The Science of Sea Level Rise

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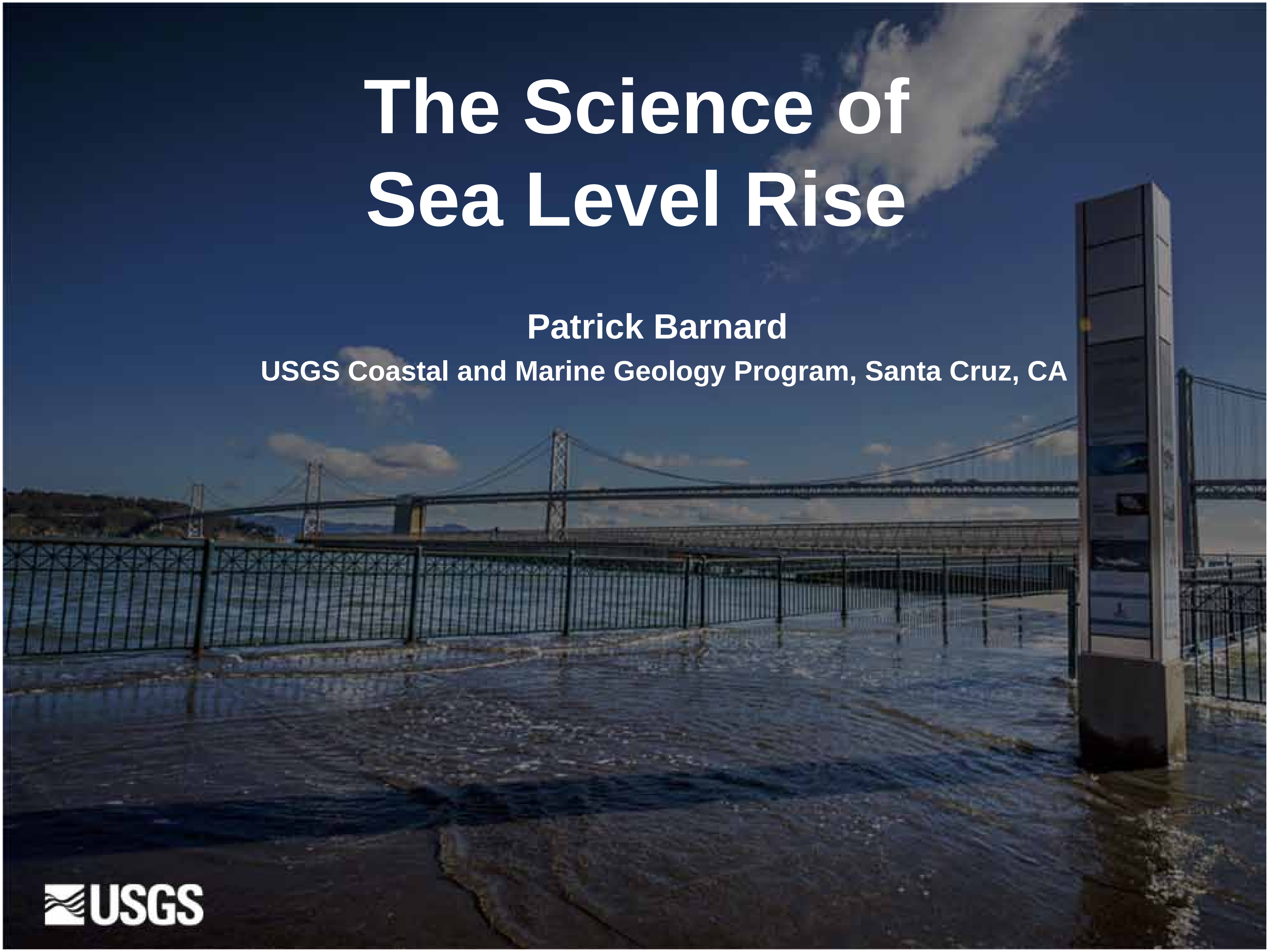

What is the problem?

- Climate change, including sea level rise, changing wave climates, and storms will place additional stresses on coastal systems worldwide
- Coastal flooding from SLR alone could displace ~200 million people by 2100
- Nationally, $1.4 trillion of coastal property could be at risk at high tide by the end of the century
- Hurricane Sandy caused $50 billion in damage
- 500,000 people, one million jobs, and $100 billion in property are threatened by climate change along the California coast over the next century
- 1982-83 El Niño storms caused more than $200 million in damage to California

