Methods & measurements of relative sea level, Monitoring long-term trends and anomalies, and the June-July 2009 East Coast event

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National Ocean Service

Types of Sea Level Change

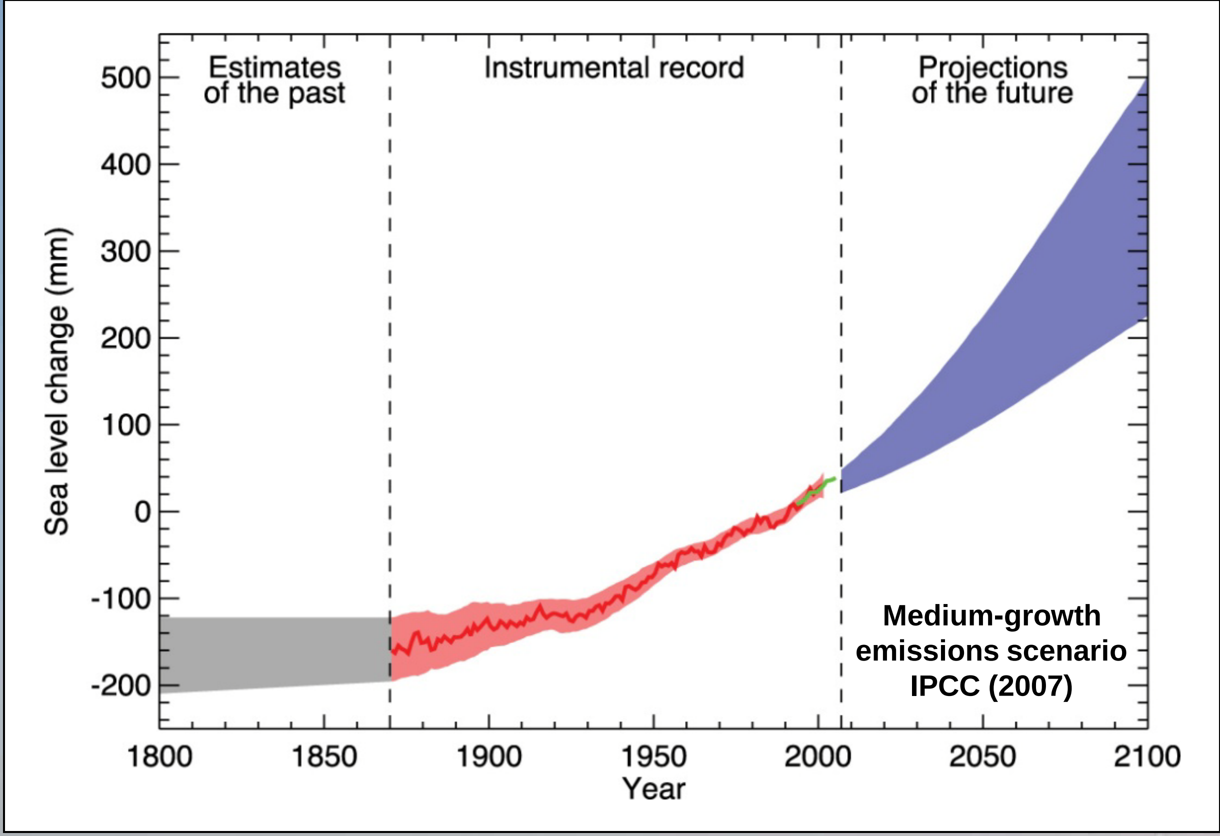
1. **Relative** changes at a localized region
   - Measured by tide stations
   - Includes vertical land motion and *absolute* changes

2. **Absolute** changes usually referred to on global scale
   - Measured by satellite and by tide stations in tectonically stable regions
   - Water volume changes from thermal expansion and ice exchange

Relative SL Change =

Absolute SL Change (-) Vertical Land Motion

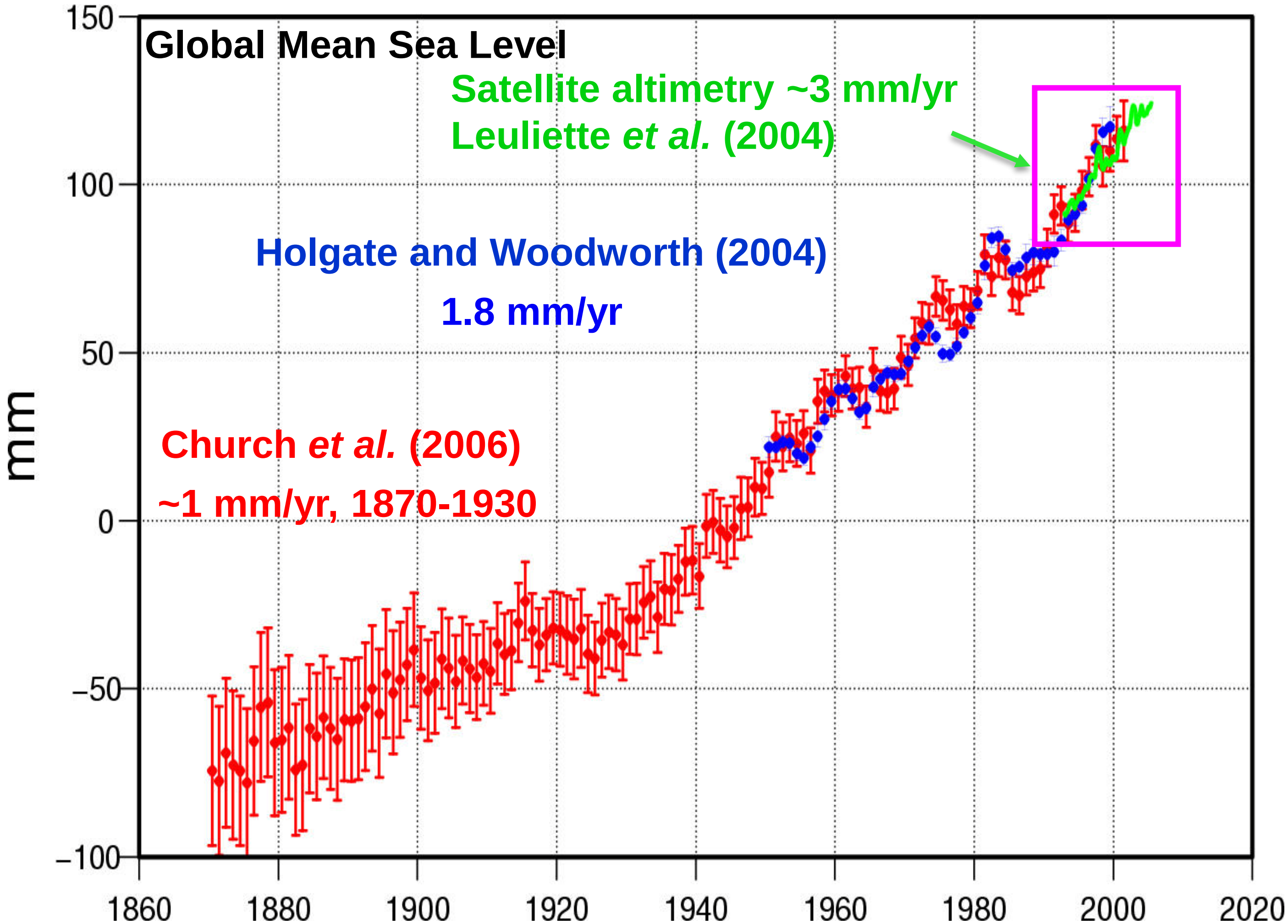
Global Sea Level Predictions



- The Intergovernmental Panel on Climate Change (IPCC) 2007 report projects a 18 to 59 cm absolute sea level (SL) rise during the 21st century

    - Accelerated ice flows in Greenland and Antarctica not considered

- Evidence that global SL rise has accelerated over the last half century



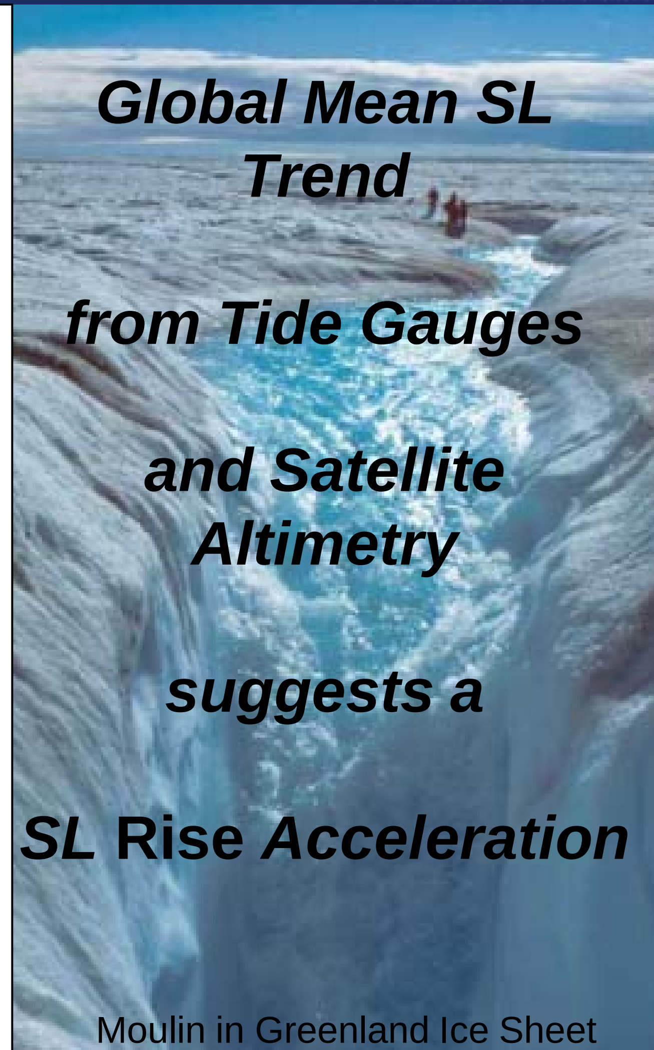
Global Mean SL Trend

from Tide Gauges

and Satellite Altimetry

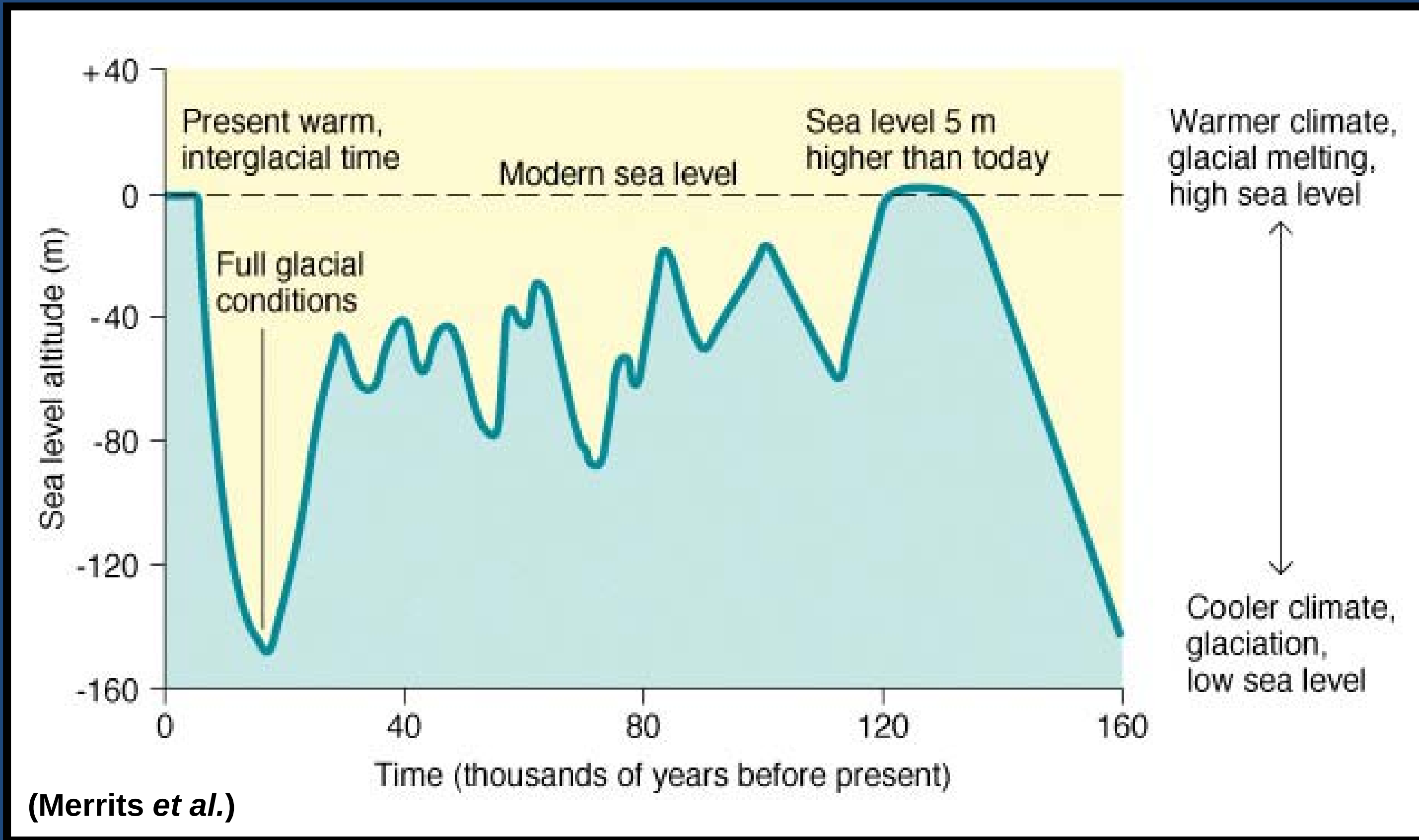
suggests a

SL Rise Acceleration

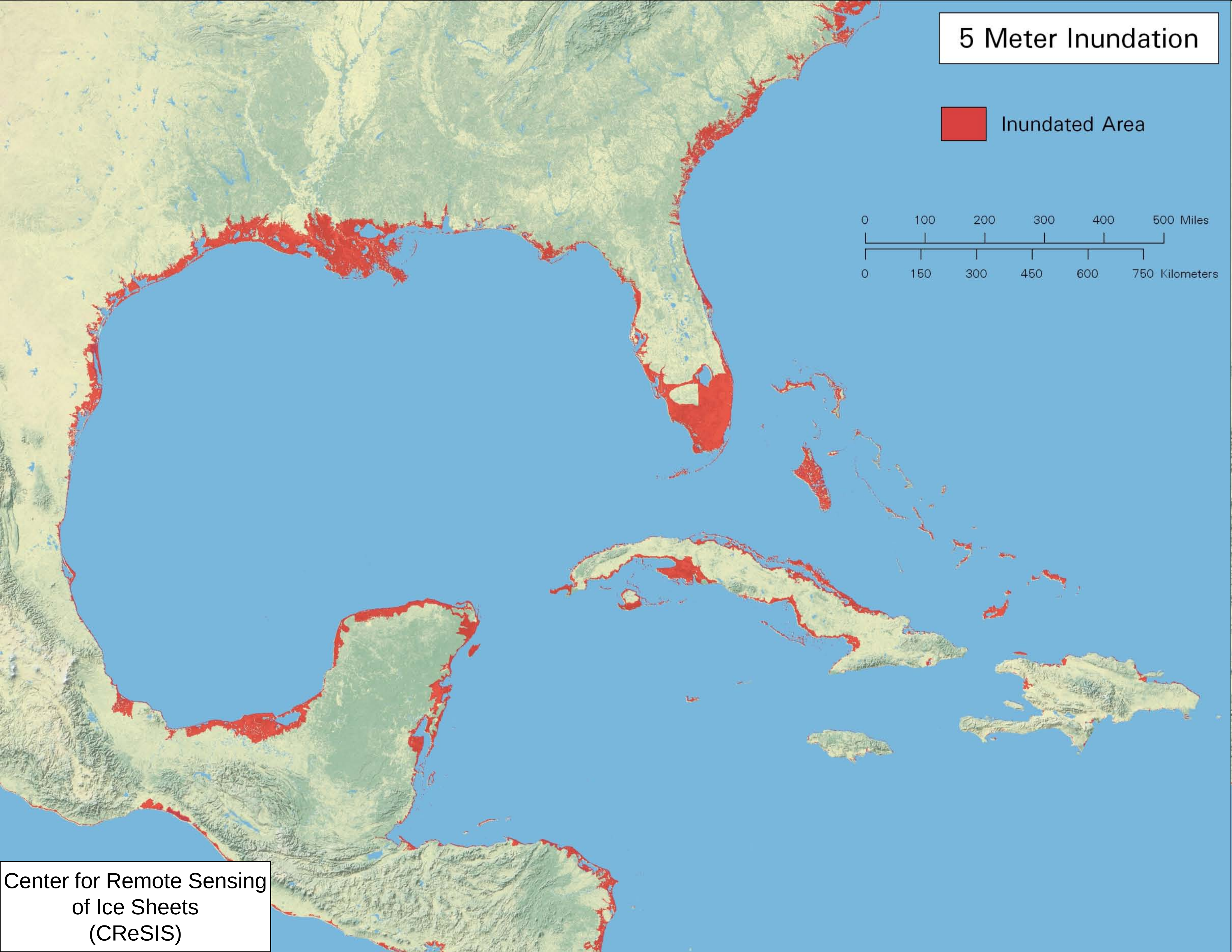


Moulin in Greenland Ice Sheet

PAST STANDS OF SEA LEVEL



Long-term absolute variability driven mainly by glacial cycles
(and relative vertical land motion: subsidence & rebound)



