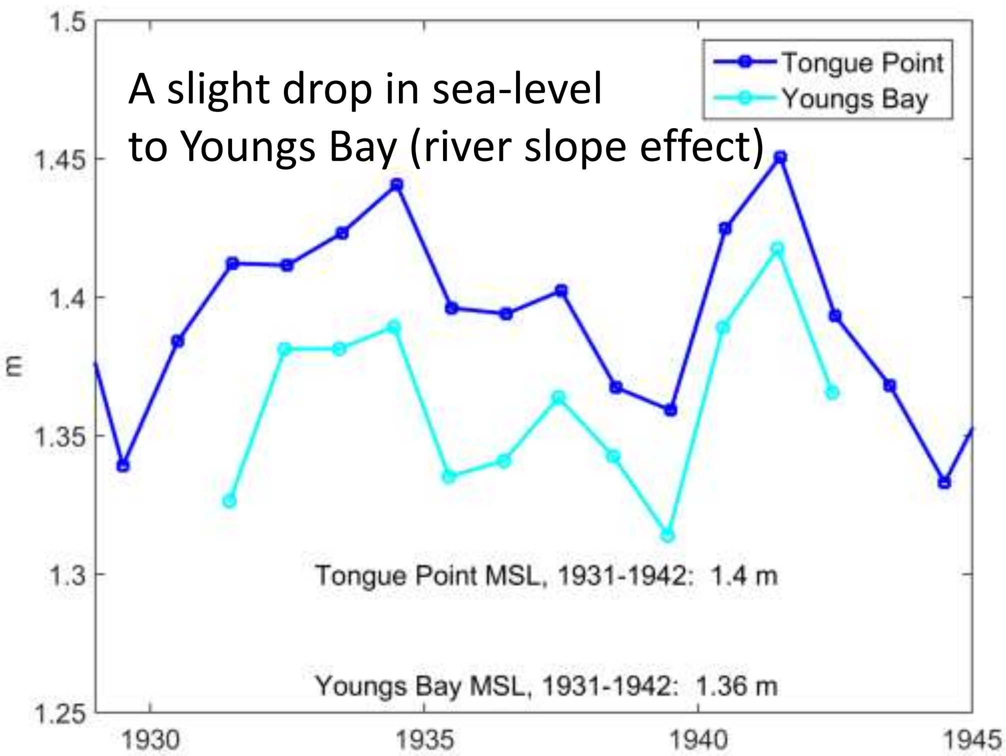
# Astoria Datum Correction



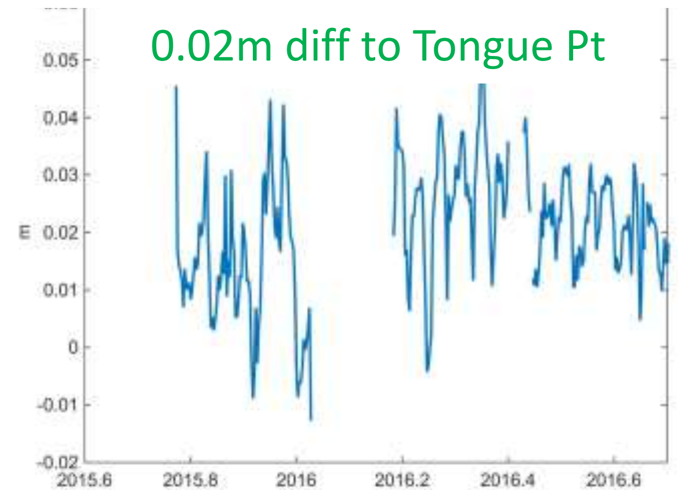

Observation #1: Unfortunately, the primary reference benchmark for the Astoria gauge to the early 1960s was Unstable (Burgette et al., 2009)




Observation #2: However, we can use the gauge check sheets to infer the magnitude of error and make a correction