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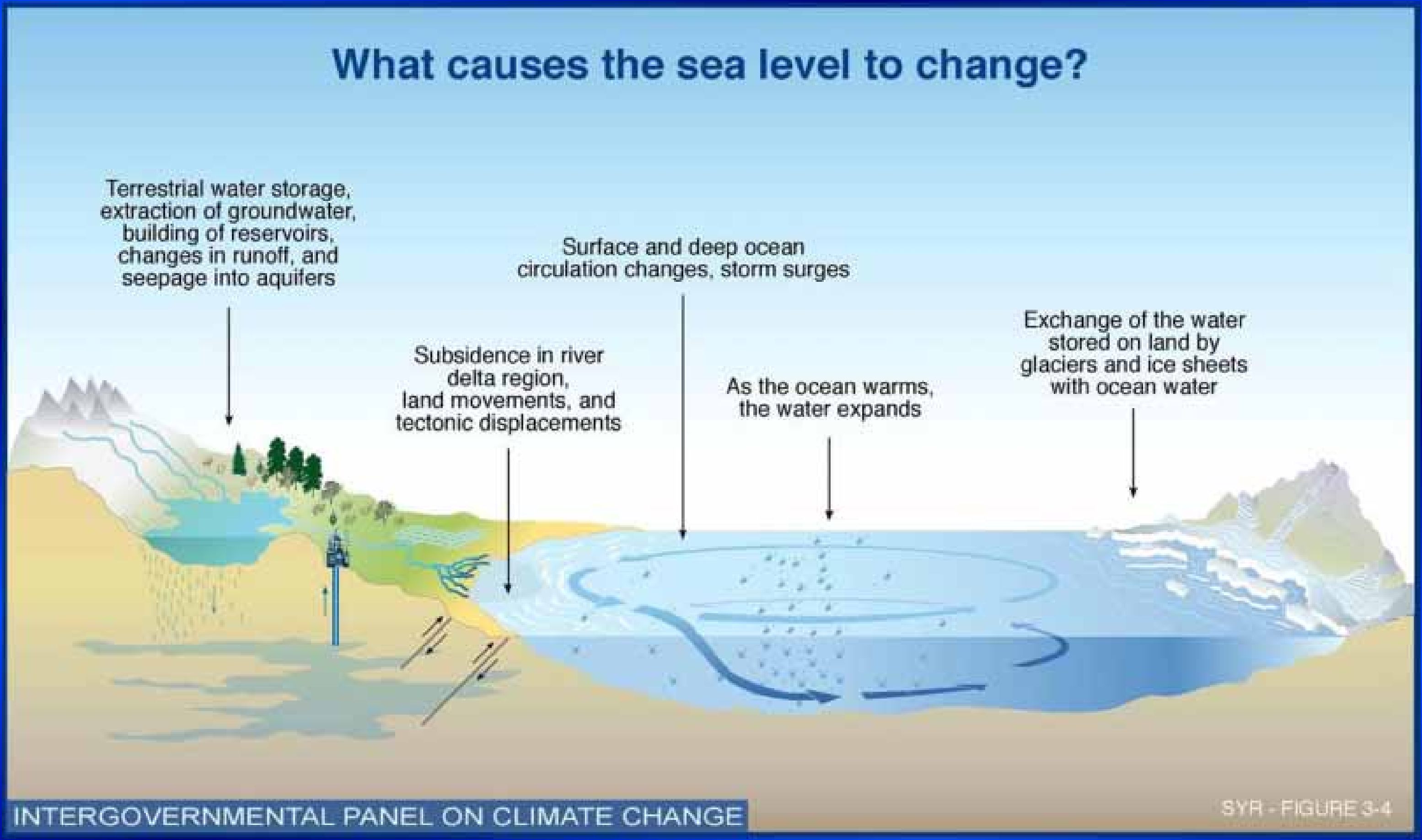
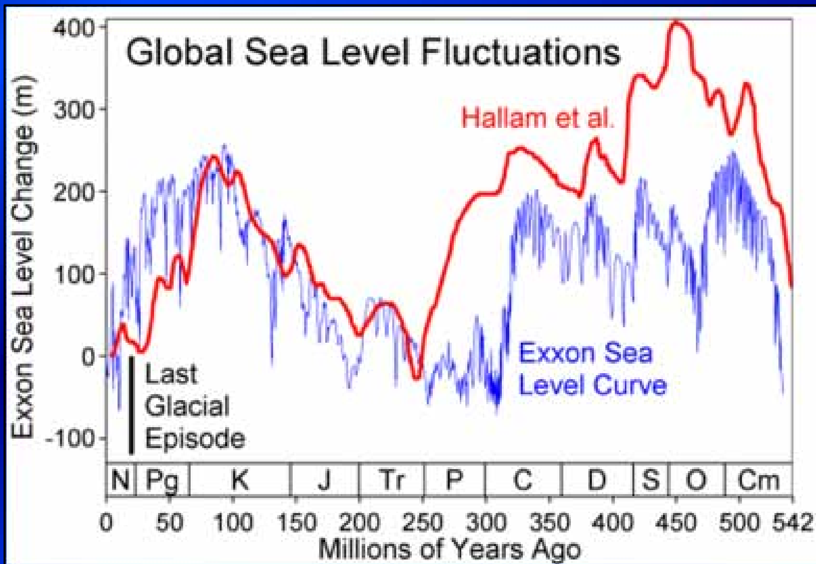
Sea Level Rise 101

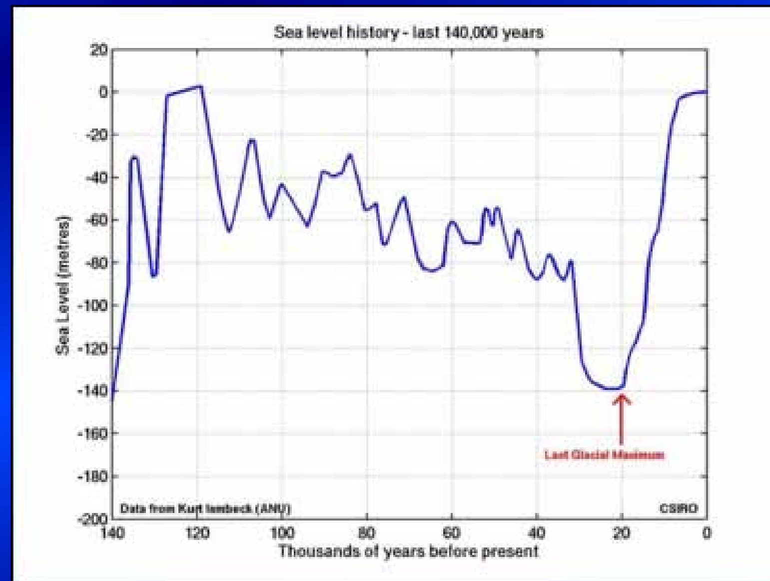


- **Other factors**
  - **Ocean basin configuration (geologic time scales)**
  - **Wind patterns (hourly to decadal)**
  - **Tidal (hourly to decadal)**
  - **Storms (hours to days)**