5 Meter Inundation
Inundated Area
0 100 200 300 400 500 Miles
0 150 300 450 600 750 Kilometers
Center for Remote Sensing of Ice Sheets (CReSIS)

TIDES & CURRENTS

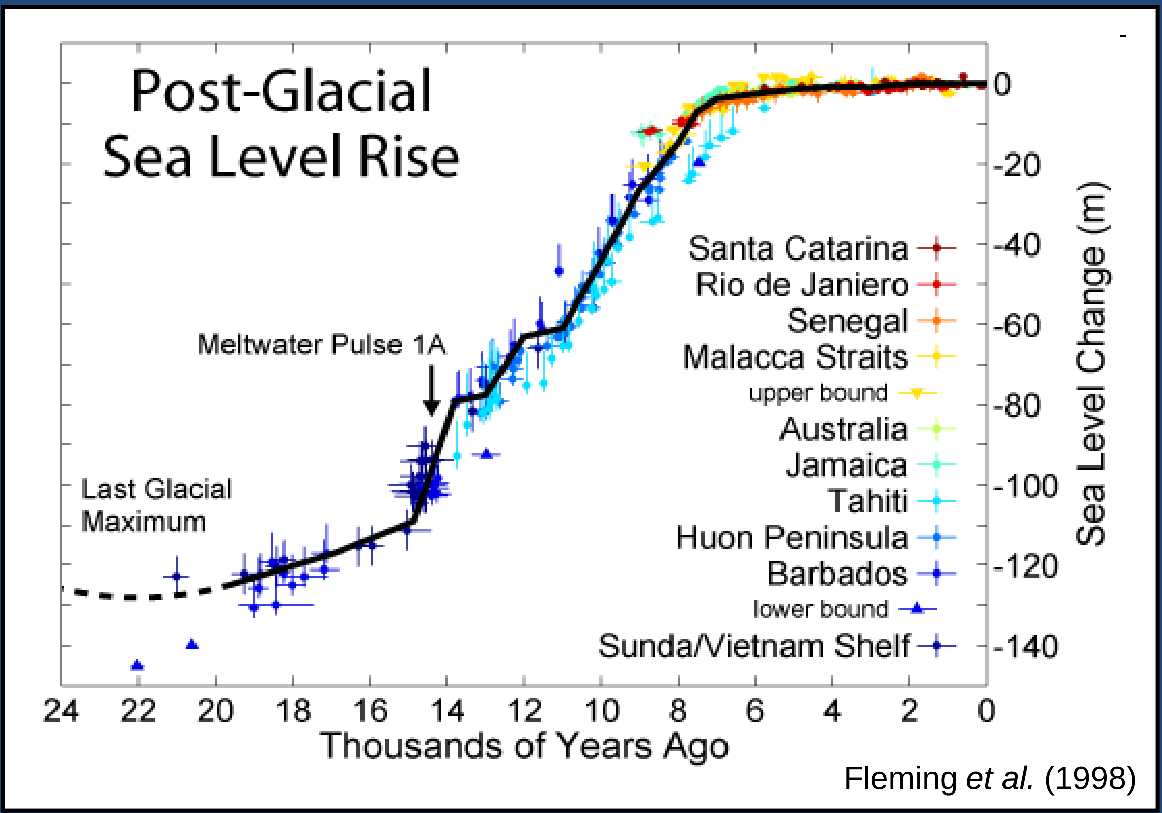
- Thermal Expansion (~ 1 meter potential)
- Water Exchange with Continents (potential)
  - Greenland Ice (7 meters)
  - Antarctic Ice (60 meters)
  - Mountain Glaciers (0.5 meter)
  - Terrestrial Water Storage Variations (< 0.5 meter)
  - Other (halosteric, etc.)

$$\Delta SL_{Total} = \Delta SL_{Thermosteric} + \Delta SL_{Greenland} + \Delta SL_{Antarctica} + \Delta SL_{Glaciers} + \Delta SL_{Storage} + \Delta SL_{Other}$$

SOURCE: R.S.NEREM, BOWIE LECTURE FALL AGU 2005

Recent Global Sea Level Rise:

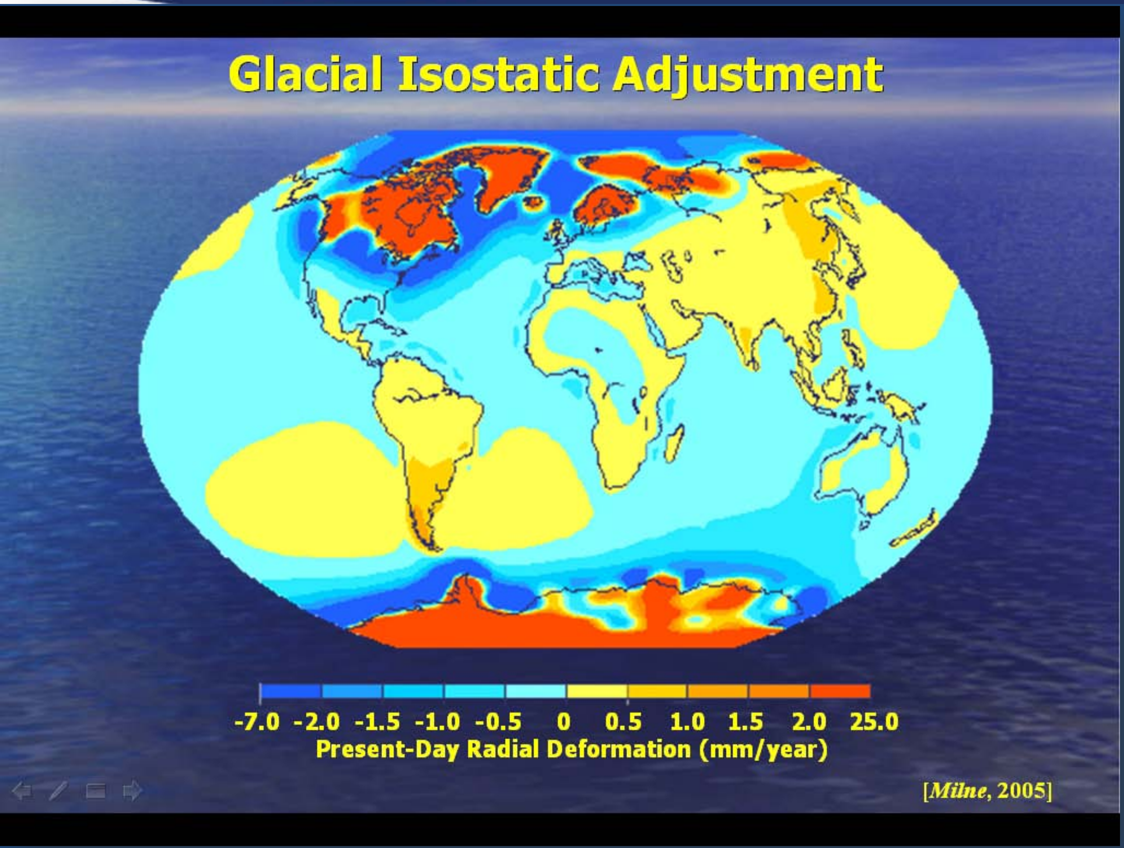
Based on Relative Proxy Measurements



Fleming *et al.* (1998)

Coral reef Analysis

- Depths ~ pace with SL
- 4 m/century rise possible
- Relative rates adjusted for vertical land motion (uncertainty in magnitude)



Quantifying vertical land motion is important to model past SL changes and better predict future rates of relative SL rise

Sources of vertical motion, best measured by long-term GPS measurements:

1. Adjustment of crust to ice-load removal (constant ~10,000 yrs)
2. Subsidence / compaction from sediment loads
3. Localized depression from oil / gas / water extraction

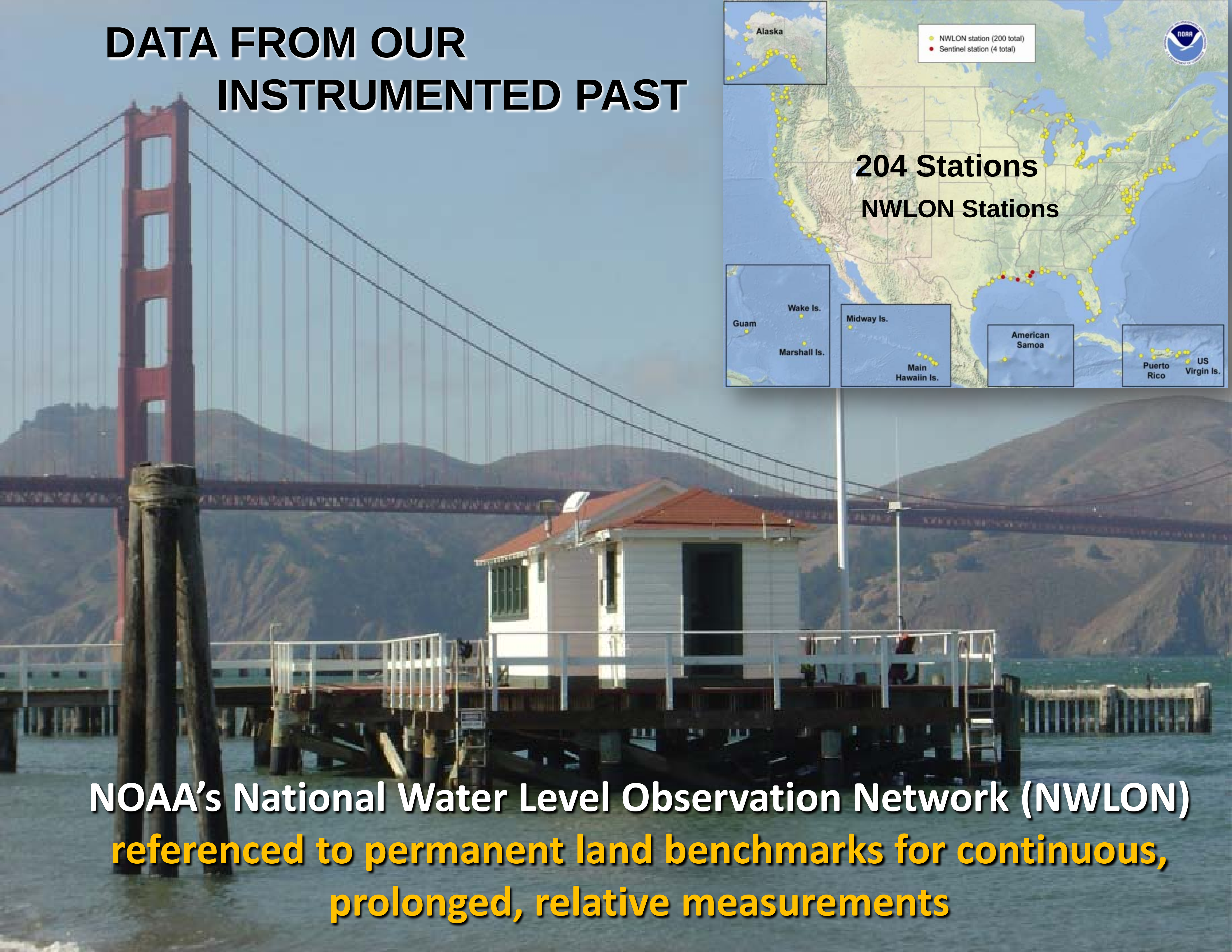
Past stands of SL: Will history repeat itself?

San Clemente Island, California

Ancient shorelines show historic SL – different rates of tectonic uplift

6-m high shoreline (120,000 yrs old)
Swansboro, NC

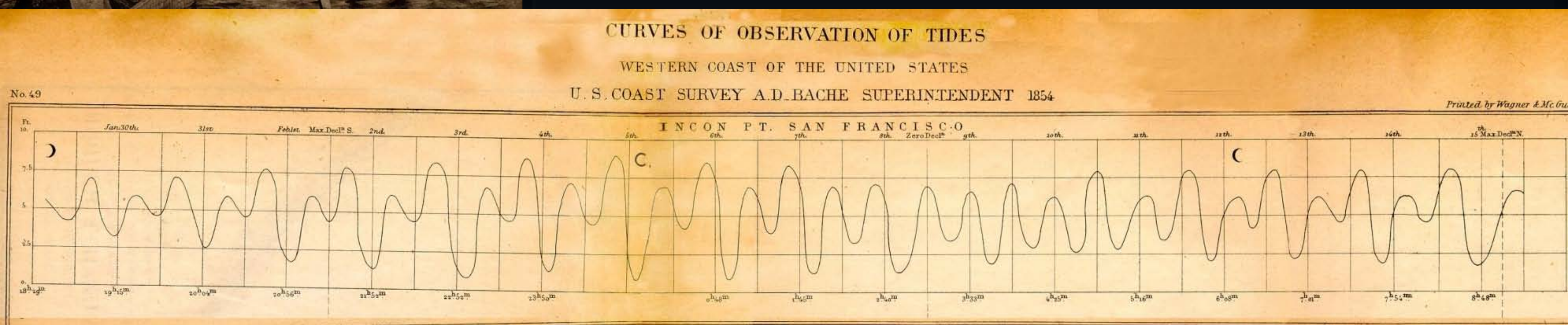
DATA FROM OUR INSTRUMENTED PAST

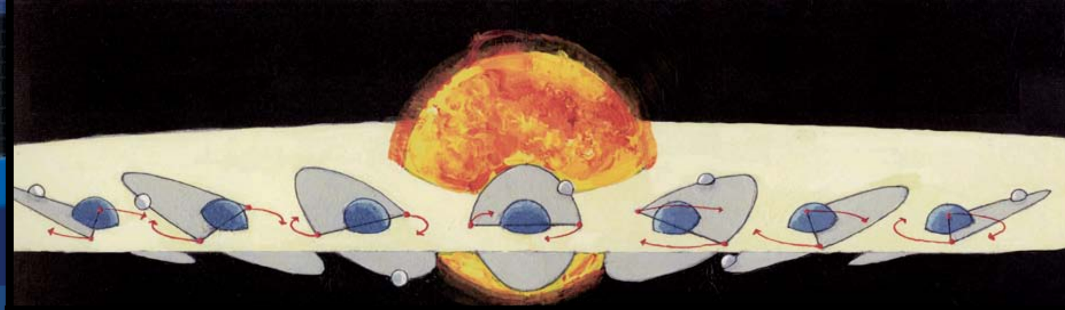


NOAA's National Water Level Observation Network (NWLON) referenced to permanent land benchmarks for continuous, prolonged, relative measurements

NOAA's History of Sea Level Monitoring

- 1807 MISSION: Establishing SL reference for charting, shoreline and marine Boundaries
- Provides U.S. Tide Predictions
- Provides Real-Time Observations
- Legally defines Mean Sea Level (MSL) and other datums for the US
- Tracks MSL changes and SL Trends