2015-2016, Astoria River Pilots Dock

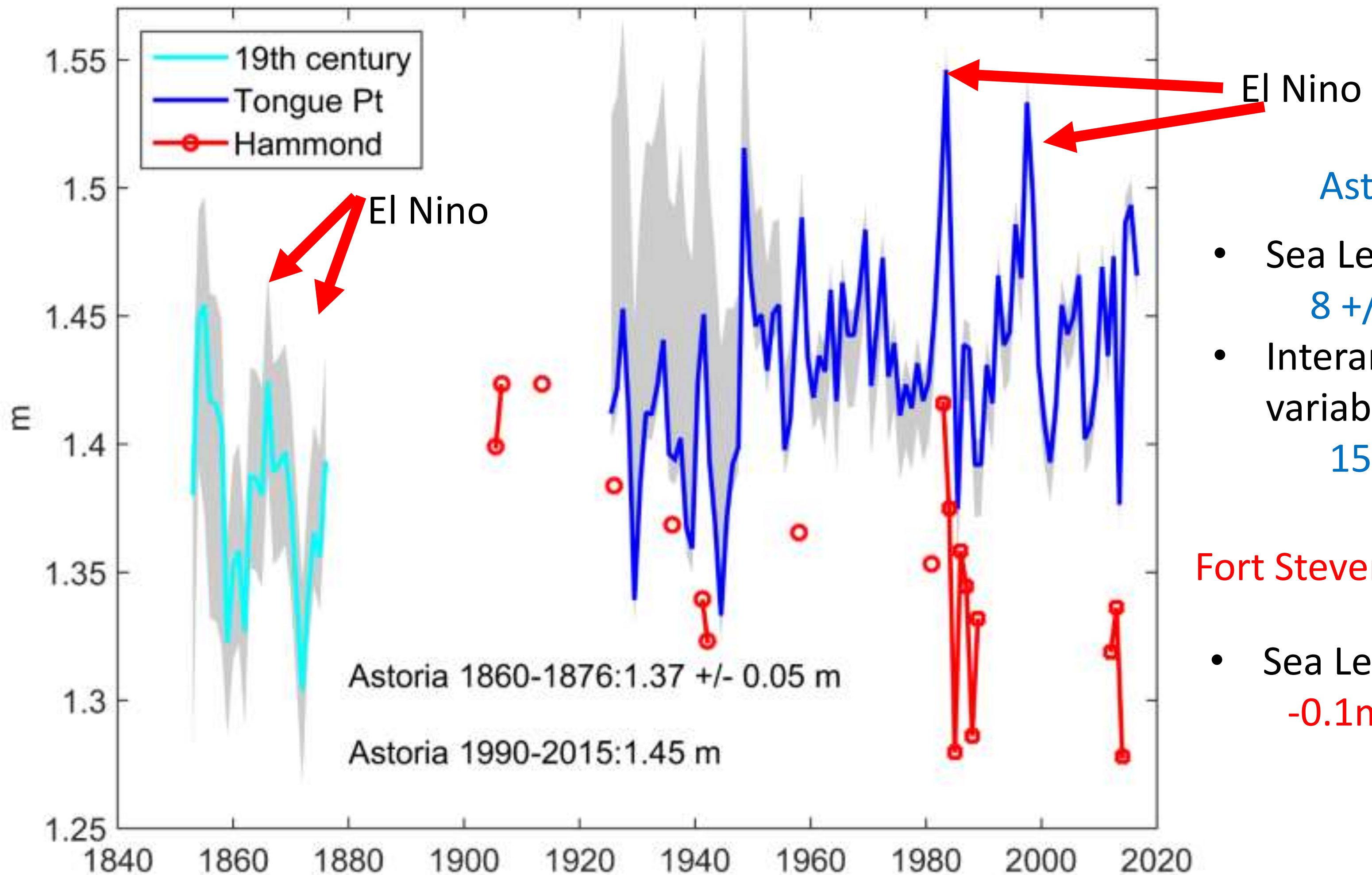



The results show that our Astoria datum correction is correct





# MSL Results, 1853-2016




El Nino

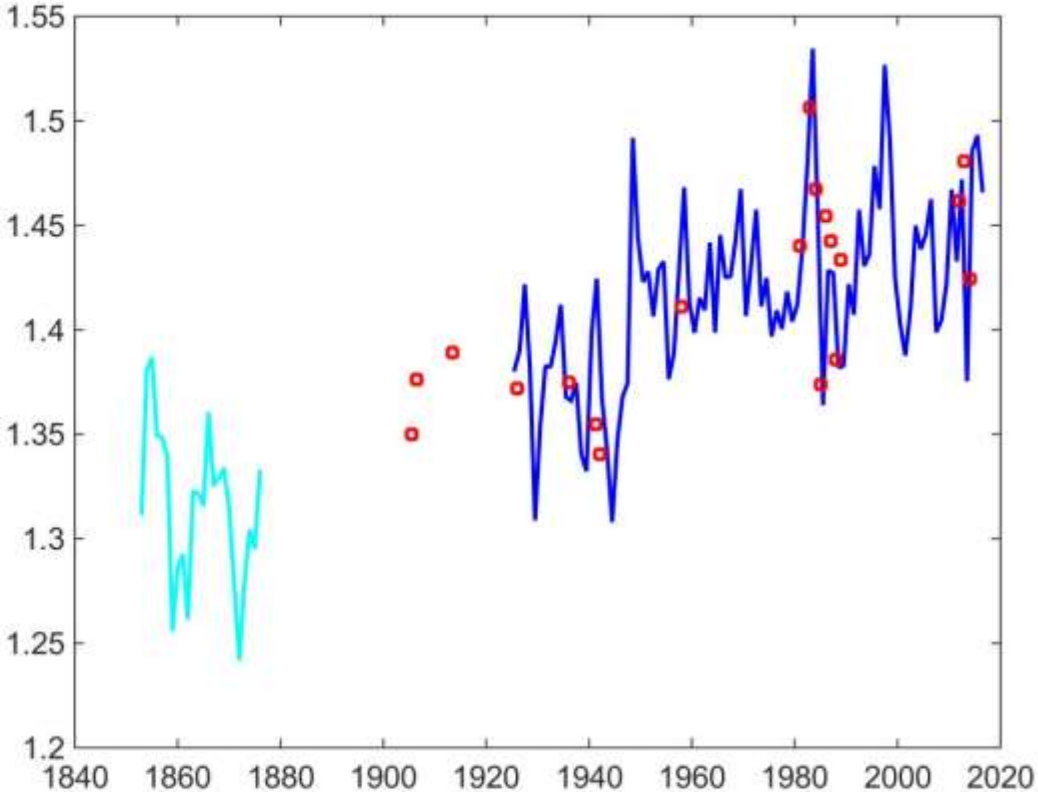
**Astoria**

- Sea Level Rise:
  8 +/-4 cm
- Interannual variability:
  15 cm

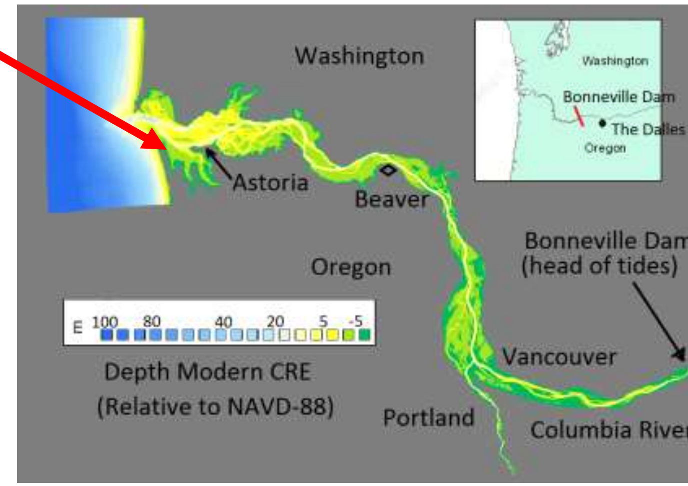
**Fort Stevens/Hammond**

- Sea Level Rise:
  -0.1m (drop)