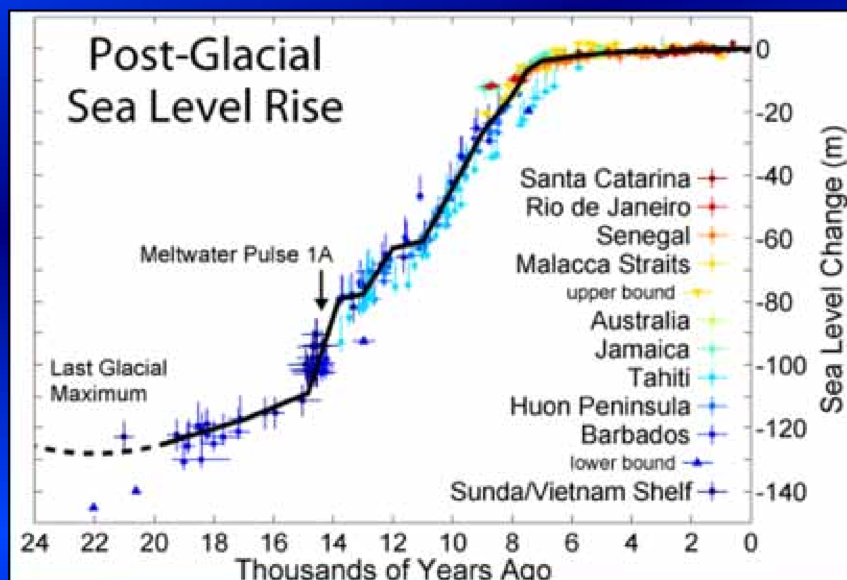
(Geologic) History of Sea Level Rise



Hallam et al. (1983), Ross & Ross (1988)



http://www.azimuthproject.org/



Fleming et al. (1998), Fleming (2000), Milne et al. (2005)

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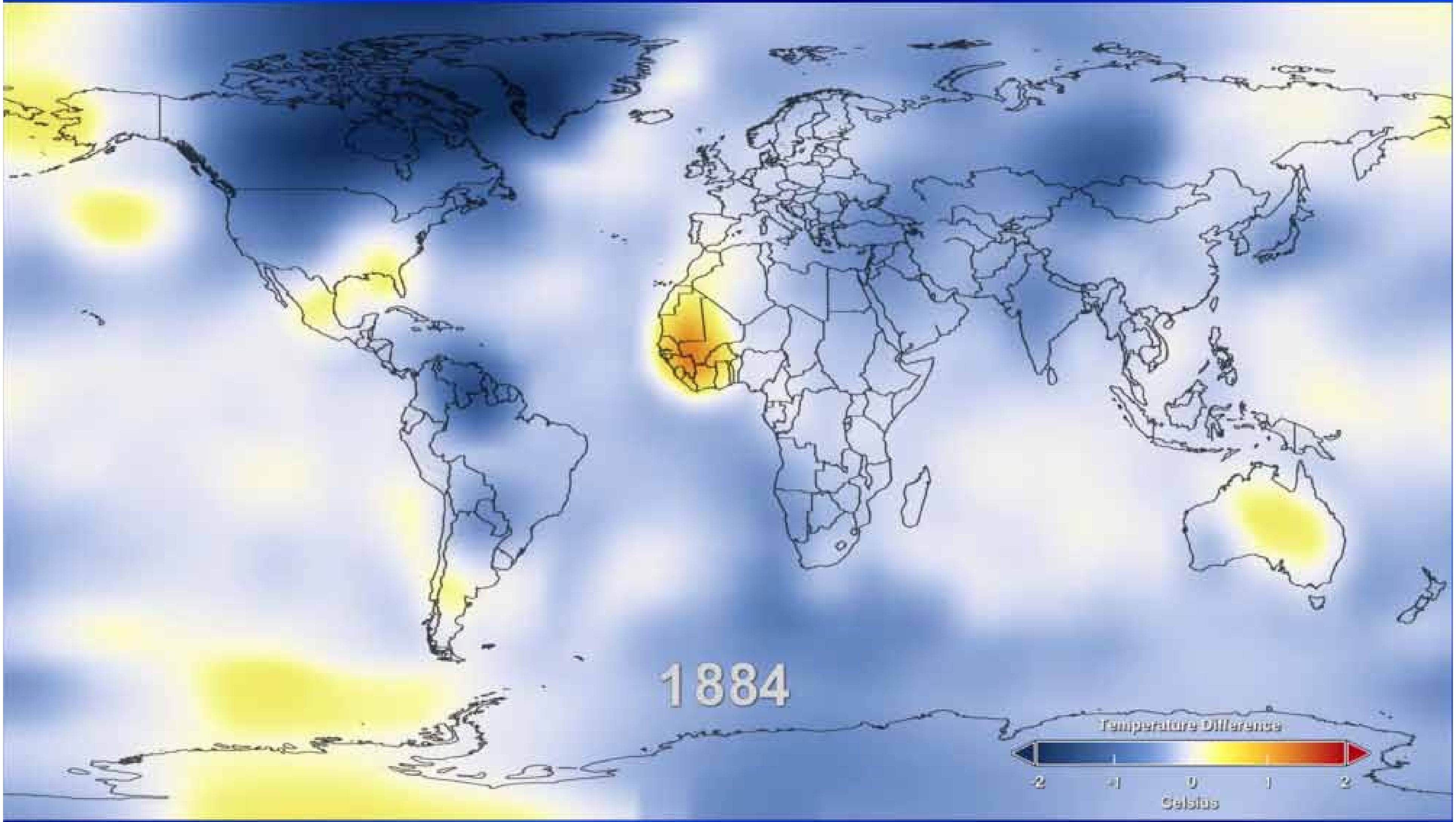
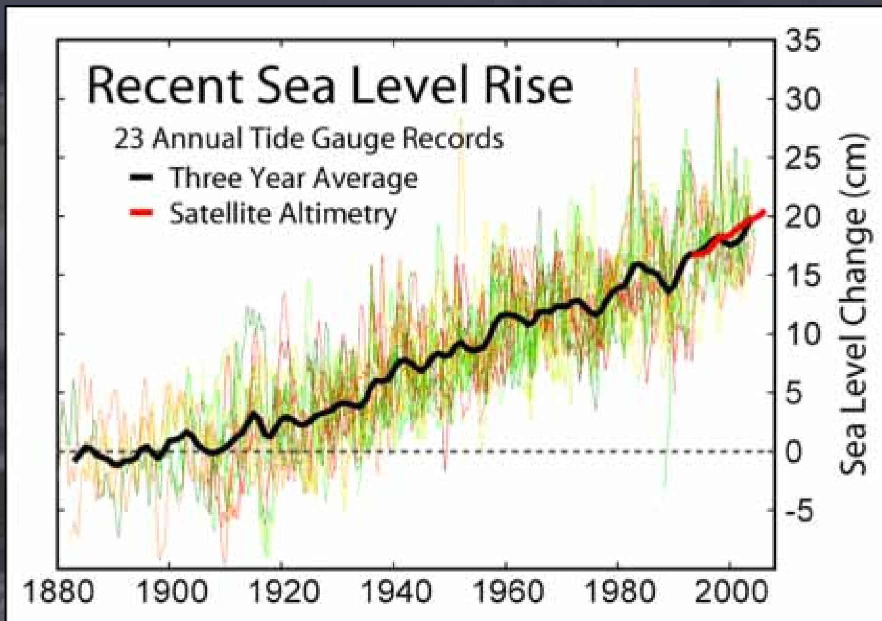
Temperature Change