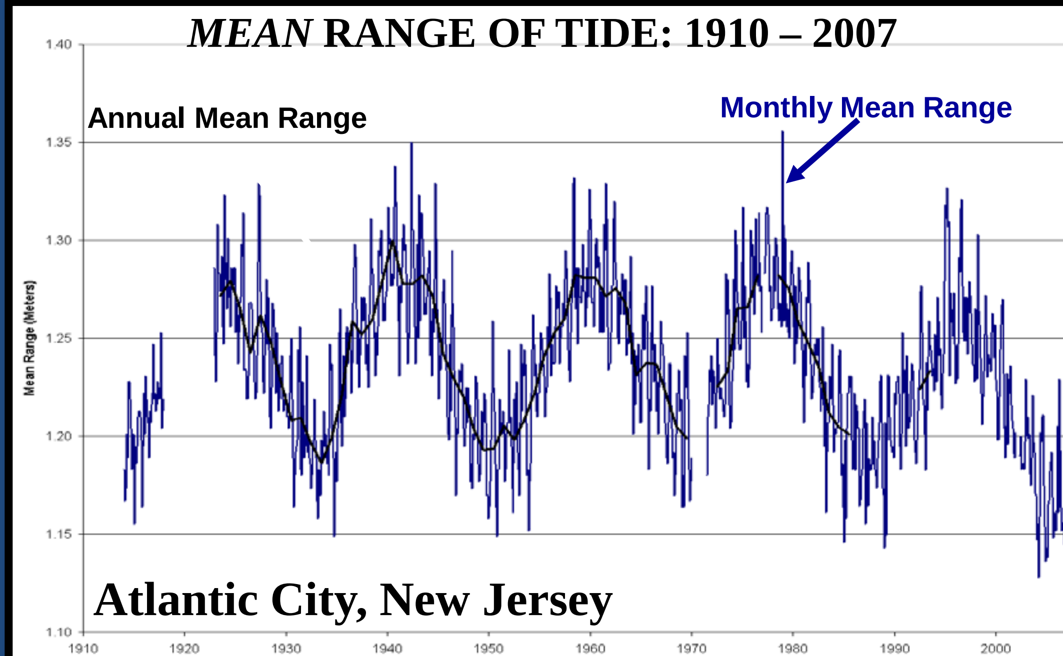


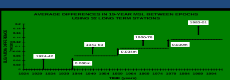


TIDAL DATUMS: 19-yr avg. at various stages of the tide

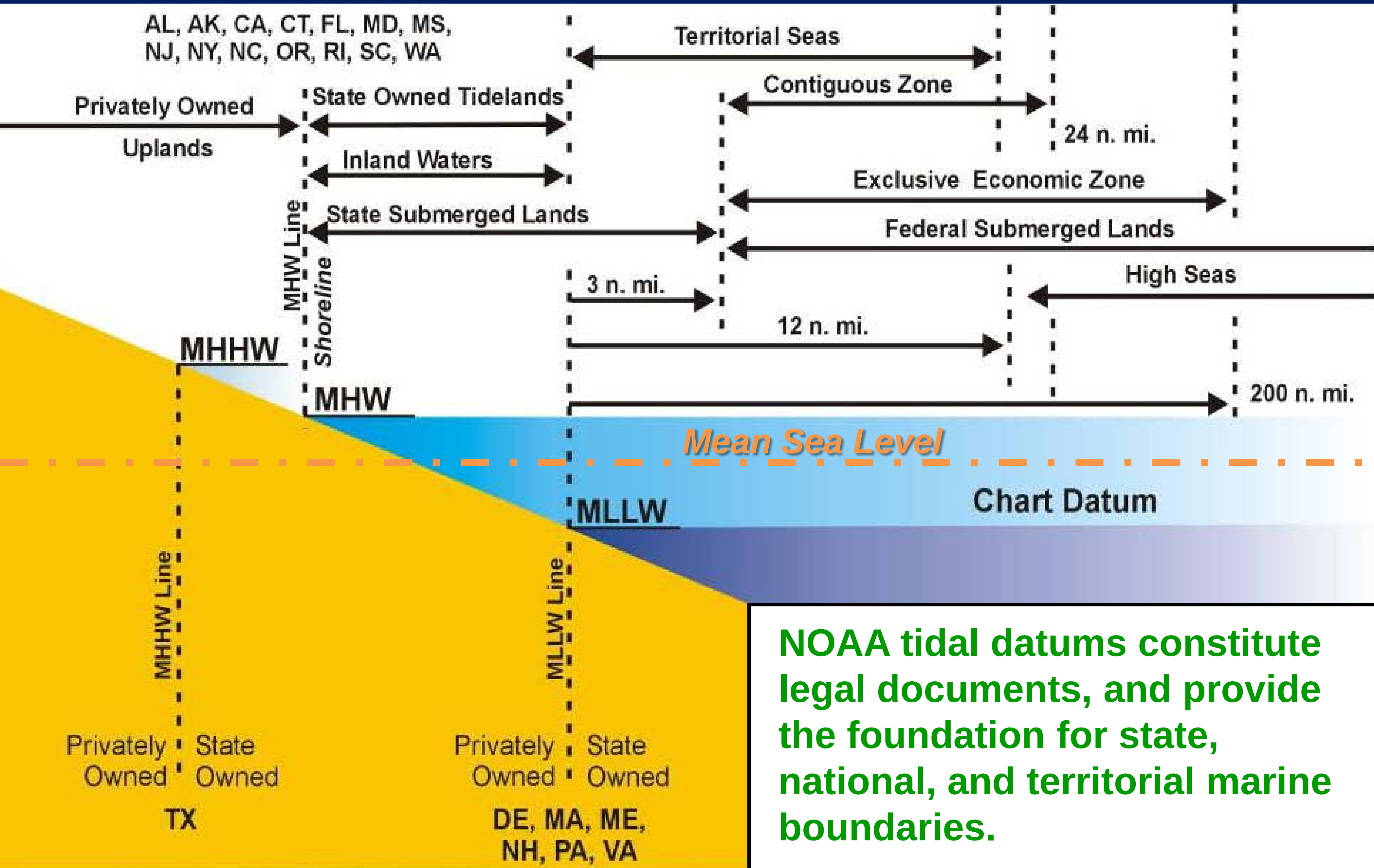
19-YR EPOCH: based on cycle of the moon's nodes

MSL RISE: EPOCH differences





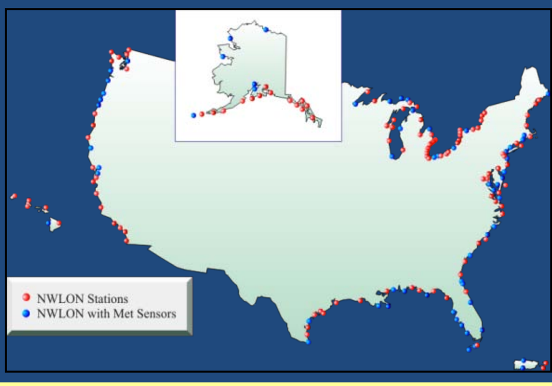
Marine Boundaries In The U.S.



NOAA tidal datums constitute legal documents, and provide the foundation for state, national, and territorial marine boundaries.

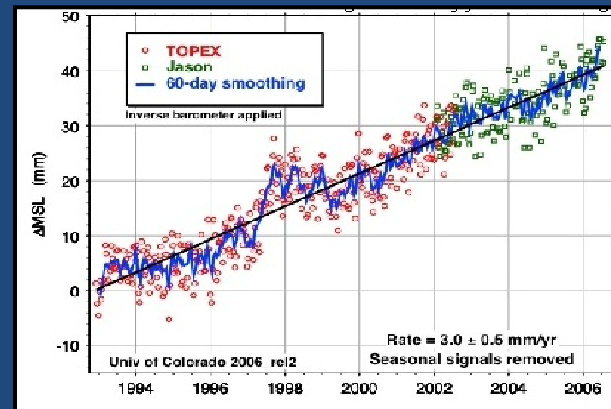
Instrumental Records
Monitoring and Predicting SL

National Water Level Observation Network (NWLON)



NWLON Platform Station calibrates Satellite Altimetry

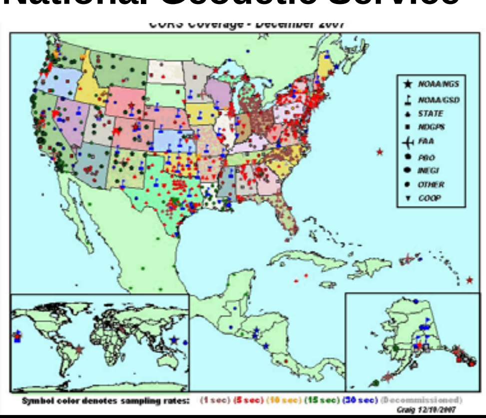
Satellite measurements of global absolute SL rise



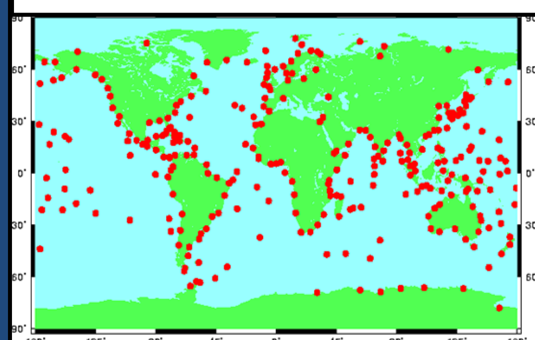
Continuously Operating Reference Stations (CORS)