Closer to Coast at Hammond… Sea level is dropping!

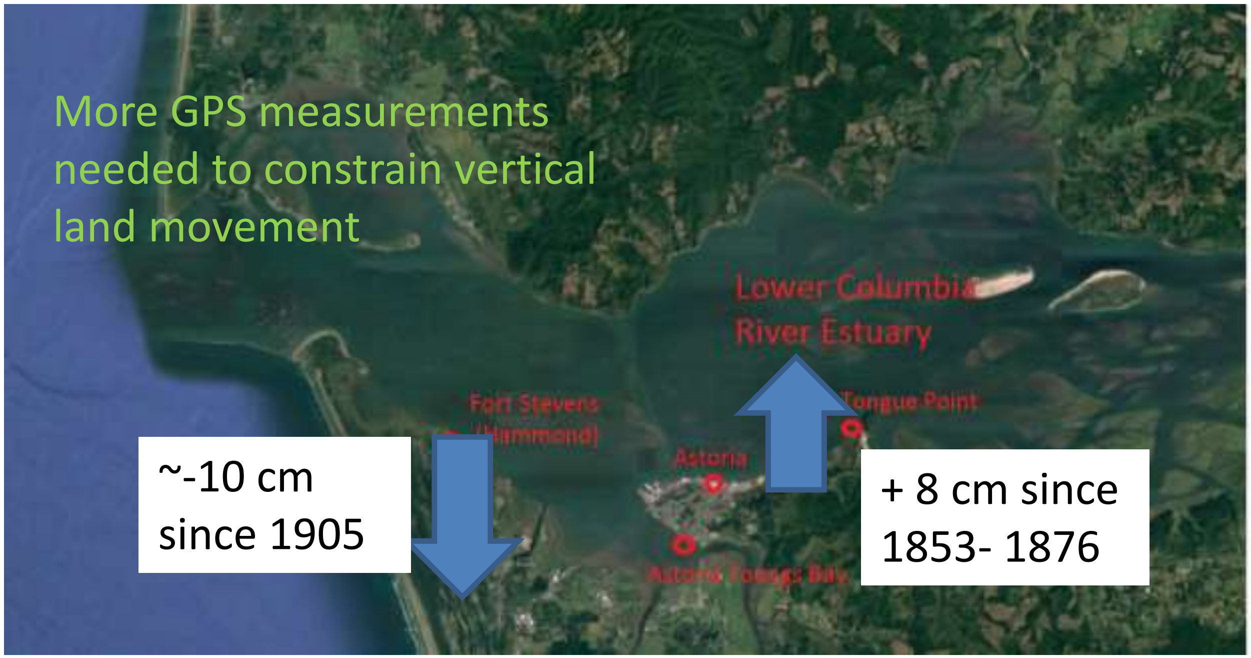



Fort Stevens




Fort Stevens and Astoria line up if a difference of ~20 cm/century is applied

# Sea Level Synopsis

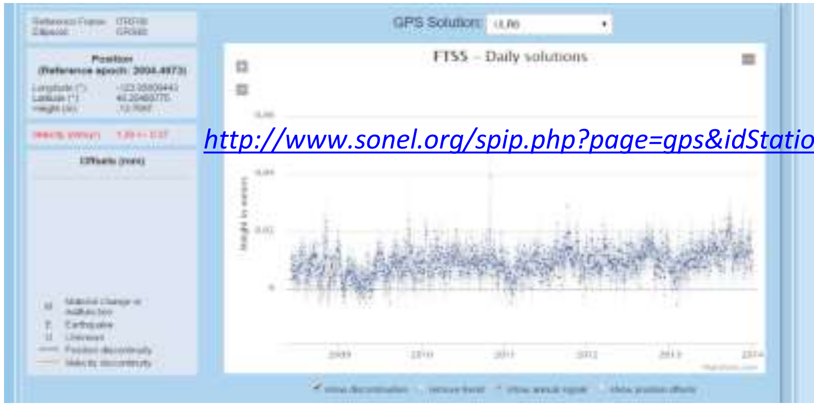



See also Burgette et al. 2009 for analysis of local tectonics

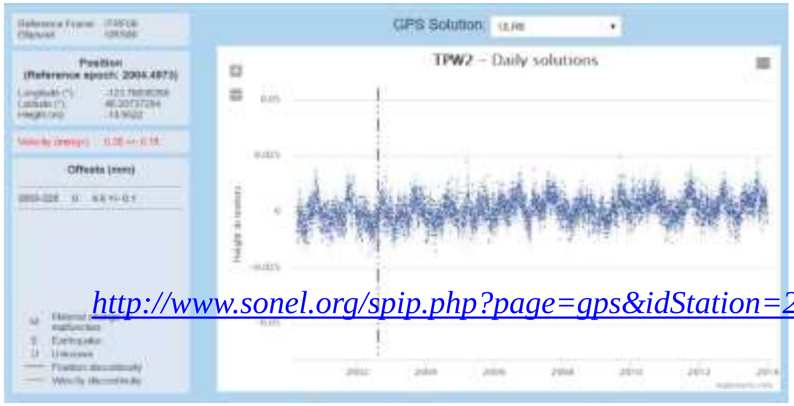
Take Home: Plate tectonic signal rivals sea level rise (so far)