NASA Goddard Institute for Space Studies
http://www.nasa.gov/multimedia/videogallery/index.html?media_id=129395671

Recent Sea Level Rise

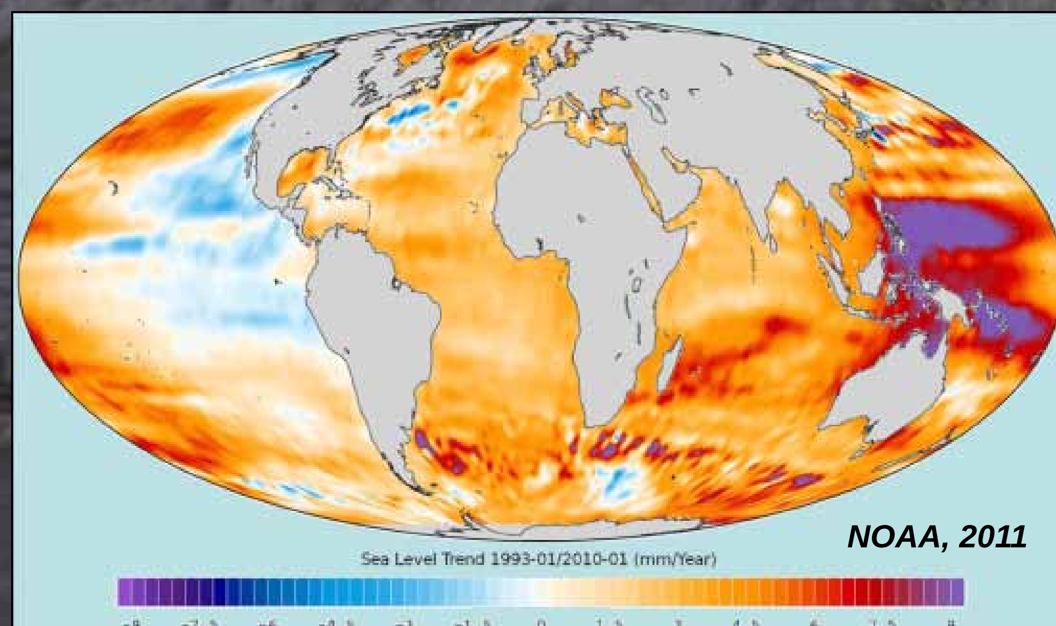


<u>Global SLR is accelerating</u>:

- **20th century = 2 mm/yr (e.g., Church et al., 2004)**
- **1993-present = 3 mm/yr (e.g., Merrifield et al. , 2009)**

<u>Regional factors:</u>

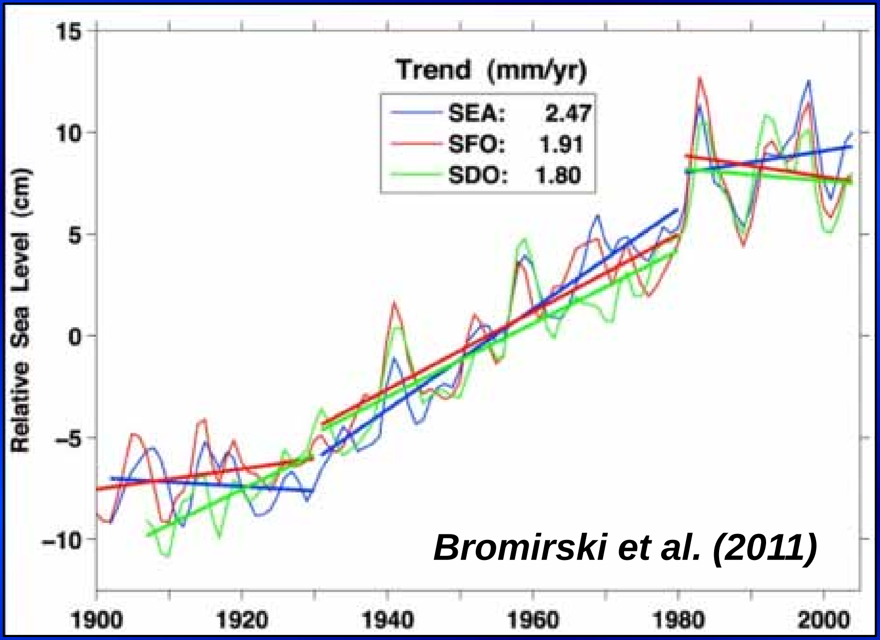
- **The global sea level rise signal is NOT spatially uniform due to variations in:**
  - **prevailing wind and ocean circulation patterns**
  - **ocean temperature and salinity ('steric effect')**
  - **gravitational forces ('glacial fingerprinting')**



NOAA, 2011

West Coast SLR

- Excellent historical record dating back to 1854 (SF), averaging ~2 mm/yr
- West Coast sea level rise has been suppressed for the last thirty years due to prevailing wind patterns in the Eastern Pacific
- The current cold phase of the PDO may continue to suppress sea levels for a decade or more, but then rates may become extremely high