GPS Measurements

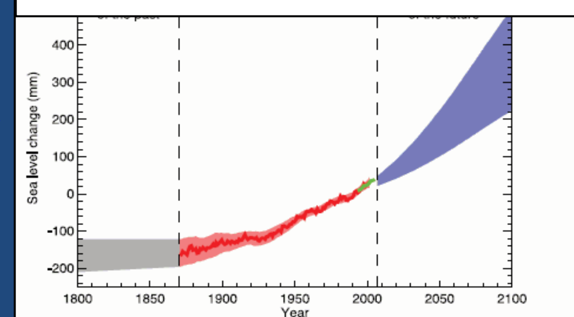
National Geodetic Service

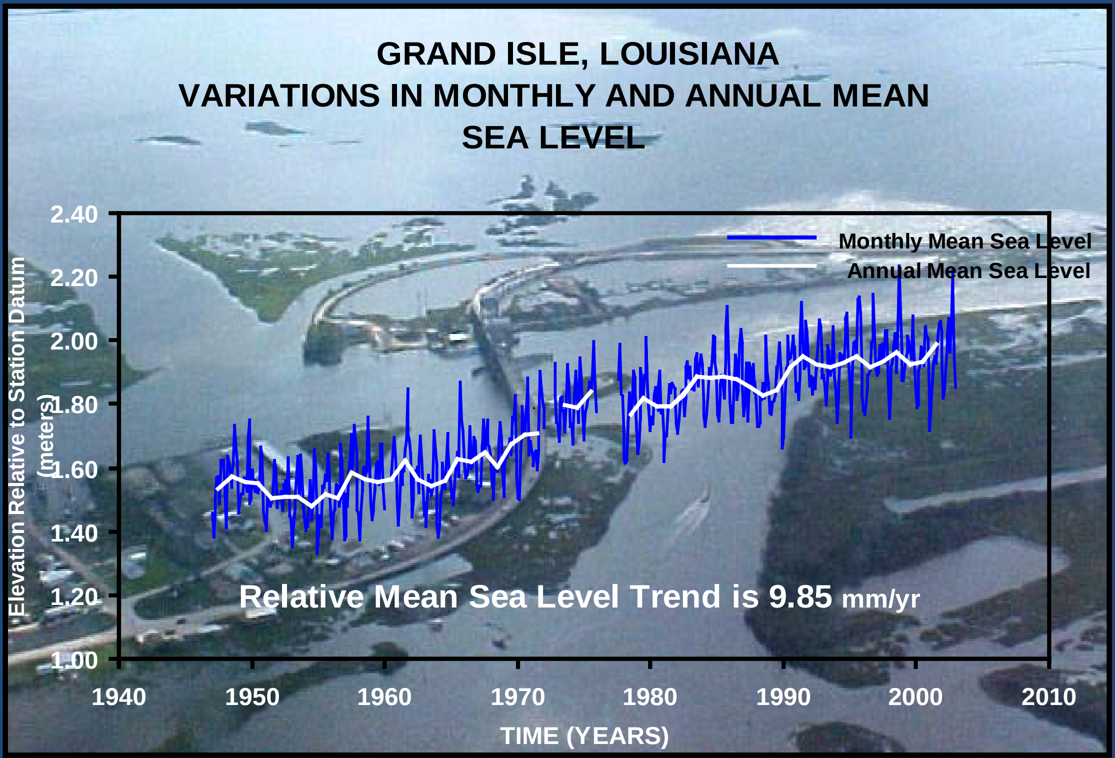


Global Sea Level Network

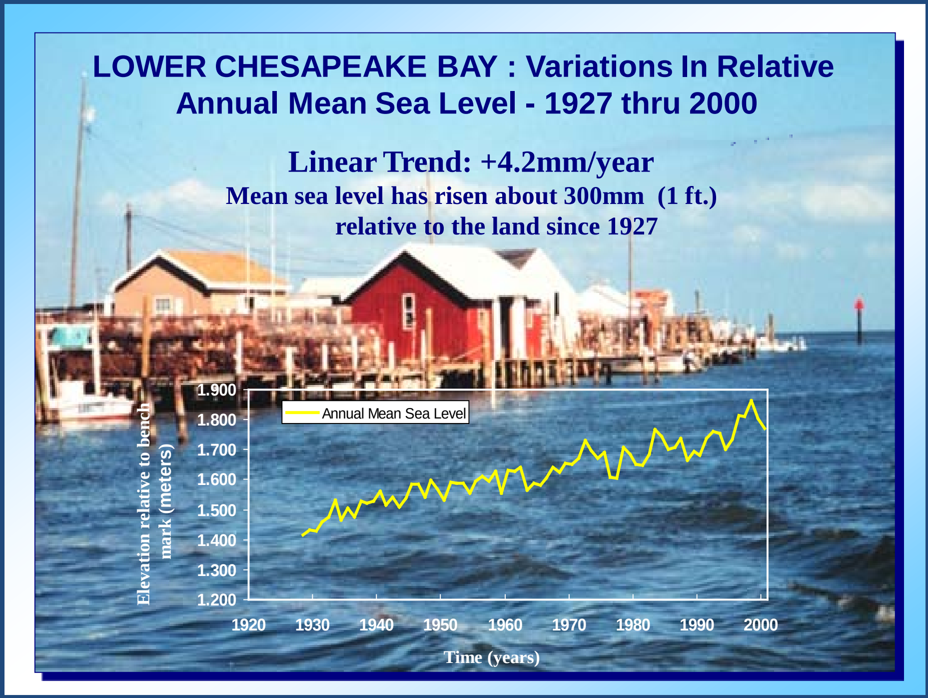


Global Sea Level Rise Estimates





Sea level rise is ***Relative***

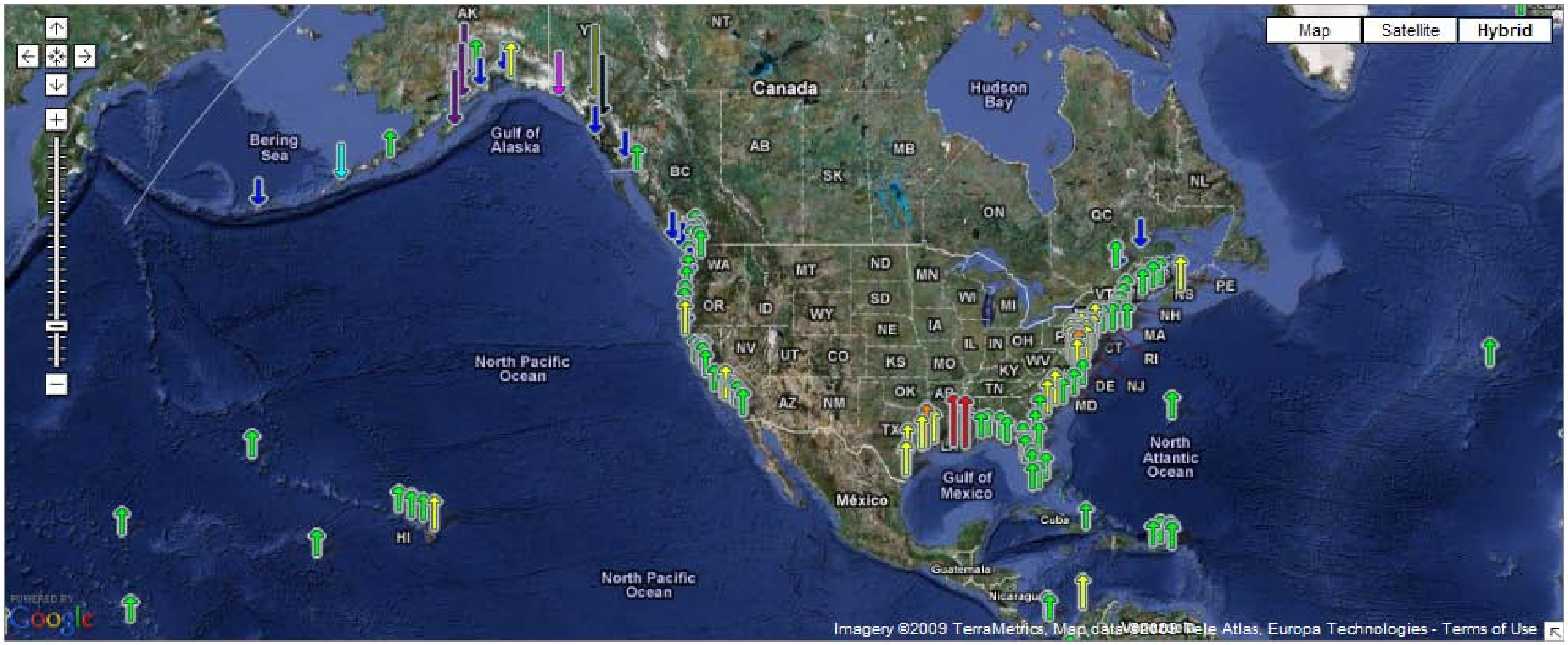


For ecosystem & society maintenance, its trends are very ***Relevant***

http://tidesandcurrents.noaa.gov/sltrends

Sea Levels Online

East Coast | West Coast | Gulf Coast | Alaska | Pacific | Global



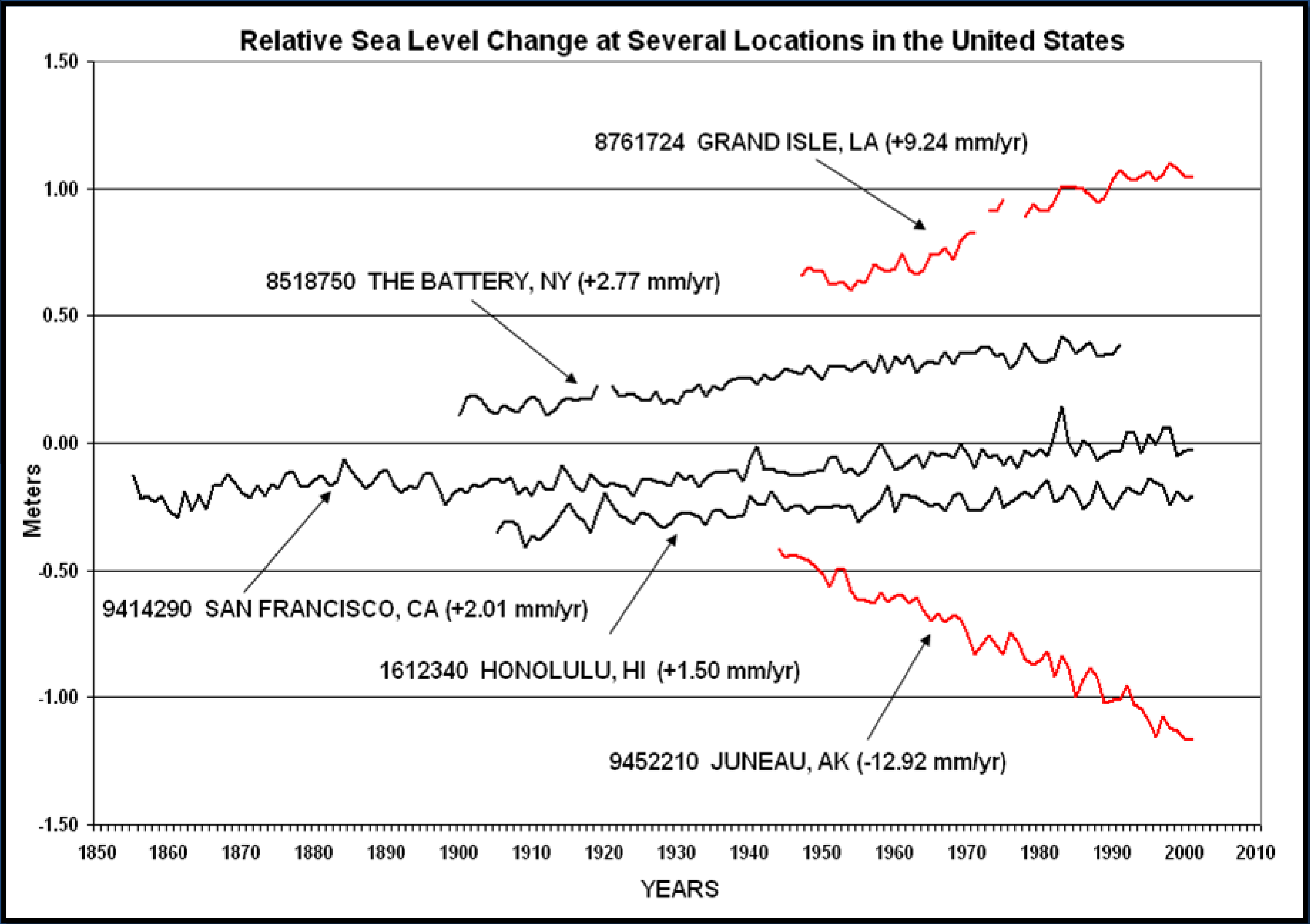
The map above illustrates regional trends in sea level, with arrows representing the direction and magnitude of change. Click on an arrow to access additional information about that station.

Sea Level Trends

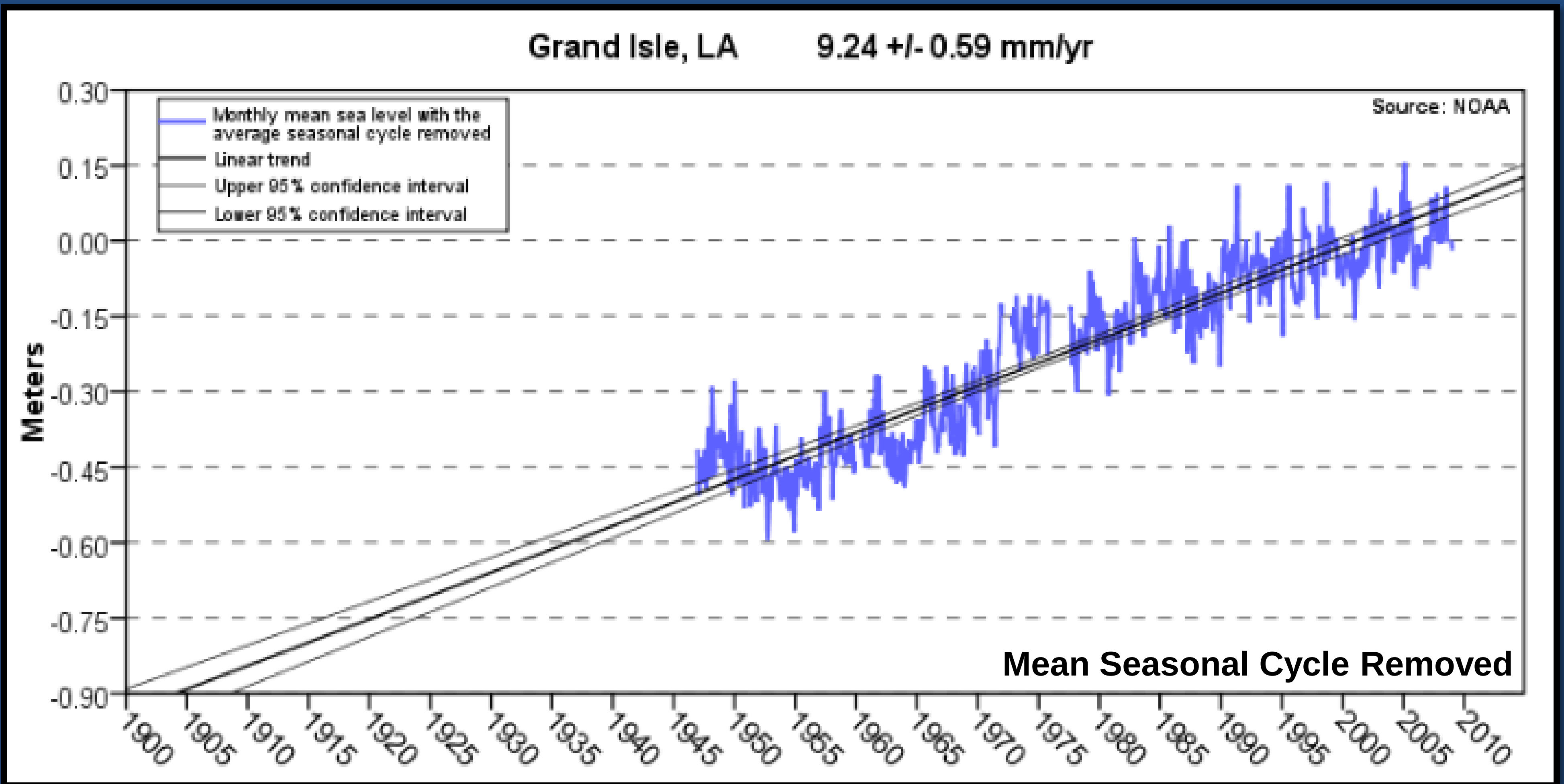
mm/yr (feet/century)

Red: 9 to 12 (3 to 4)	Yellow: 3 to 6 (1 to 2)	Blue: -3 to 0 (-1 to 0)	Magenta: -9 to -6 (-3 to -2)	Black: -15 to -12 (-5 to -4)
Orange: 6 to 9 (2 to 3)	Green: 0 to 3 (0 to 1)	Cyan: -6 to -3 (-2 to -1)	Purple: -12 to -9 (-4 to -3)	Olive: -18 to -15 (-6 to -5)

Relative long-term linear SL trends are highly variable at tide stations across the US



RELATIVE LONG-TERM TRENDS

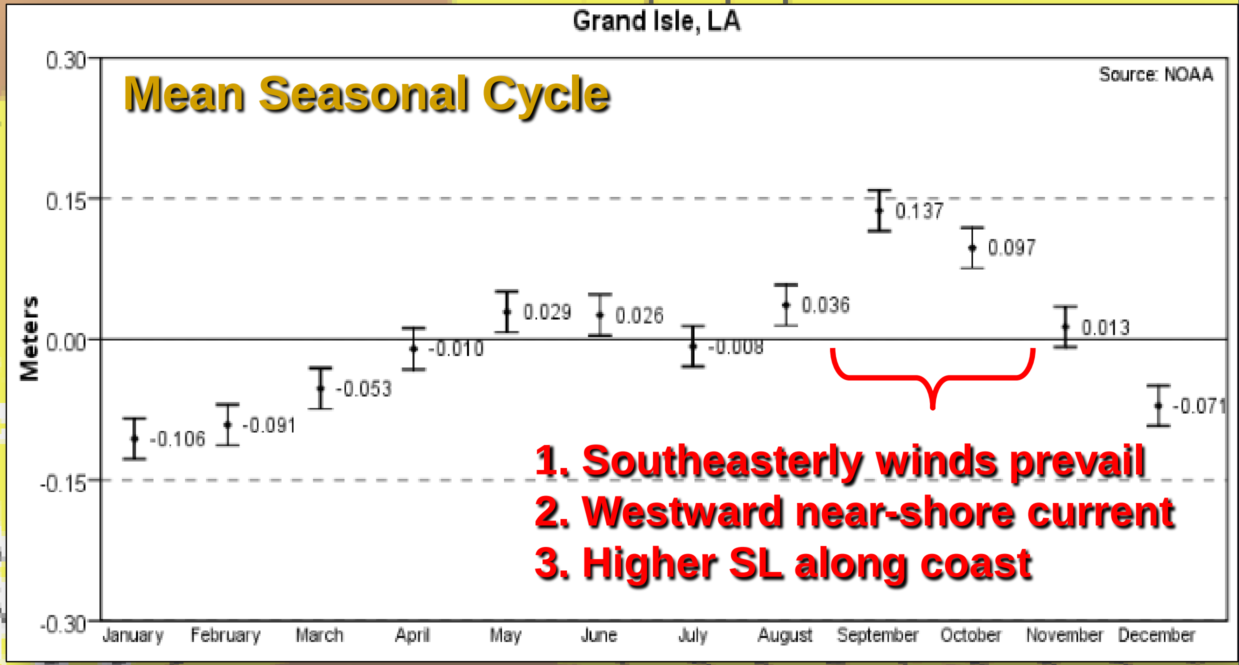


Mean sea level and the linear trend with its 95% confidence interval

LONG-TERM SEASONAL CYCLES

Monthly mean SL with 95% confidence intervals.

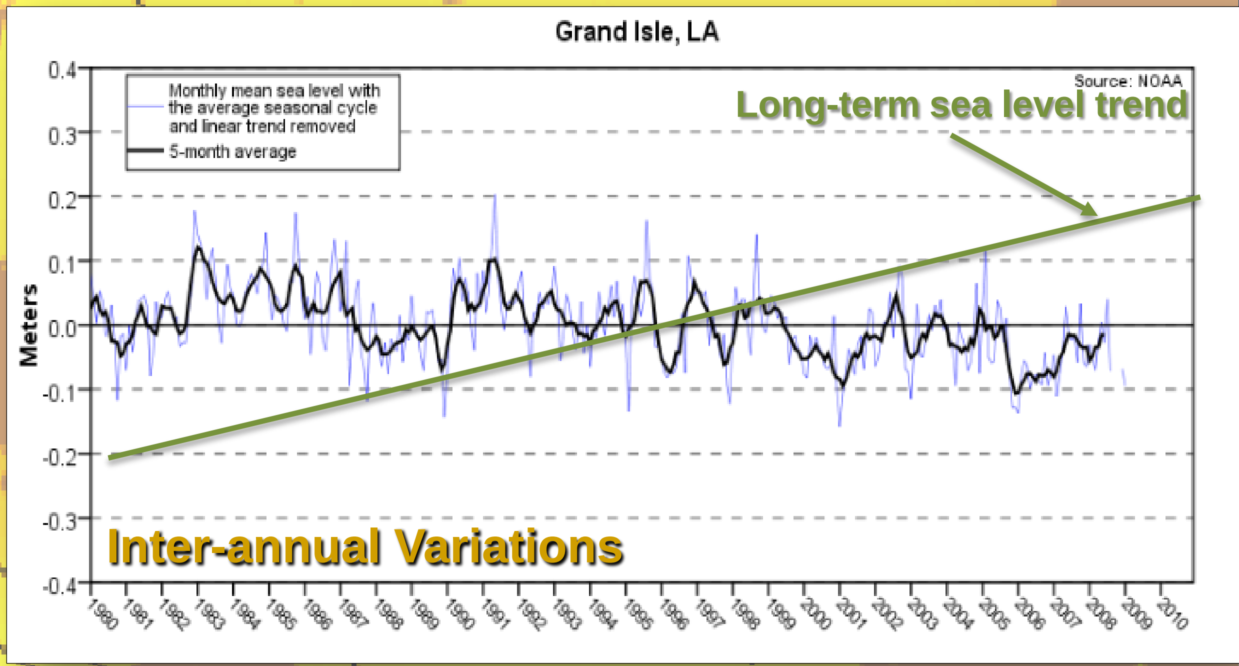
Seasonal cycle: regular fluctuations in water densities, coastal winds and ocean currents