But… Sea Level rise will occur in ~5 minutes during Cascadia Earthquake

However, GPS measurements don't yet agree….

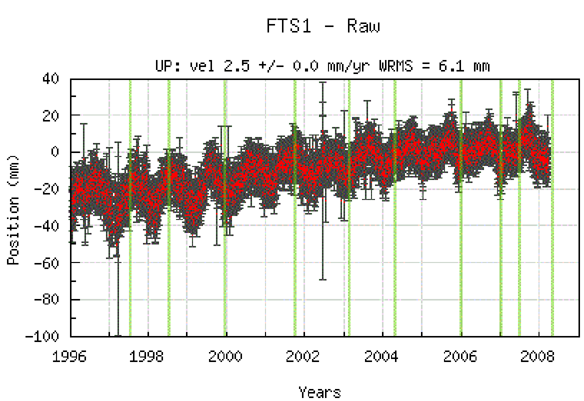


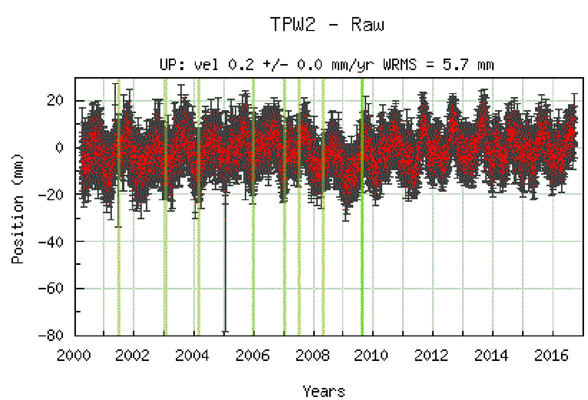

http://www.sonel.org/spip.php?page=gps&idStation=2093




http://www.sonel.org/spip.php?page=gps&idStation=2690 .

Sonel: Fort Stevens = 12.9 cm/century uplift, Astoria 3.5 cm/century



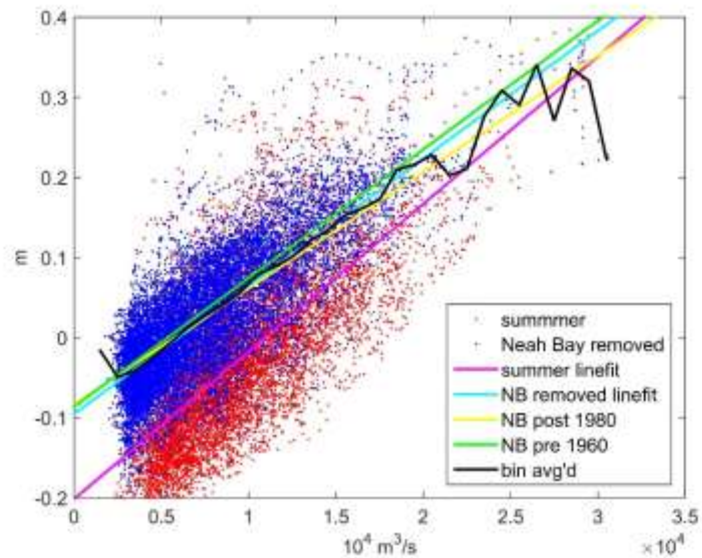




*http://www.panga.cwu.edu/data/bysite/*

Panga: Fort Stevens = 25 cm/century uplift, Astoria 2 cm/century

# Other parts of sea level budget, Astoria

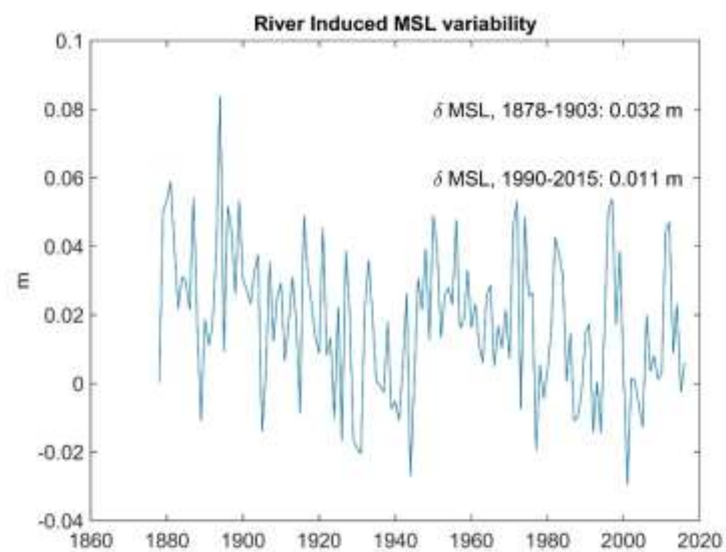
River flow today produces roughly 0.25m variation in daily mean water level at Astoria; About +/- 0.04m annually