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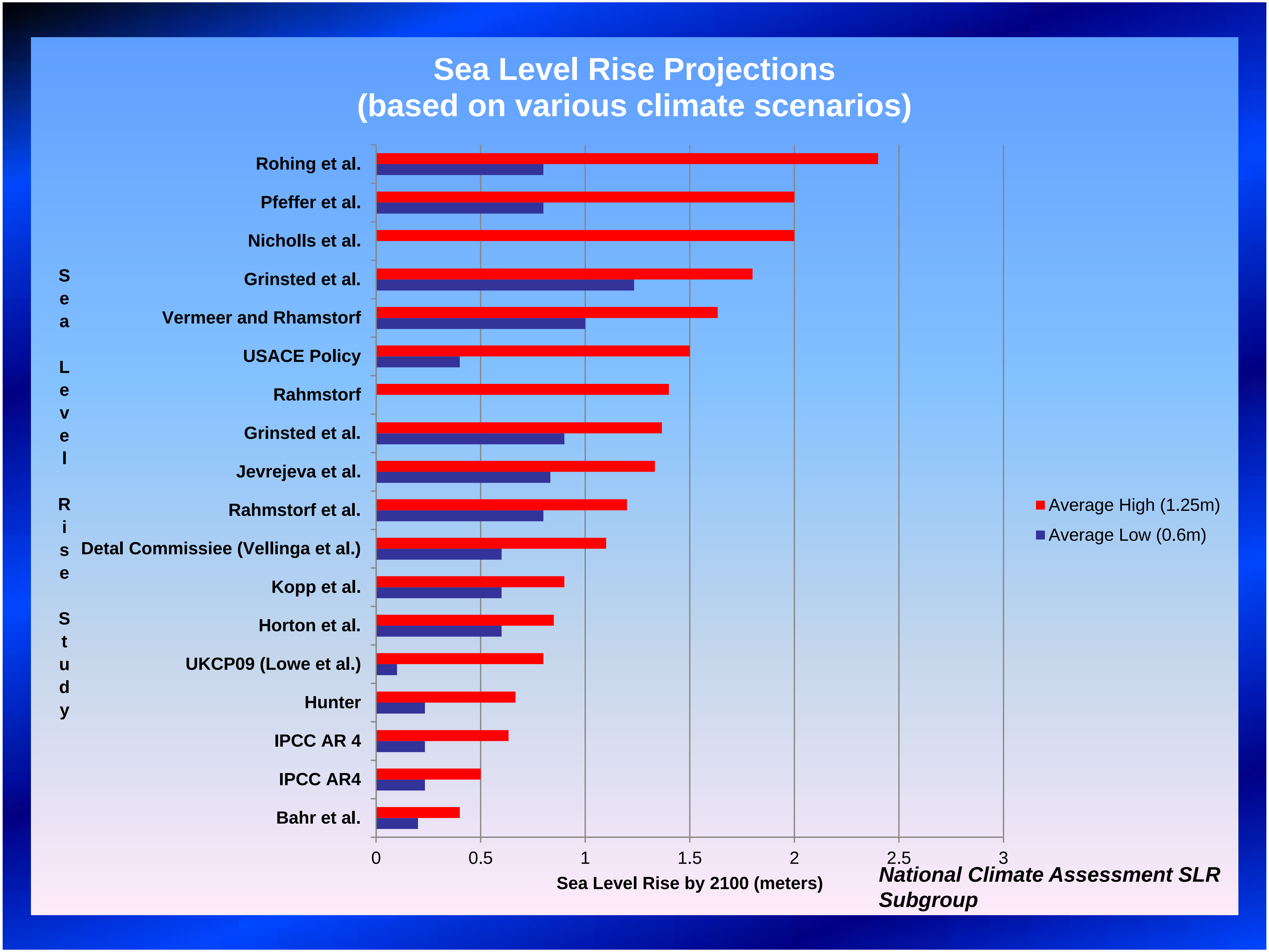
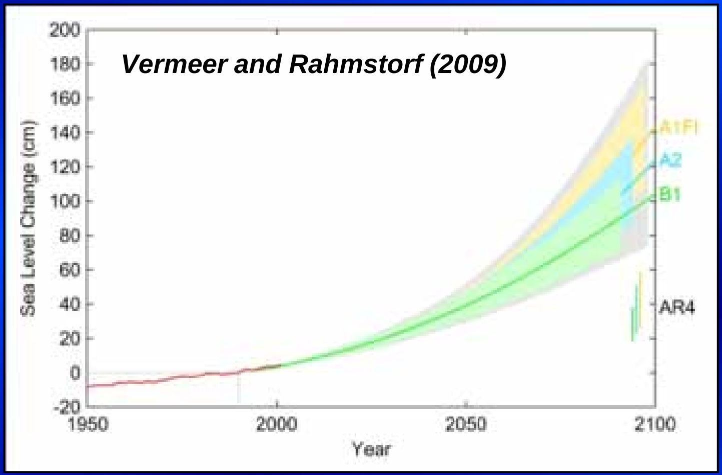
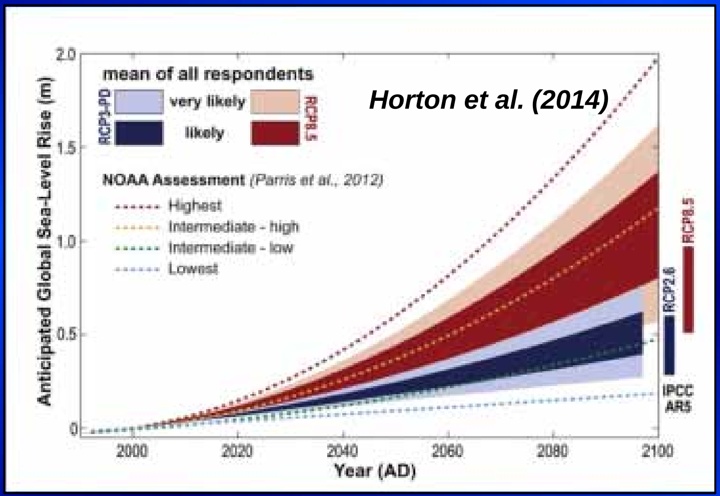

Sea Level Rise Projections
(based on various climate scenarios)
Sea Level Rise Study
Rohing et al.
Pfeffer et al.
Nicholls et al.
Grinsted et al.
Vermeer and Rhamstorf
USACE Policy
Rahmstorf
Grinsted et al.
Jevrejeva et al.
Rahmstorf et al.
Detal Commissiee (Vellinga et al.)
Kopp et al.
Horton et al.
UKCP09 (Lowe et al.)
Hunter
IPCC AR 4
IPCC AR4
Bahr et al.
0
0.5
1
1.5
2
2.5
3
Sea Level Rise by 2100 (meters)
Average High (1.25m)
Average Low (0.6m)
National Climate Assessment SLR Subgroup