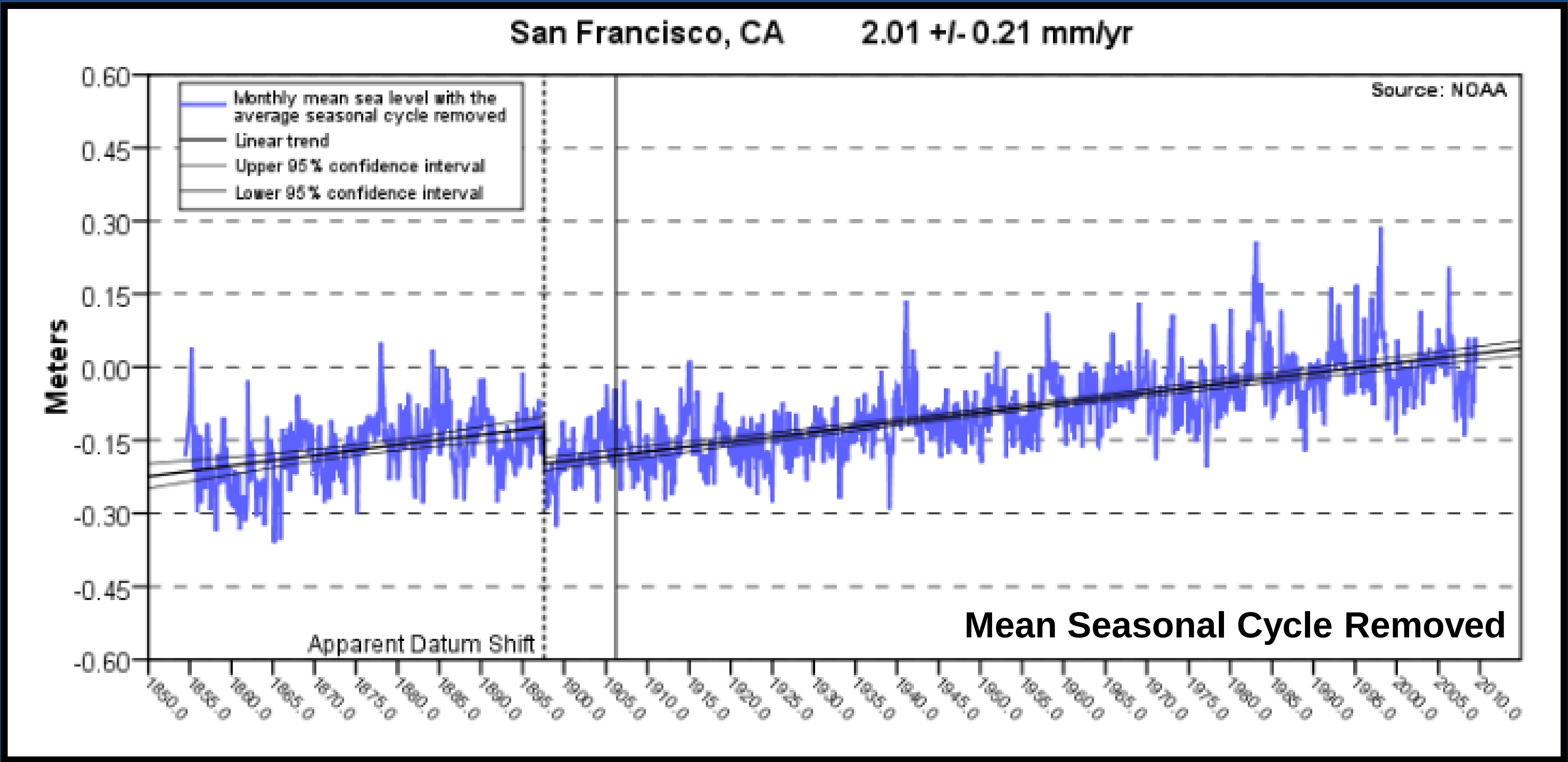
LONG-TERM TREND AND SEASONAL CYCLES REMOVED

5-month mean SL with the seasonal and long-term trend removed

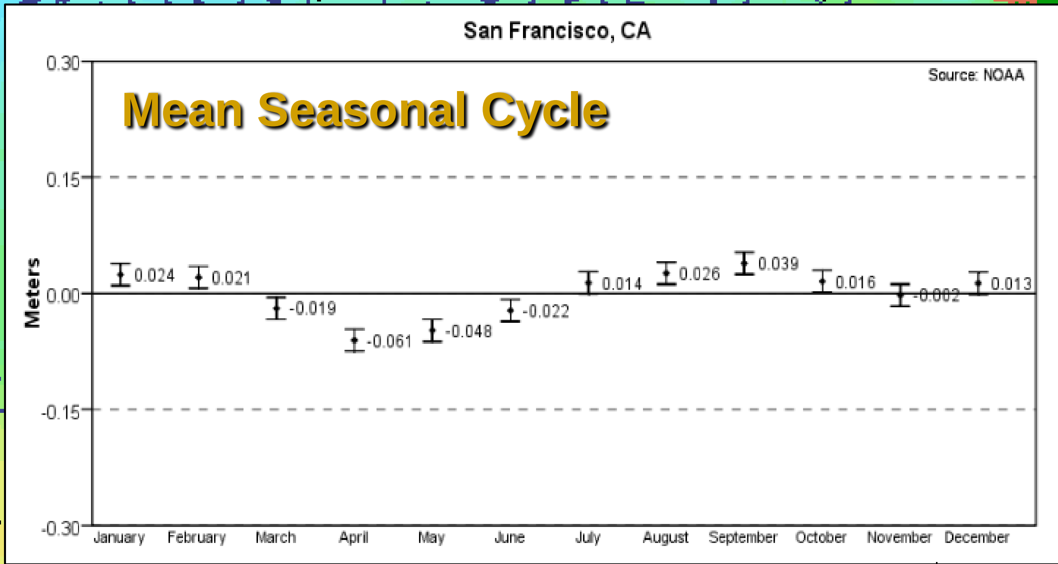
Inter-annual variations (i.e., ENSO) caused by anomalous fluctuations of forcing mechanisms



RELATIVE LONG-TERM TRENDS

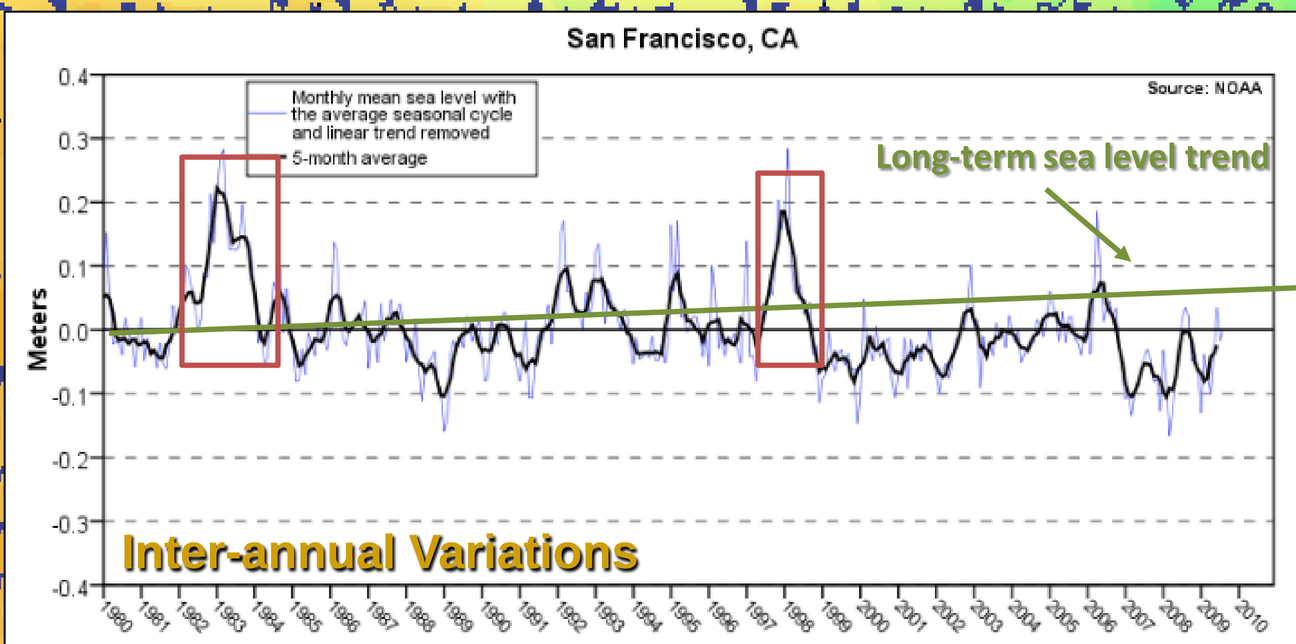


Monthly mean SL and linear trend with 95% confidence interval



- Upwelling period in **Spring**
- Northerly (southward) winds
- Westward rise in sea heights (lower coastal SL)
- Southward California Current

- Downwelling period in **Fall**
- Variable winds
- Northward coastal current (Davidson)
- Elevated coastal SL



Inter-annual variations (i.e., ENSO) is caused by anomalous fluctuations of forcing mechanisms

During Normal /La Niña Conditions

- Easterly Trades: normal to stronger than normal
- SL higher in western Pacific and lower in east

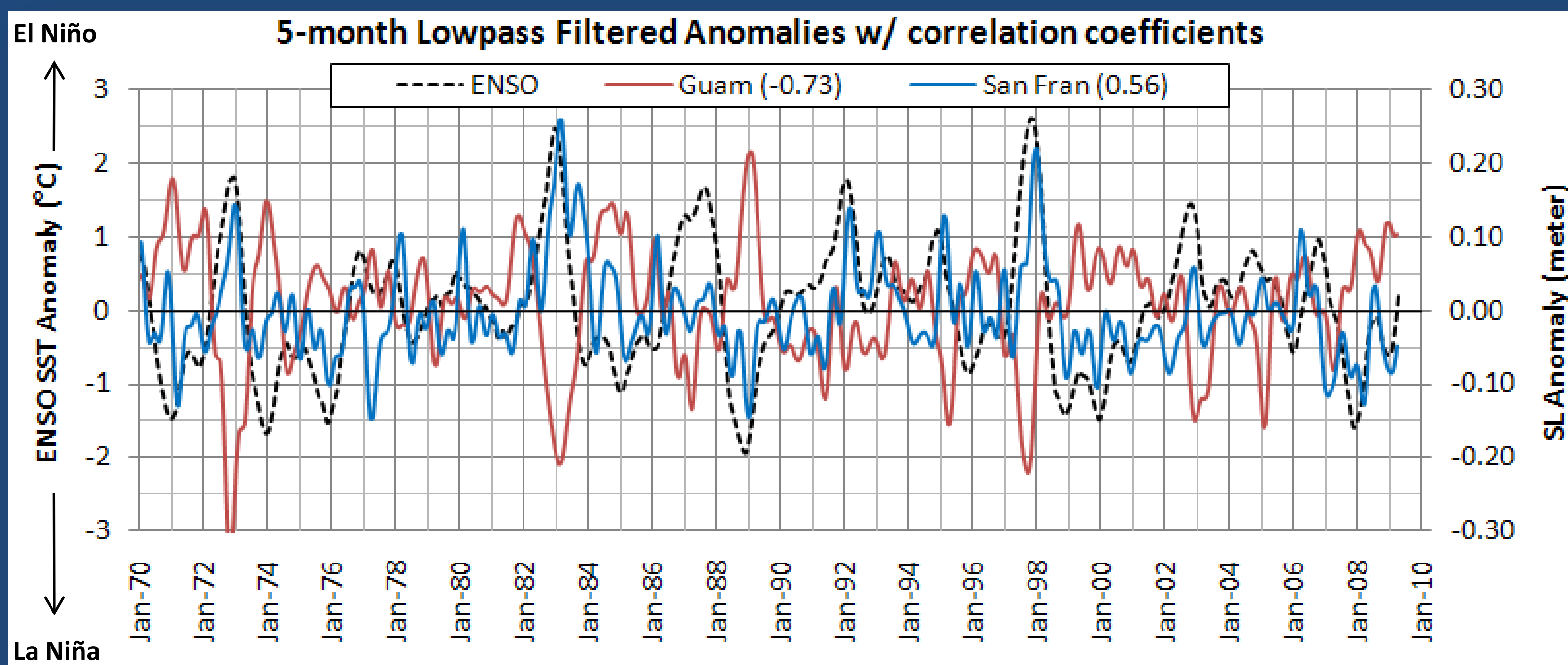
During El Niño Conditions

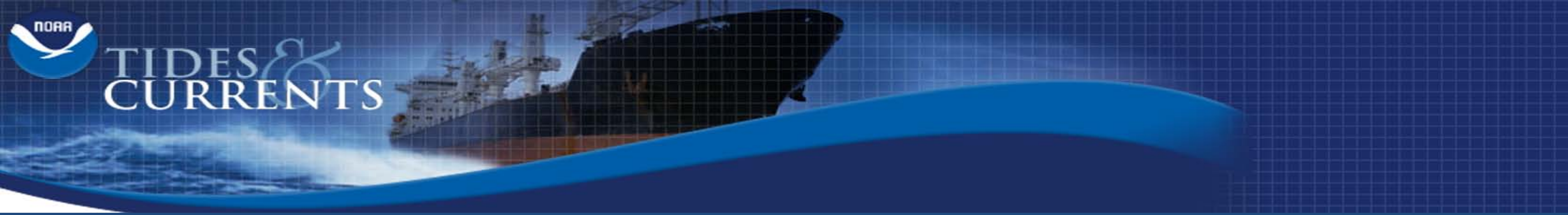
- Easterly Trades are weaker than normal
- SL falls in western Pacific (eastward moving Kelvin waves) and rises in the east Pacific

ENSO CYCLE AND PACIFIC OCEAN SEA LEVEL ANOMALIES

NINO Region 3.4

5°N – 5°S
by
170° – 120°W





[2009-08-28]
NOAA Report Explains Sea Level Anomaly this Summer along the Atlantic Coast

[2009-07-02]
East Coast water levels running above predictions

ALERT: East Coast water levels are currently running above predicted tides

Starting in early June 2009, observed tides have been increasingly elevated above predicted tidal elevations along the entire U.S. East Coast from Maine to the east coast of Florida. During the period from June 19 thru June 24 for instance, these water levels were running between 0.6 to 2.0 feet above normal depending upon location. As of July 1, these anomalies continue, but running lower at 0.3 to 1.0 ft. above normal. It is not unusual for smaller regions and estuaries along the U.S. East Coast to experience this type of anomalous event at this time of year, however the fact that the geographic extent of this event that includes the entire East Coast event is anomalous. CO-OPS will continue to monitor this event and will provide further information on the causes, amplitudes, geographic extent, and the duration of the event.

For further information, please contact:

User Services
Center for Operational Oceanographic Products and Services (CO-OPS)
1305 East-West Highway
Silver Spring, MD 20910-3281
E-mail: User Services