River flow vs. Daily sea-level

(Astoria)

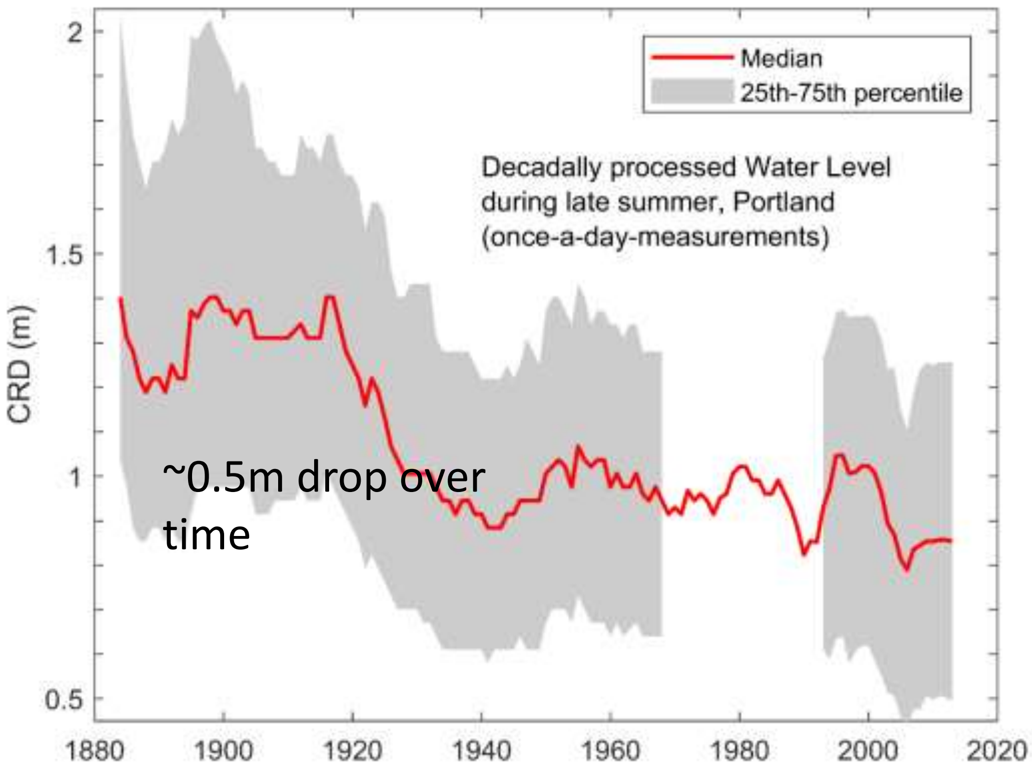
River flow contributed roughly 0.02m more annual to water levels in 19th century than today (in Astoria)



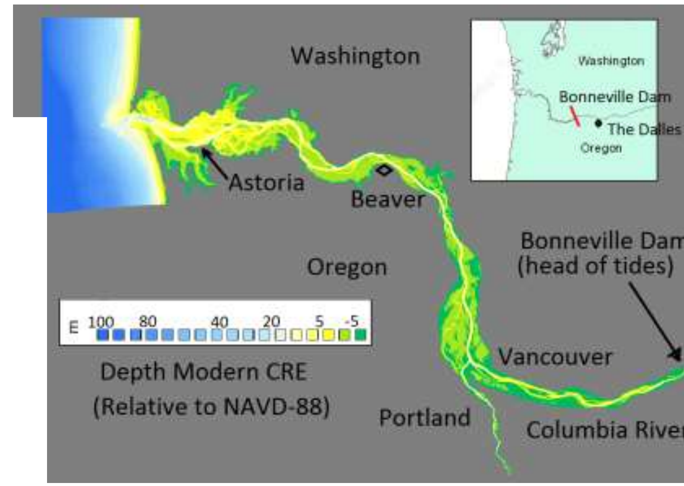

Year-to year sea-level variability

from river flow

Also a need to characterize trends upstream




~0.5m drop over time




Portland Water Level at low flow (August 1st –October 15th)


## Conclusions

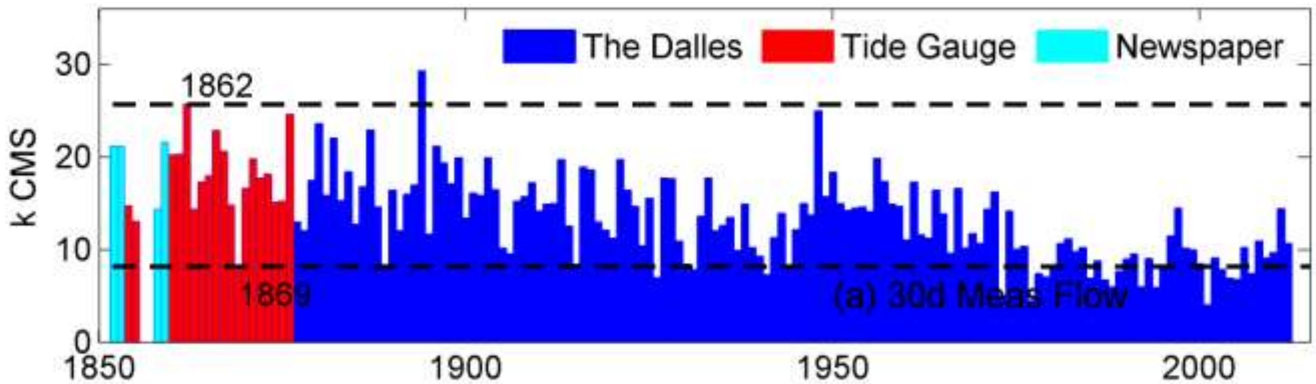
1. Sea-Level rise up to 20 cm/century different in different regions of estuary