Global Sea Level Projections (by 2100)

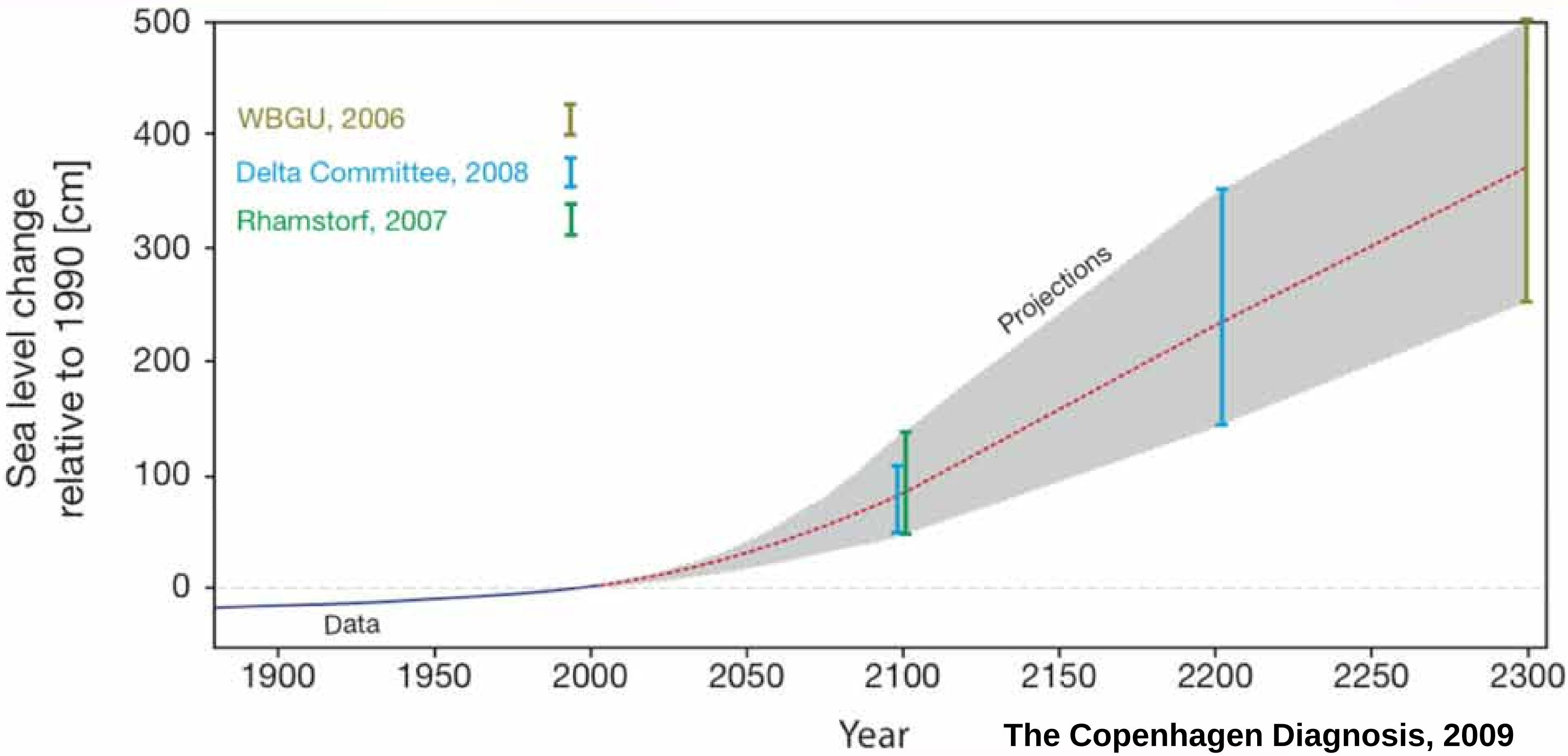
- **0.5 to 1.9 m** Rahmstorf (*Science*, 2007)/ Vermeer and Rahmstorf (*PNAS*, 2009)
  - relates sea level rise to mean surface temperature
- **0.8 to 2 m** Pfeffer et al. (*Science*, 2008)
  - constrained by observations of ice sheet dynamics
- **5 m** Hansen (*Environ. Res. Lett.*, 2007)
  - non-linearity, amplifying polar feedbacks- ‘albedo flip’
  - sea level was 75 m higher at ~50 Ma
  - at 5 Ma, sea level was ~25 m higher , but only 2-3ºC warmer (A2 emissions scenario is 4.5 ºC warmer)
  - sea level rose up to 4 m/century since LGM



- **0.26 to 0.82 m** Intergovernmental Panel on Climate Change (*IPCC*, 2014)
  - ice sheet contributions from Greenland (7 m stored) and Antarctica (60 m + stored) included (excluded in AR4: IPCC, 2007)
- **0.4 to 1.2 m** Horton et al. (*QSR*, 2014)
  - expert assessment of median range



Sea Level Rise Beyond 2100



The Copenhagen Diagnosis, 2009

- **1.8 to 5.5 m of SLR by 2500 using latest IPCC Models (2014)**

- **Sea level will rise for several centuries after stabilization (Jevrejeva et al., 2011)**

Local Water Level Factors

- **Regional factors:**
  - **Ocean circulation patterns**
  - **Glacial fingerprinting**
  - **Tectonics (large-scale)**
  - **Isostasy**

- **Local factors:**
  - **Subsidence**
  - **Local tectonic deformation**
  - **Fluvial discharge AND sediment supply changes**
  - **Development and restoration**

Poland and Ireland, 1988

Subsidence in San Jose (1933-1969)

- **Seasonal and storm impacts:**
  - **Steric effects**
  - **Waves and storm surge**
  - **River discharge**

<u>National Research Council study provides guidance on West Coast SLR, including relative land movement, ocean circulation, and storminess.</u>