Back to Tides & Currents

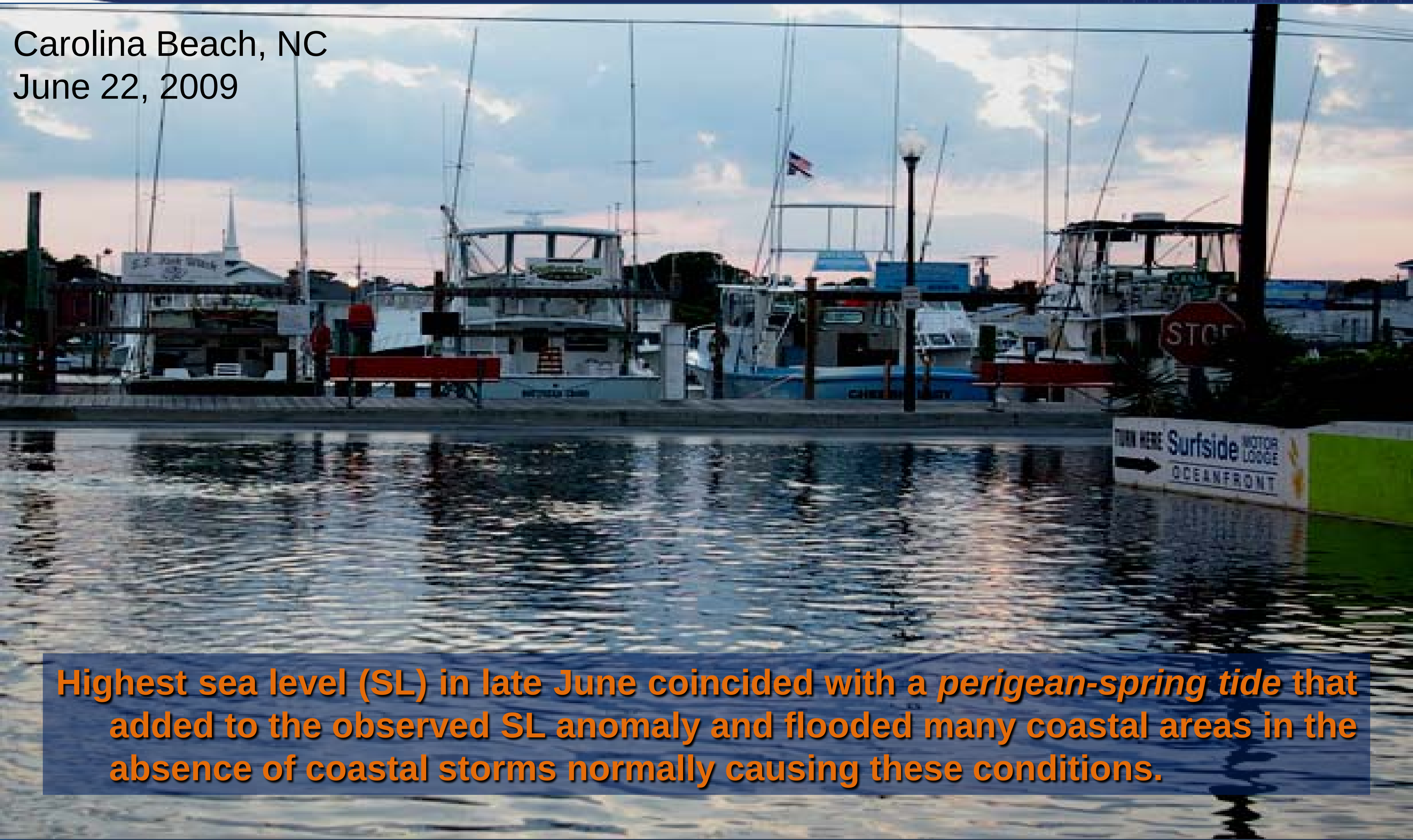
NOAA Technical Report NOS CO-OPS 051

ELEVATED EAST COAST SEA LEVEL ANOMALY:
June – July 2009

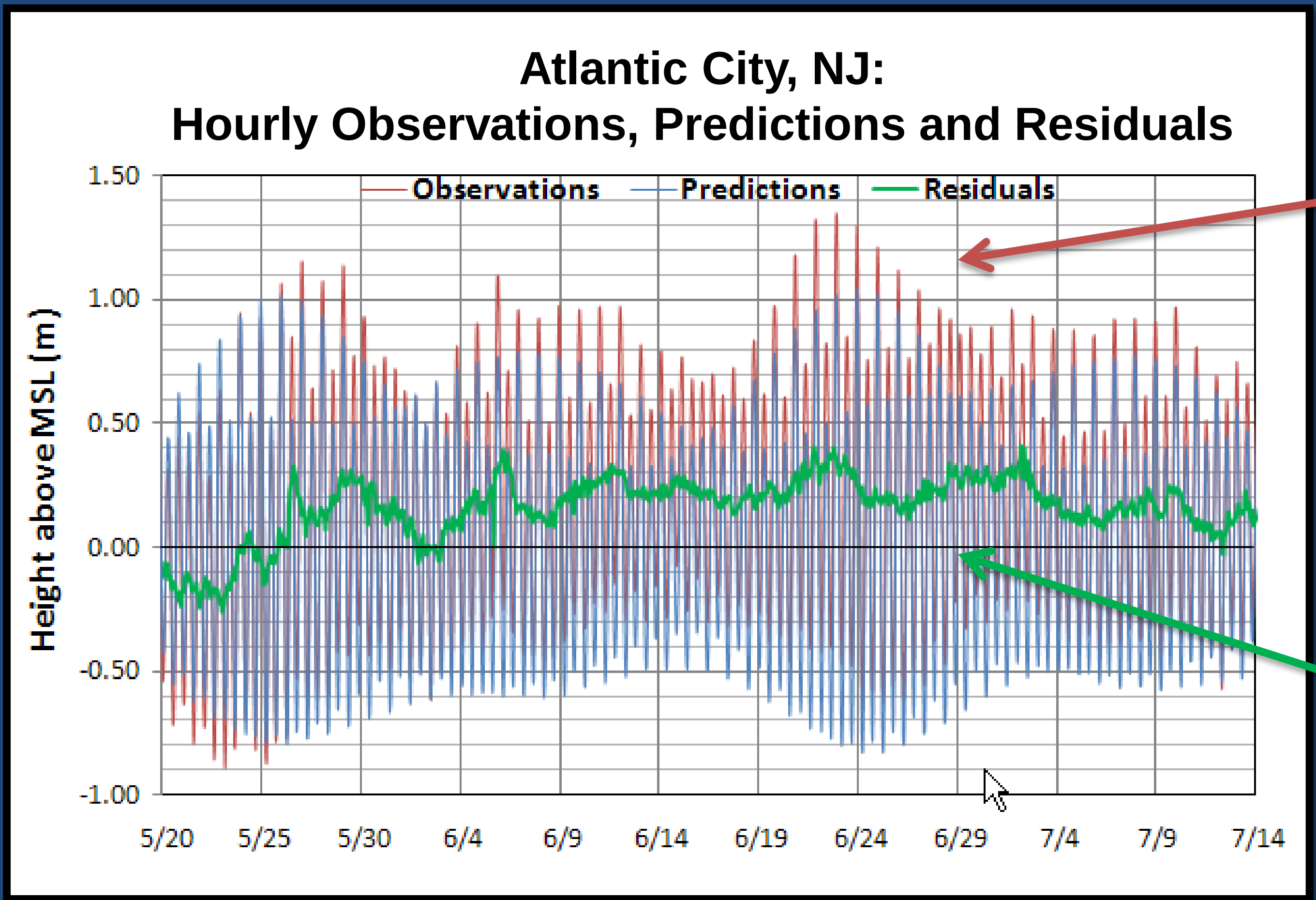
Silver Spring, Maryland
August 2009

noaa National Oceanic and Atmospheric Administration
U.S. Department Of Commerce
National Ocean Service
Center for Operational Oceanographic Products and Services

Carolina Beach, NC
June 22, 2009



Highest sea level (SL) in late June coincided with a *perigean-spring tide* that added to the observed SL anomaly and flooded many coastal areas in the absence of coastal storms normally causing these conditions.

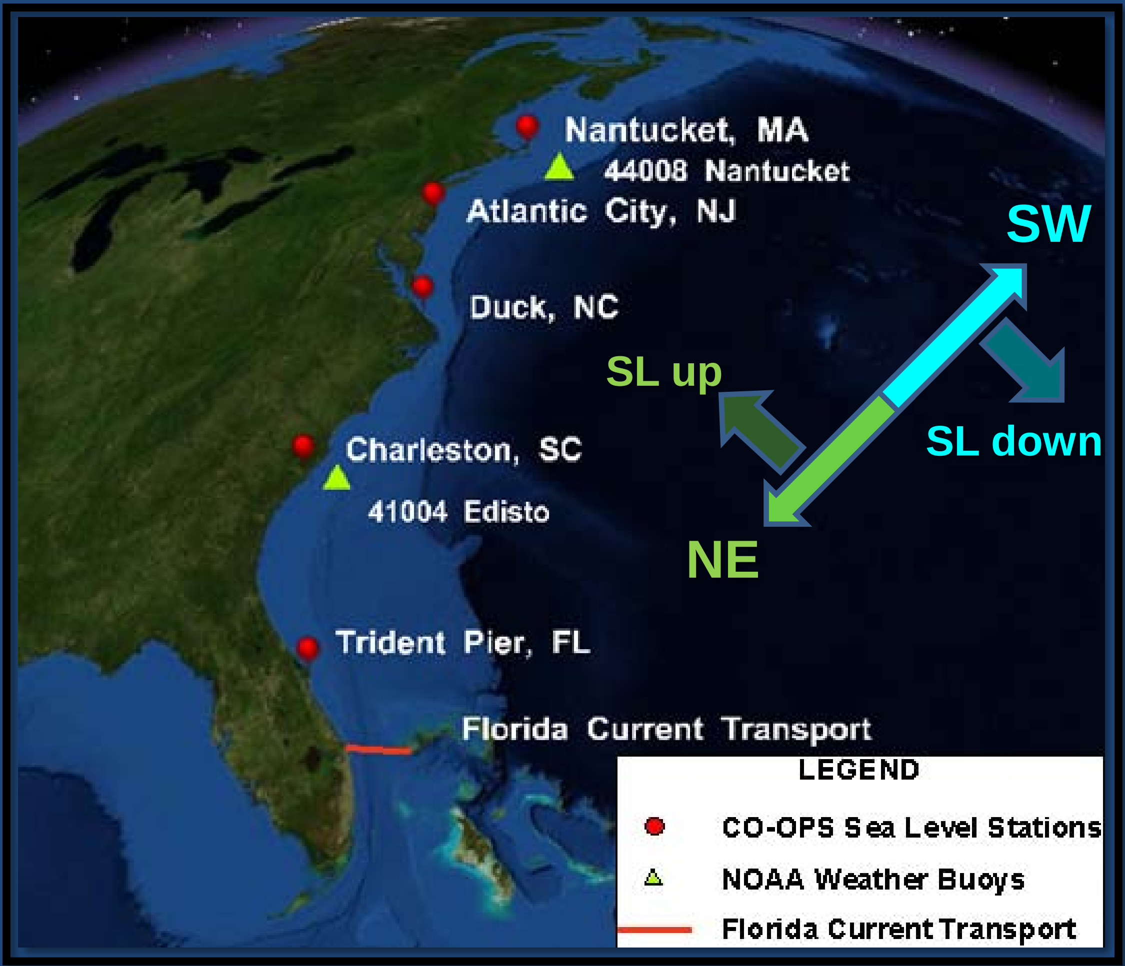


Flooding occurred 6/22-24 during *perigean-spring tide*

Tide event recorded in observations **and** in the predictions

Residuals capture underlying effects of remote forcing

DATA USED FOR ANALYSIS



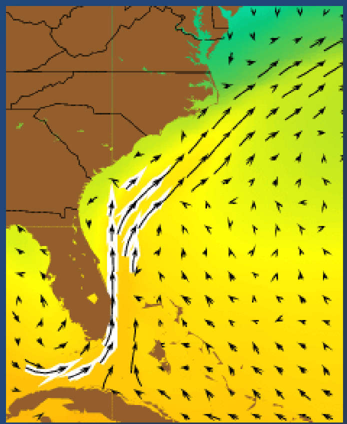
Time Series

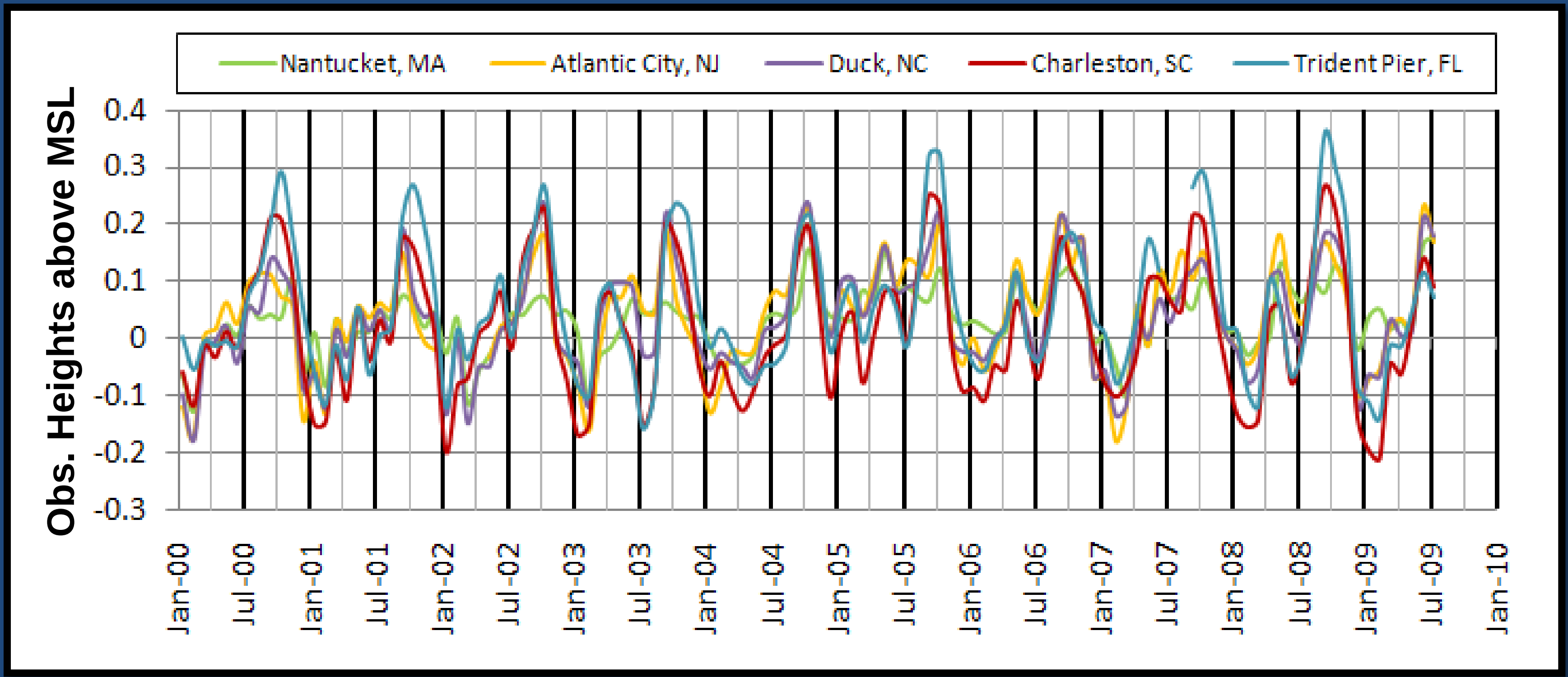
- Monthly means (i.e., June 1 – 30)
- Lowpass filtered ~ running mean

1) SL at 5 CO-OPS stations

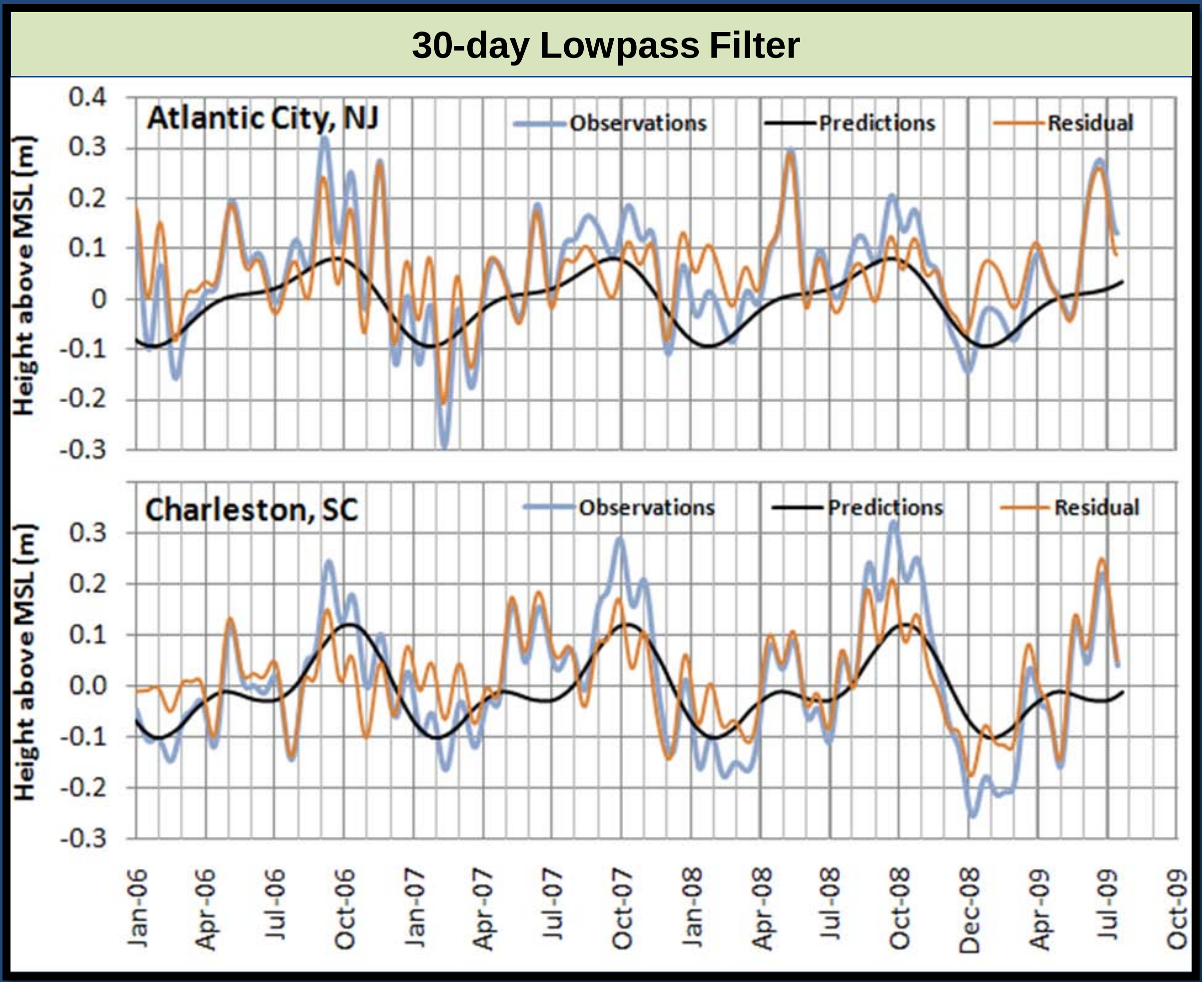
2) SW/NE'ly winds at NOAA buoys
(EKMAN Transport to right in N. hemisphere)

3) Florida Current (FC) transport
(www.aoml.noaa.gov)