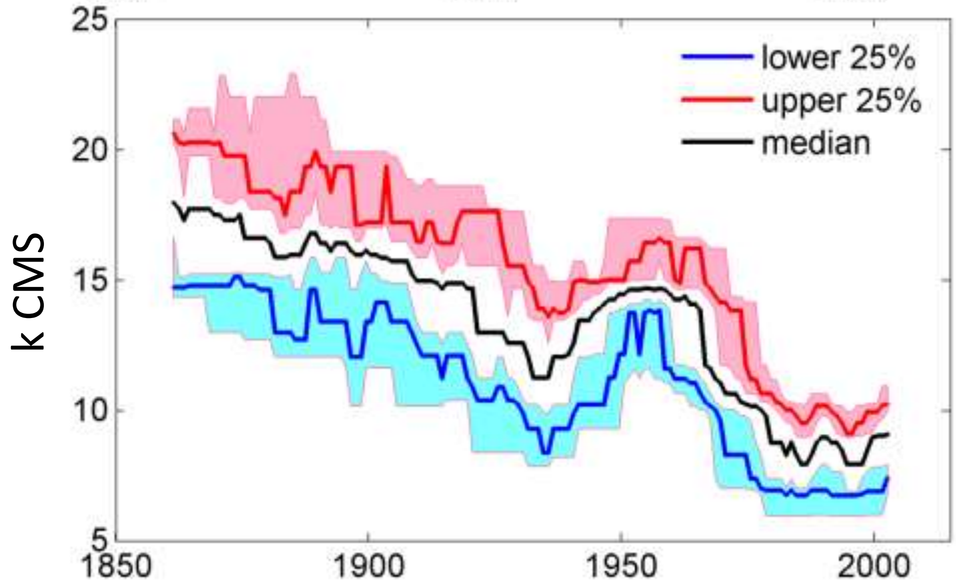
2. Plate tectonics largest local factor

3. Hydrodynamic and river flow changes causing measurable trends, but pretty small
   → Large in Portland, however

4. Ocean dynamics/natural variability a large signal that masks long-term trends

# Other effects on Water Temperature:
# Long term trends in Columbia River Peak Flow since 1850




Top 10 Meas 30d Flows
(1) 1894
(2) 1862
(3) 1948
(4) 1876
(5) 1880
(6) 1887
(7) 1866
(8) 1882
(9) 1859
(10) 1852

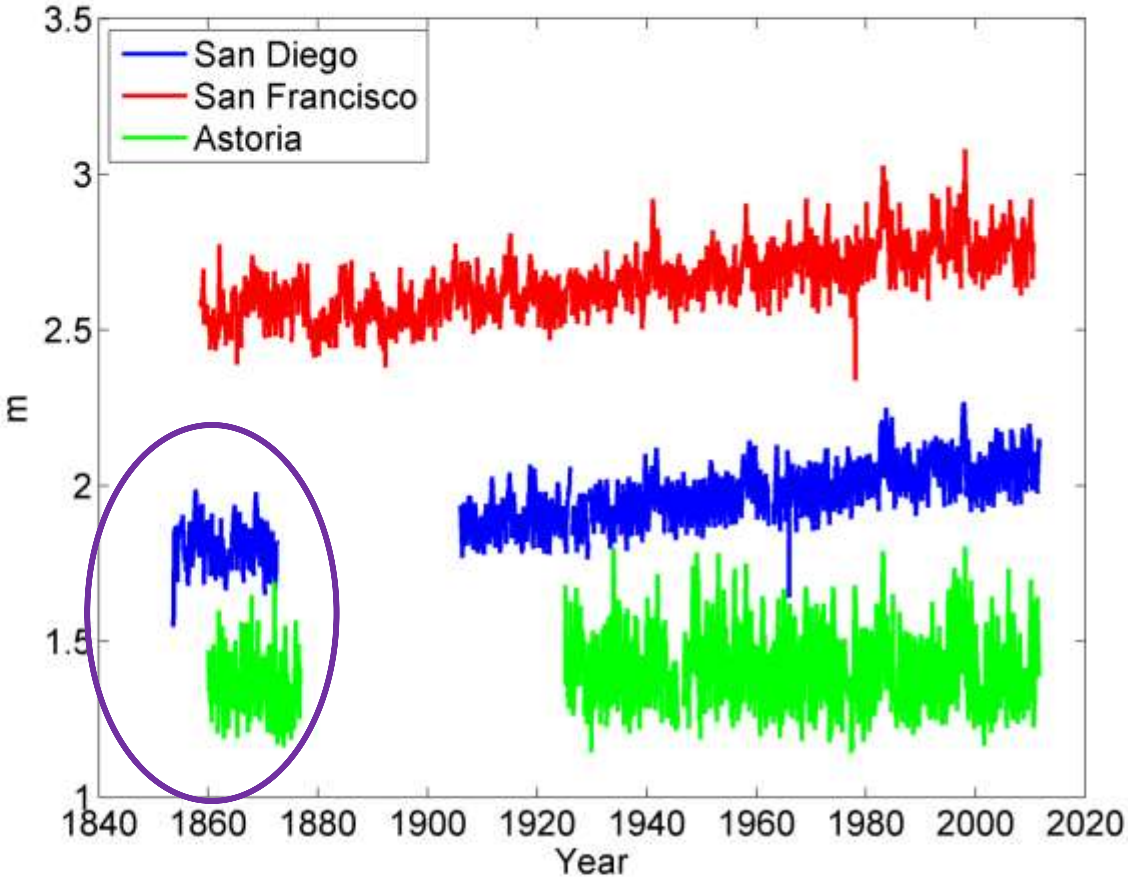
Measured annual peak

Our results: 20-25% decrease in annual flow

The river is now in permanent ‘drought’, relative to historical norms

Timing and magnitude of spring flows changing. What is effect on water temperature?