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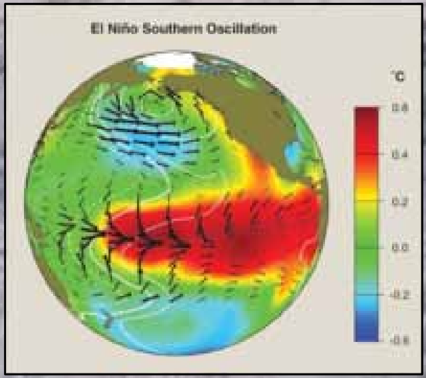
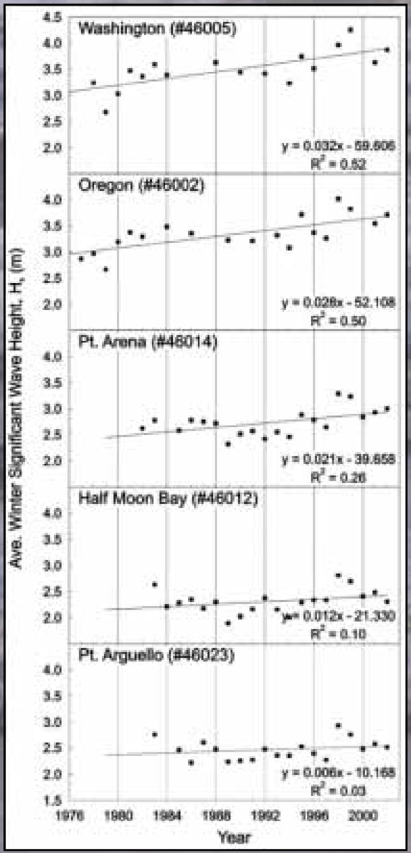
Recent Findings- Storms

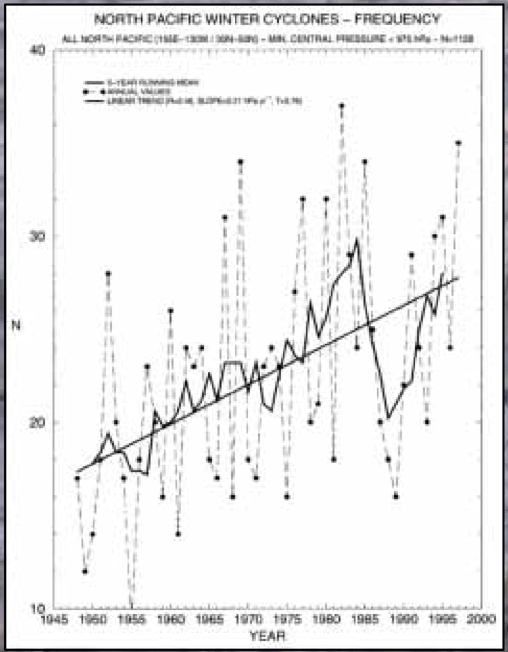
- Storms and average winter and extreme waves are getting larger and more frequent for much of U.S. West Coast
- No evidence for changes in the strength or frequency of El Niños over last ~150 years (Ray and Giese, 2012) but perhaps a shift in styles



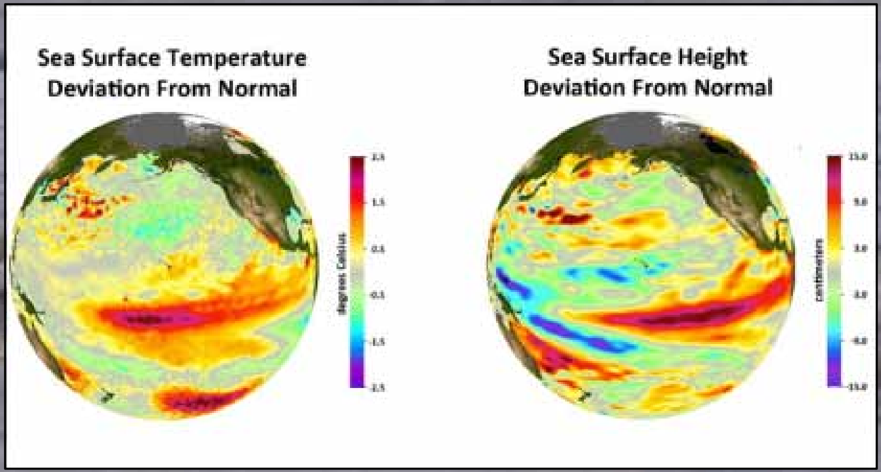
McPhaden et al. (2006)



Allan and Komar (2006)



Graham and Diaz (2001)



Lee and McPhaden (2010)

Projections for San Francisco Area

SLR for San Francisco (NRC, 2012)

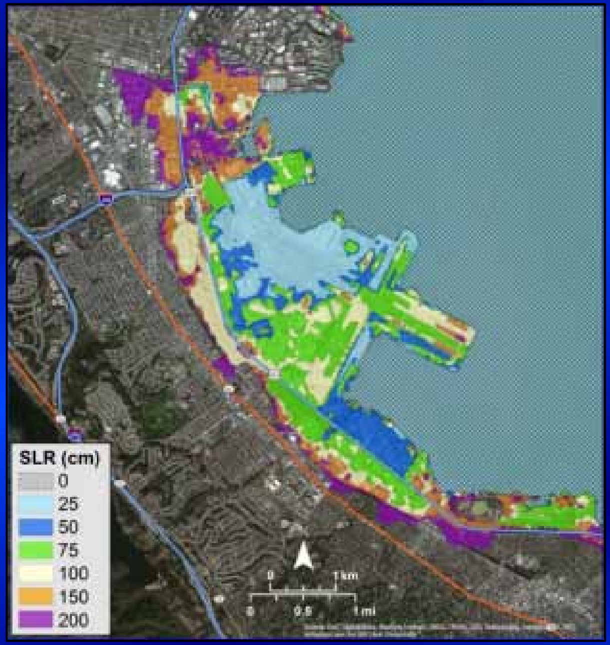
-28 cm of sea level rise by 2050 (range 12-61 cm)
-92 cm of sea level rise by 2100 (range 42-166 cm)