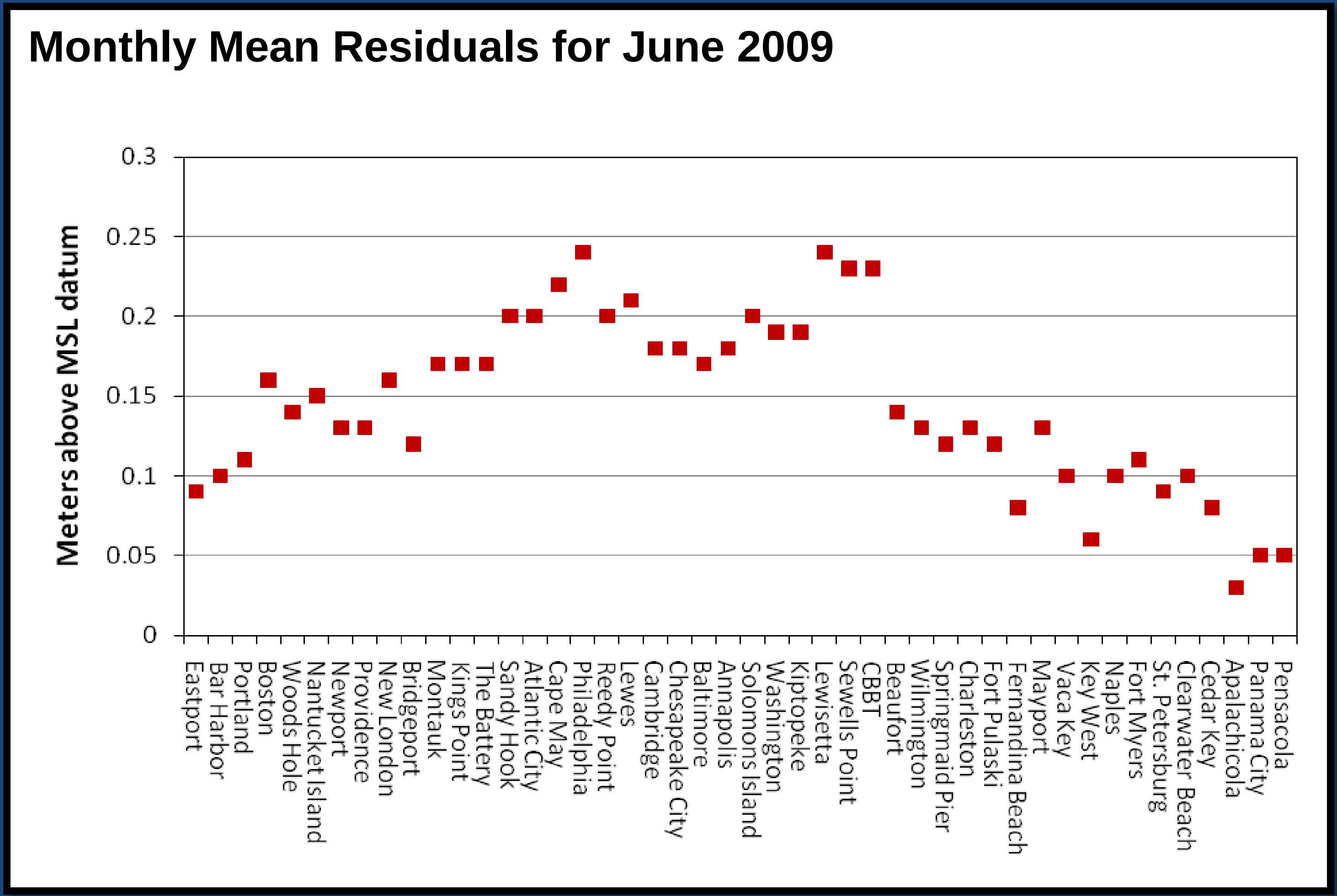


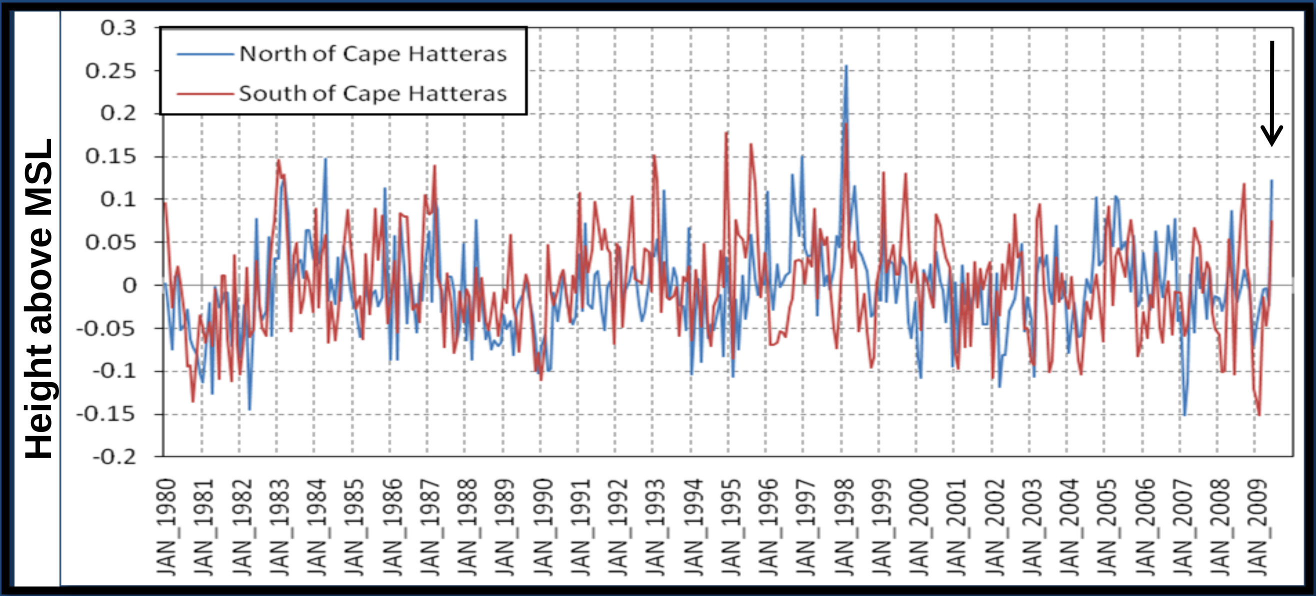
- SL peaks in late summer, lowest in late winter and smaller peak in late spring
- Magnitude of SL heights not too anomalous
- Timing is anomalous: June/July ‘09 SL ~ many historical summertime values



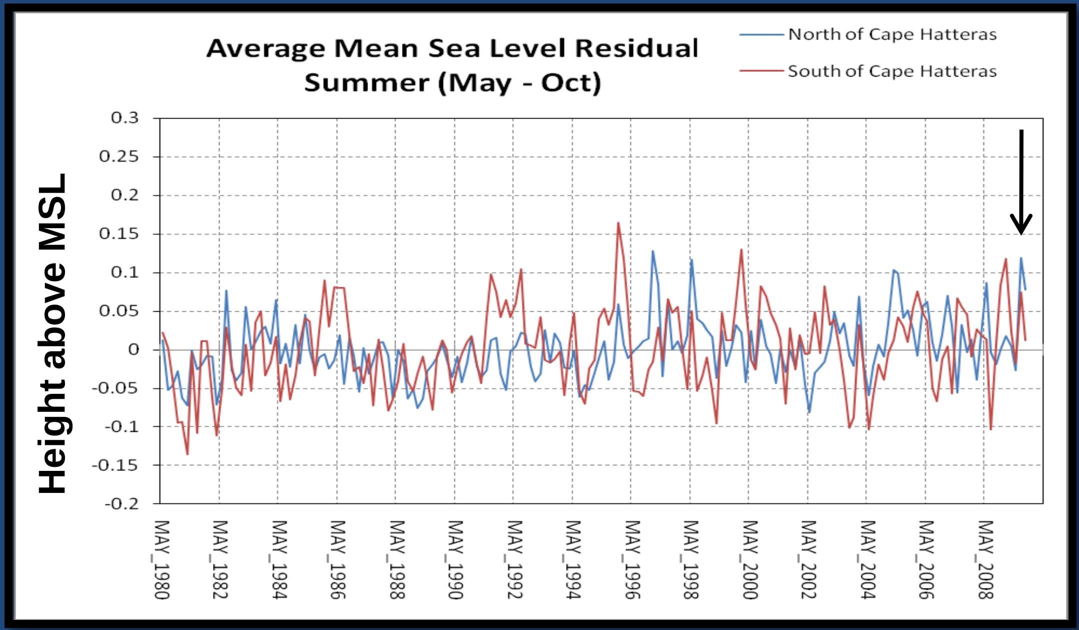
- Predictions include seasonal response of oceanic/atmospheric forcing
- Charleston SL higher Oct '07 & '08, synced predictions = smaller residuals
- June/July 2009 SL deviates from long-term mean along East Coast

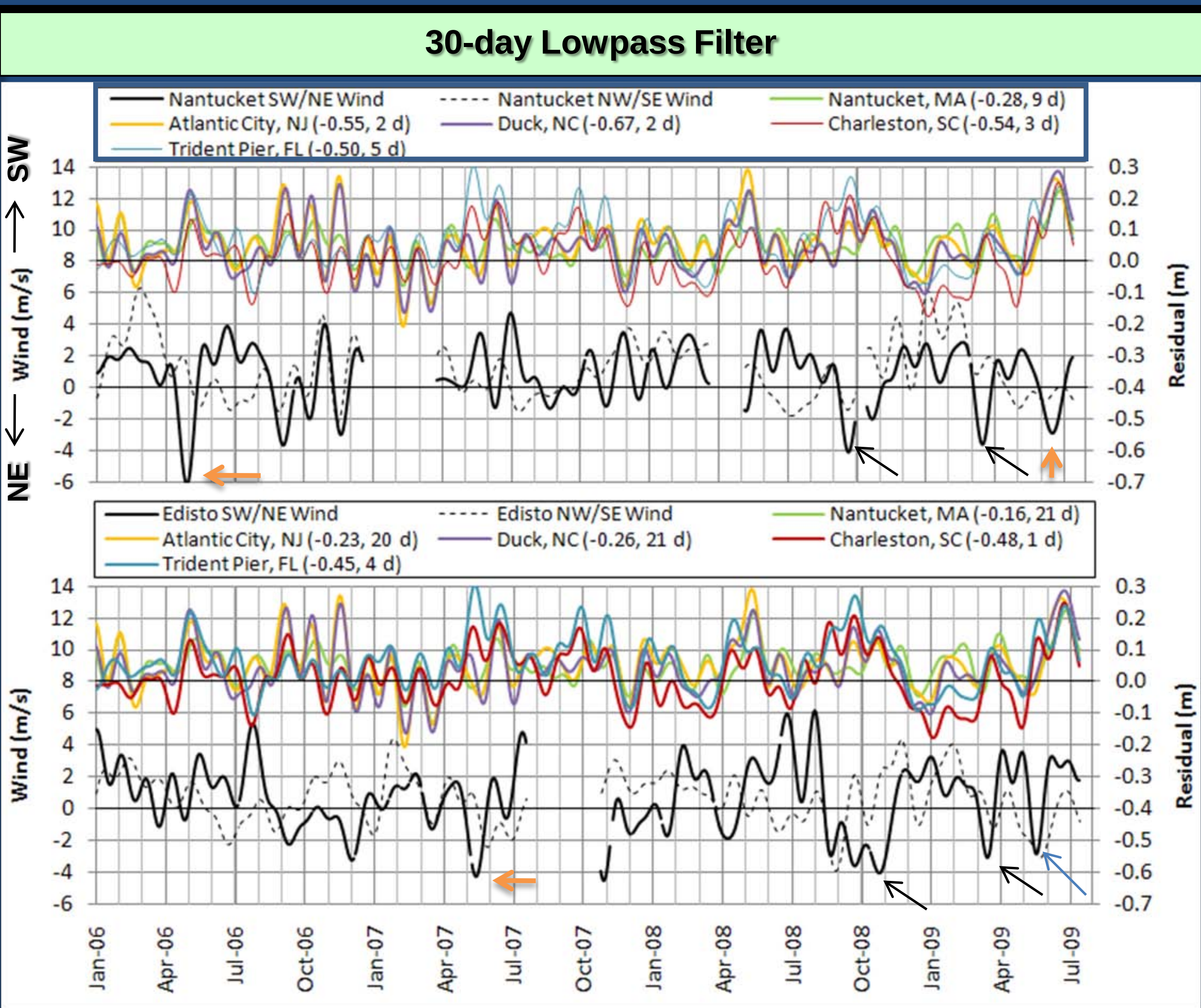
Highest Values in Mid-Atlantic Region from New Jersey to North Carolina



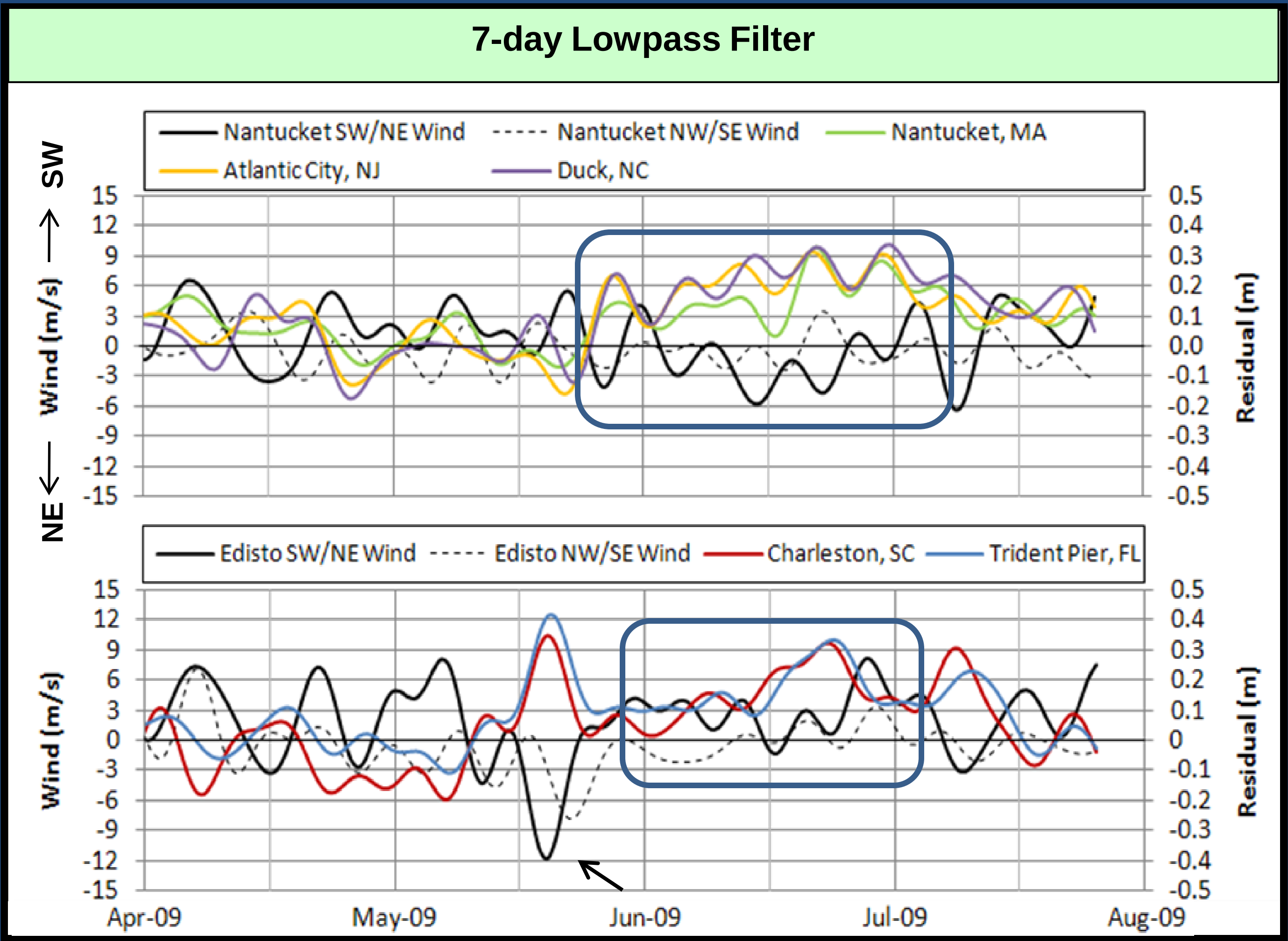


Average of June '09 SL residuals north and south of Cape Hatteras highest during a summer since 1980