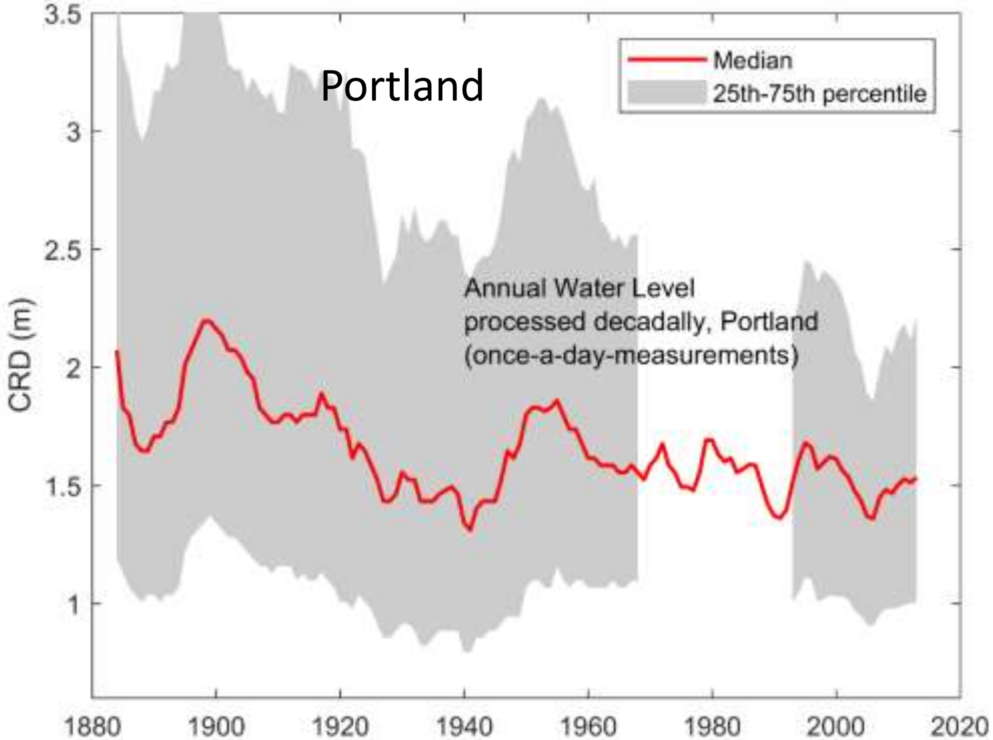
# Sea-Level:  Comparison




Original 1853 Astoria benchmark on backside

Benchmark F31—it seems to have subsided 0.2 feet relative to other benchmarks

Data recovered by Talke &Jay




Annual Water Levels

→Median has decreased by 0.5m

→ Variability has decreased by ~1m

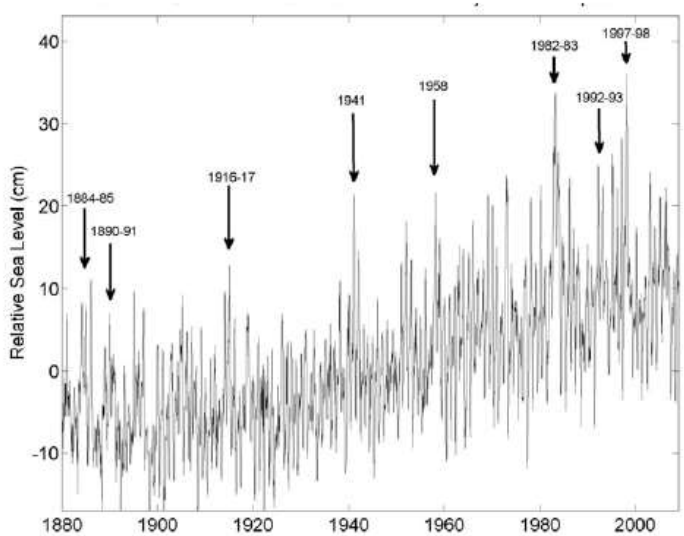



FIGURE 4.2 San Francisco tide gage record showing relative sea-level increases during major El Niño events. SOURCE: Tide gage data from the Permanent Service for Mean Sea Level.

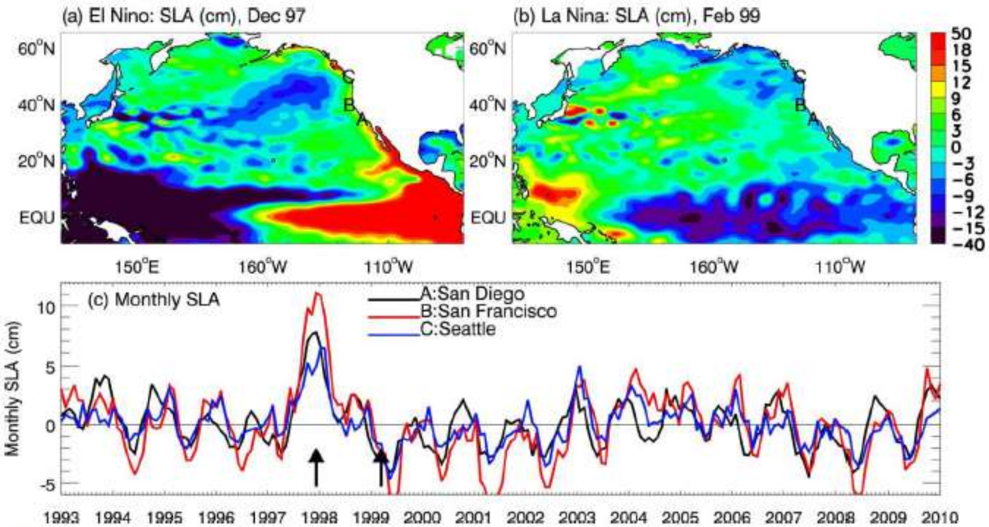
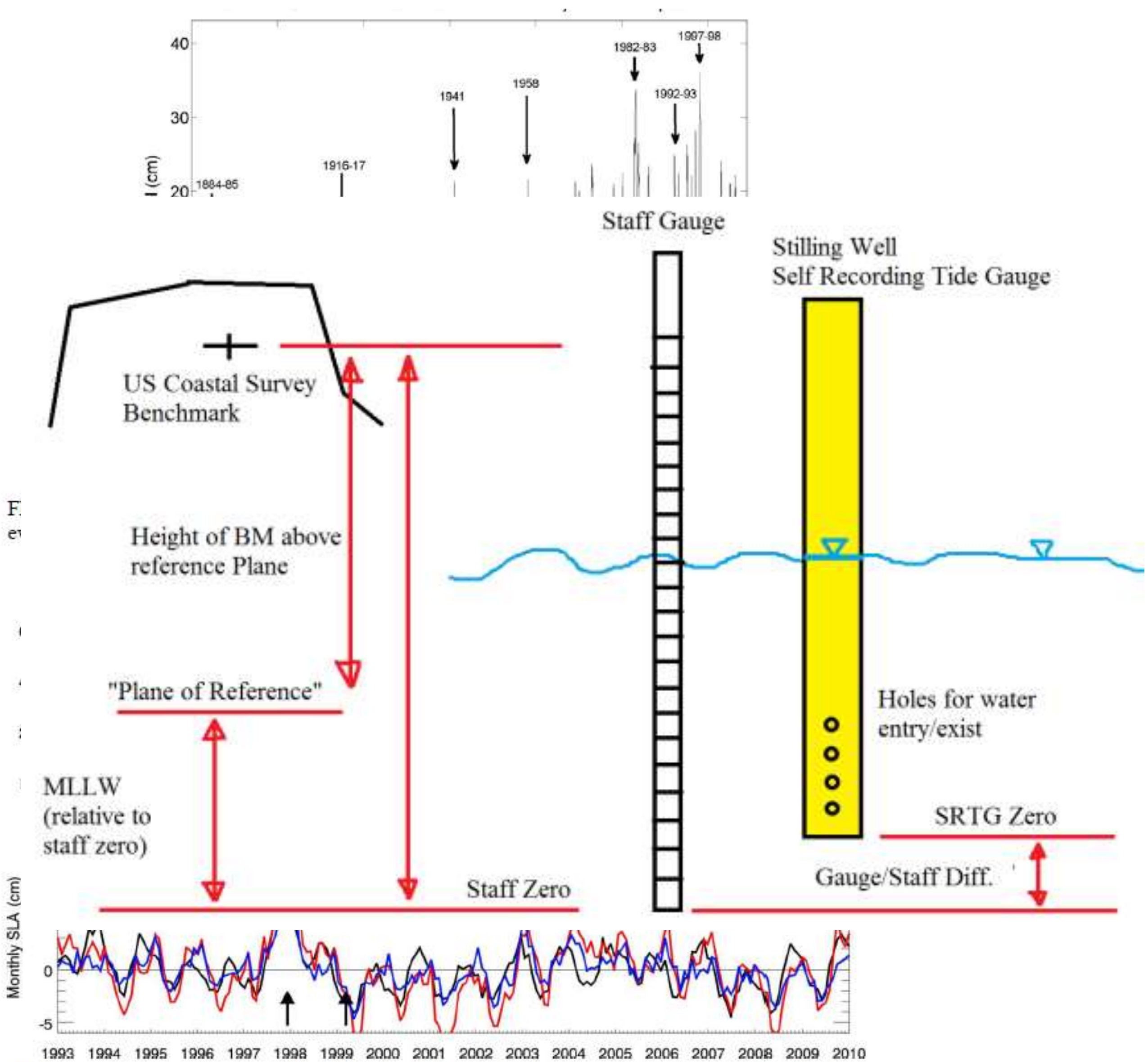



FIGURE 4.3 (*a*) Sea-level anomaly (SLA), the difference between mean sea level for 1993–2009 and sea level during the December 1997 El Niño. (*b*) Same as (a) but for a La Niña event in February 1999. Color scale on right is in cm. (*c*) Time series of monthly SLA offshore San Diego, San Francisco, and Seattle. The two black arrows correspond to the dates shown in the upper figures. SOURCE: AVISO satellite altimetry data from <http://www.aviso.oceanobs.com/>.

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