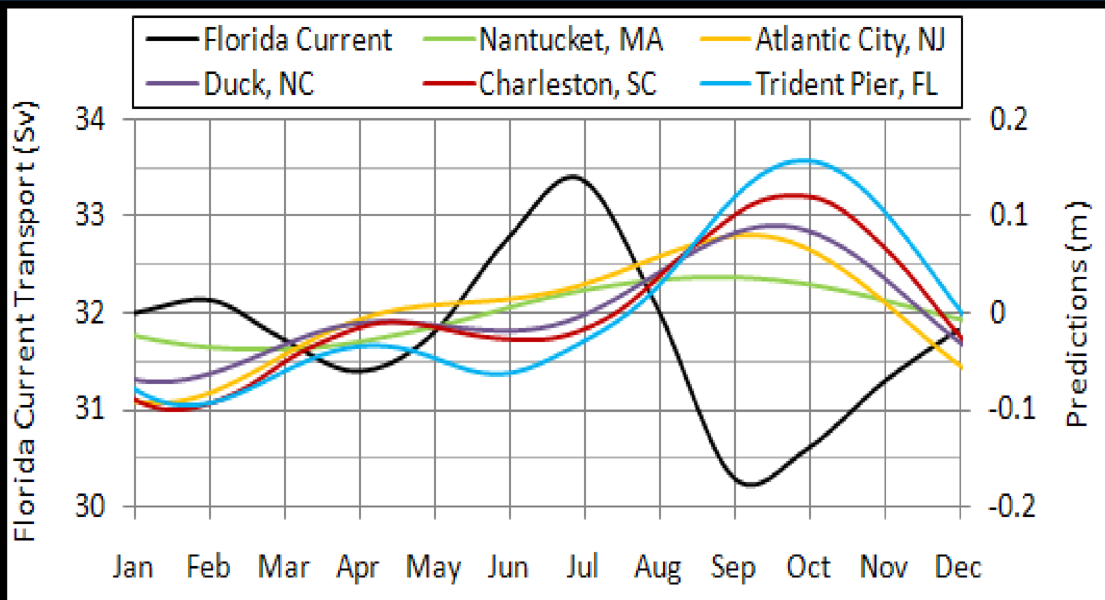


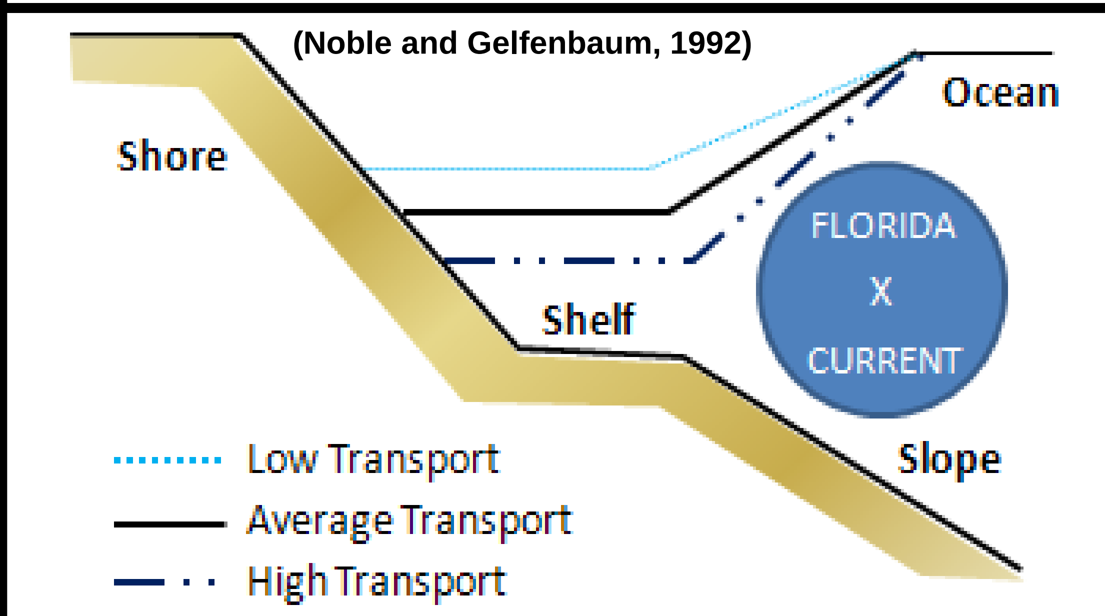


- SL correlation > w/ Nantucket wind
- Moderate NE wind (Nantucket) Jun'09, SL residuals rise
- Similar NE winds Oct '08 & Mar '09 w/ smaller SL residual (> predictions)
- <u>May '06 Nantucket & May '07 Edisto:</u> NE wind > Jun'09; Residuals < Jun'09
- NE winds at Edisto in May 2009: 5-day storm @ southern stations



- Residual SL rise north of Hatteras with NE winds
- In south, NE wind storm raises SL in mid-May
- June residual rise in south under ~ SW wind, thus other mechanism





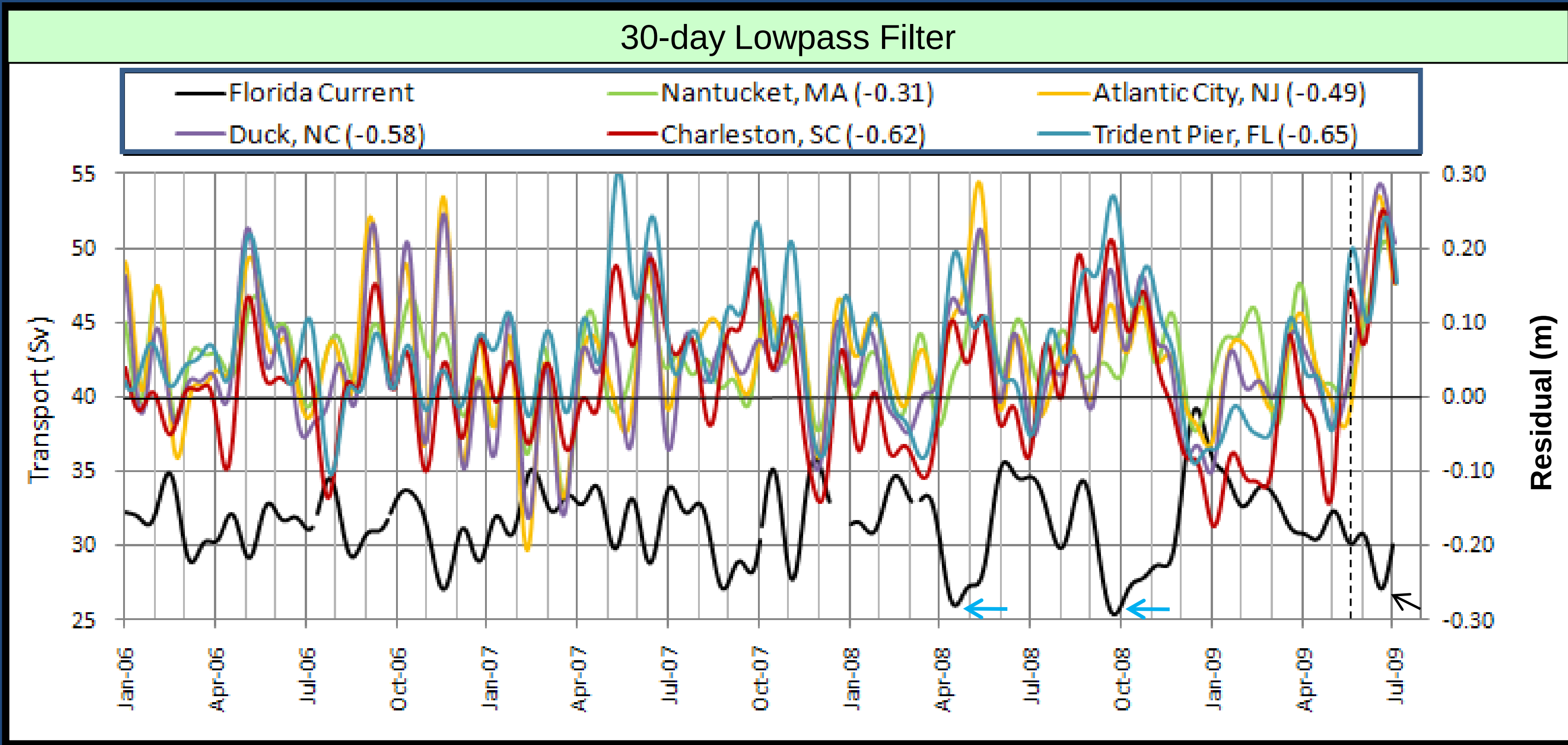
- Seasonal SL predictions & monthly mean 90-d lowpass FC transport from June 2000 – June 2009

- Inverse relationship - FC strength is inherent in SL signal

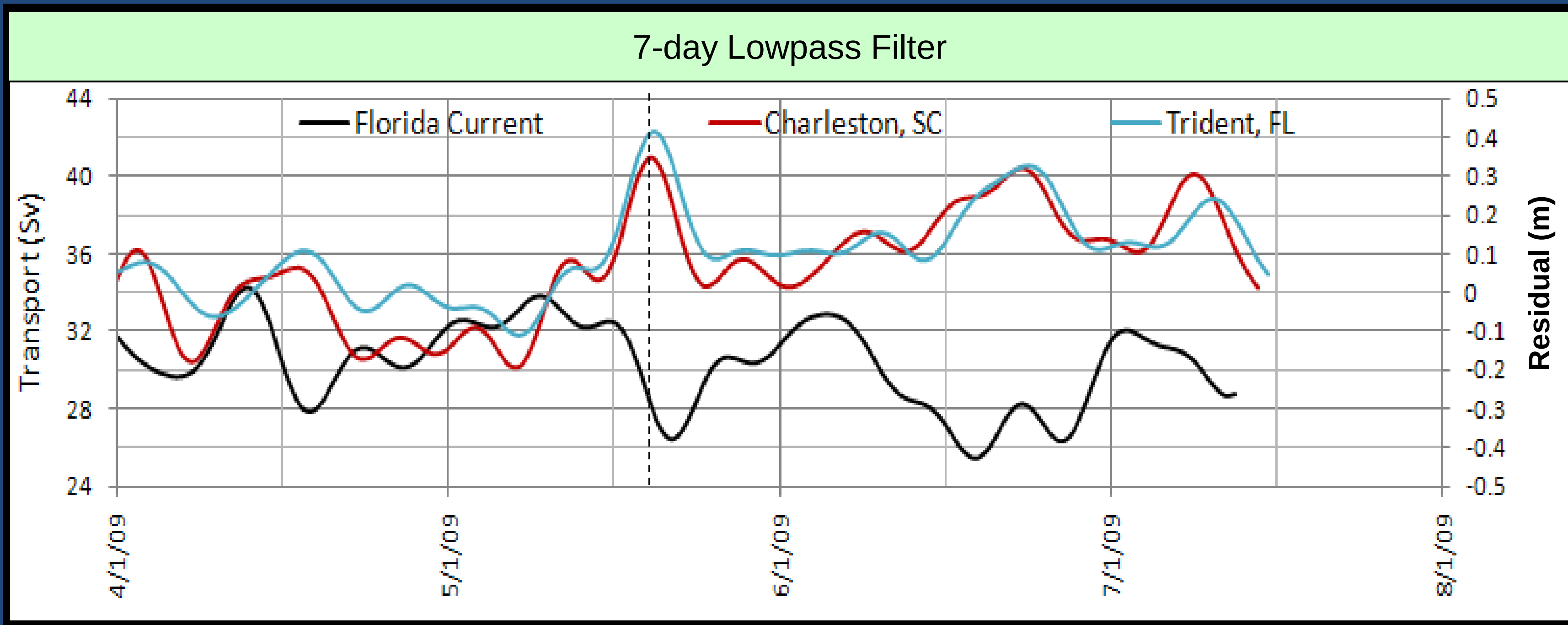
- Northward currents require eastward rise of SL (geostrophy)

- FC transport low:
  - weak cross-current gradient
  - high coastal SL

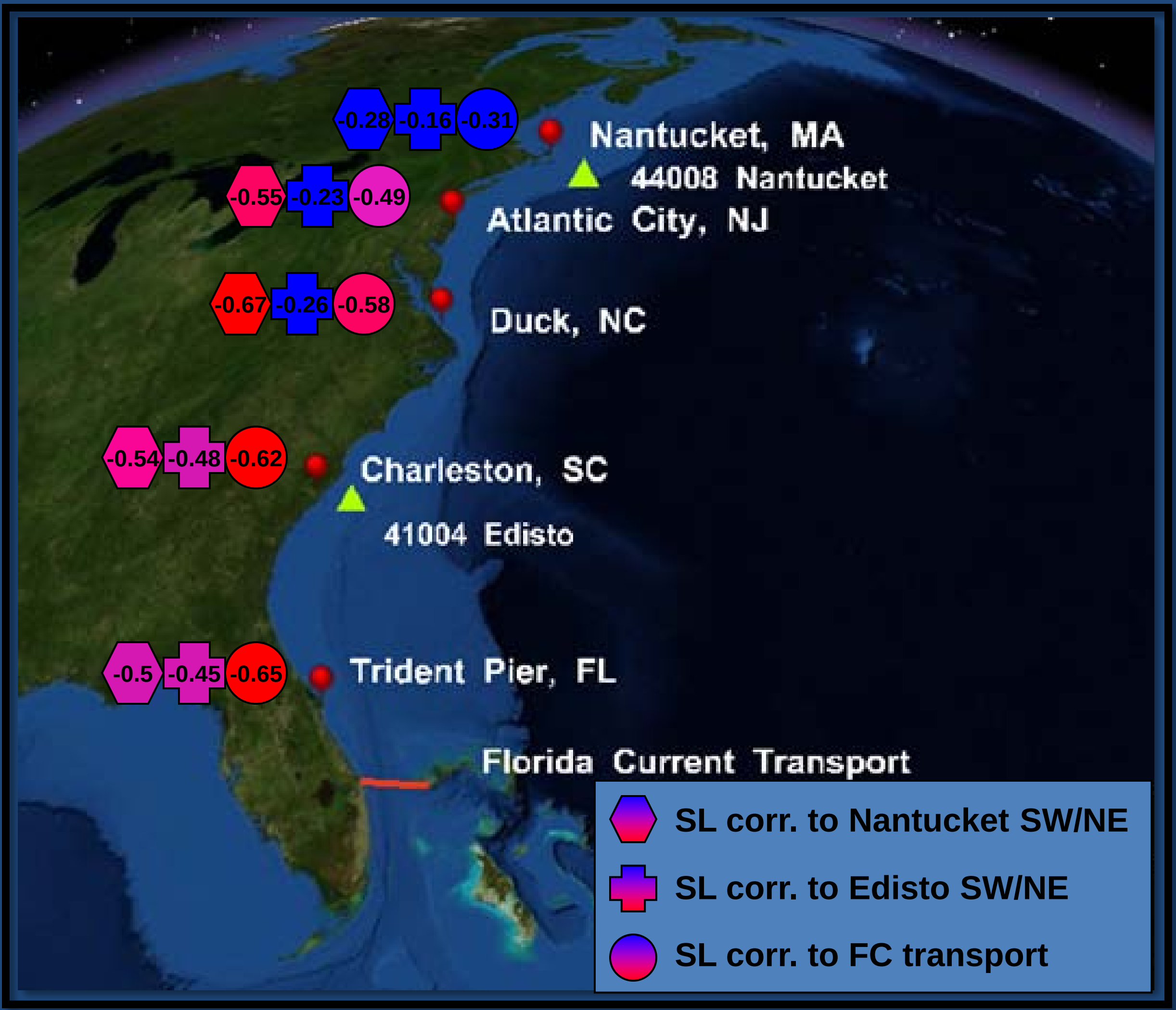
  (Opposite with high FC transport)



- Negative correlation to SL residual - lessens northward as FC moves offshore
- **FC low in Jun '09; lower Apr '08 (< NE wind) & Sep '08 (> NE wind)**
  - Overall MSL Obs. lower in Apr/May and similar in Oct 2008
  - Predictions higher in Apr and Sept '08 = smaller Residuals
- SL rise in south in May '09 w/ FC decrease - related to NE wind storm (shown earlier)



- NE winds (shown earlier) in mid-May raise SL with lagged FC response
  - Cross current gradient decreases
- Nantucket and Edisto winds ≤ 0.35 correlation to FC transport (2006-09)
  - **Winds & FC are ~independently contributing to SL response**



- Highest SL residuals from New Jersey to North Carolina
- FC transport greater affect on SL towards the south
- NE winds greater affect on SL towards the north
- Mid-Atlantic region > combination from both forcing mechanisms

JUNE – JULY 2009 SEA LEVEL ANOMALY

1. June/July '09 SL anomalous in time (residual) and space (entire East Coast)

2. NE winds & FC transport not at respective peak high or low
   - Highest values in mid-Atlantic from overlapping effect

3. What can drive inter-annual variability in regional winds and FC transport?
   - North Atlantic Oscillation: delta in Atm. P. between Azore H. & Iceland L. inversely affects trades and FC strength
   - Global meridional overturning circulation (MOC) in Atlantic

Sea Level Advisory Project

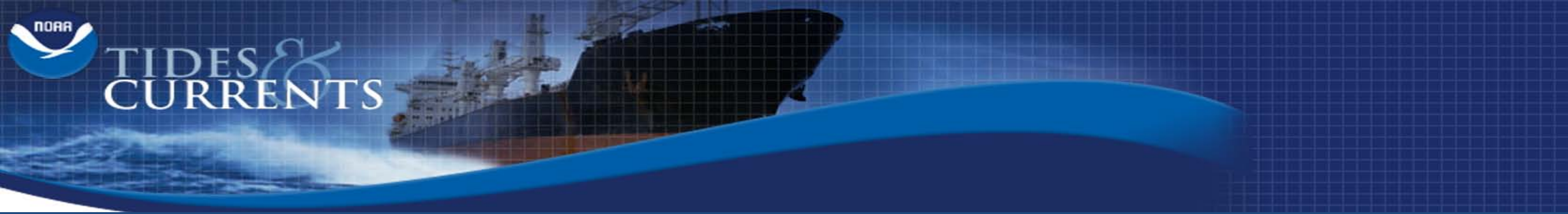
To report of high (flooding) and low water anomalies (shipping) and track climatic changes in anomaly intensity and frequency from the mean record

1. ***Define*** **SL anomaly: statistical review of historical data sets for time and space criteria**

2. ***Detect*** **anomalies: an automated scheme to track and alert**

3. ***Determine*** **physical forcing producing anomalies: identify relationships to regional winds, current patterns and other major climatic indexes**

4. ***Disseminate*** **information about events on NOAA/CO-OPS website**



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