Storms for Northern California

-No significant changes in storms, wave height
-ENSO projections vary widely

*****Net effect*****

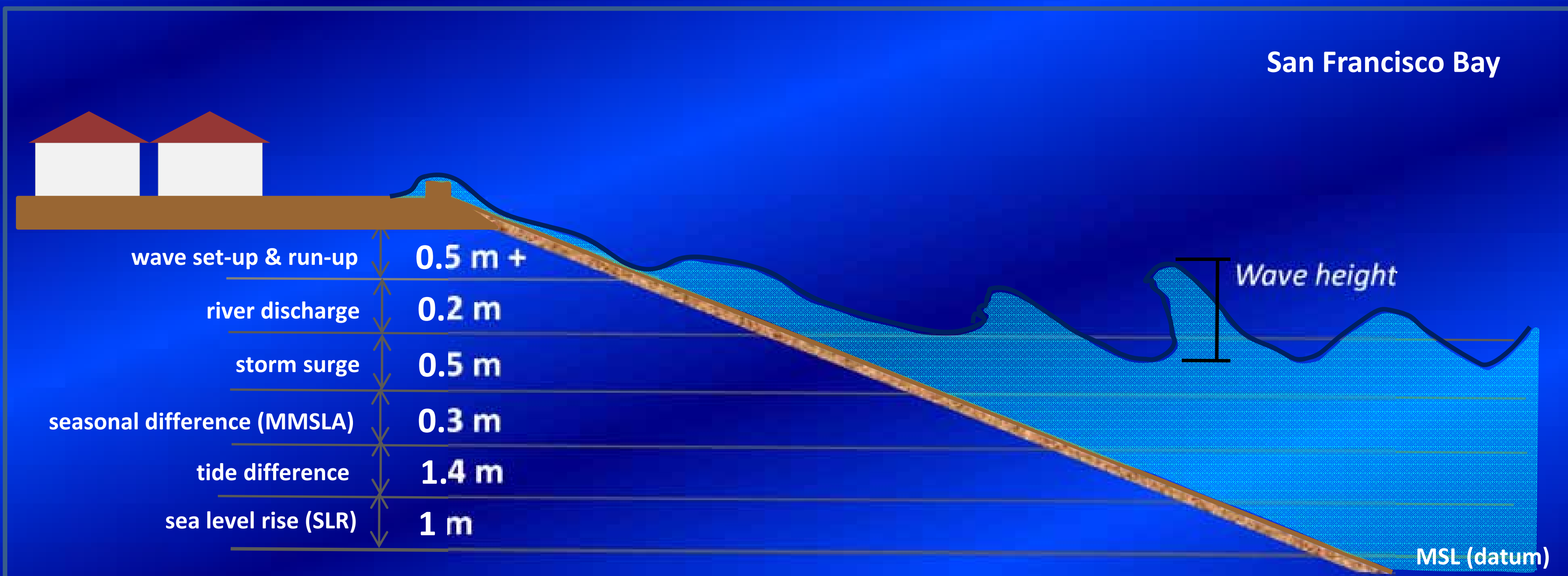
-Today's 100-year coastal water level event is projected to occur every 1-5 years by 2050 for much of California
-Greatest impacts on low-lying coastal areas (e.g., Stinson Beach, Tomales Bay, San Francisco Bay)



SF Bay Coastal Flood Contributions

Total Water Level = SLR + tides + MMSLA + waves + storm surge + river discharge

Largest in:	*South Bay*	*Central and South Bay*	*South Bay and San Pablo Bay*	*Suisun Bay*



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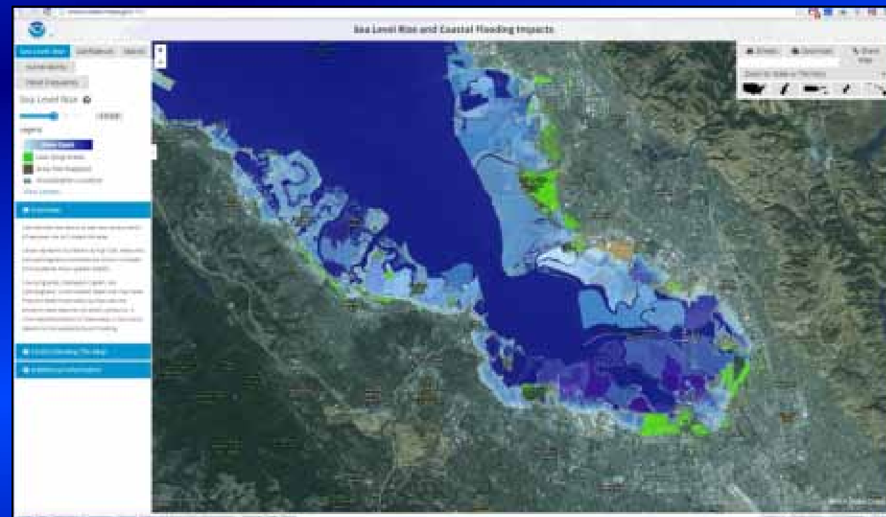
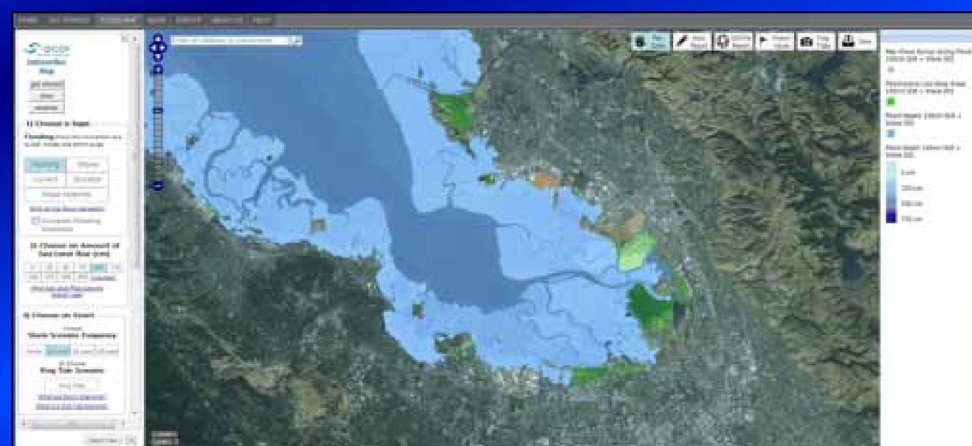
Coastal Vulnerability Approaches

- **STATIC: NOAA SLR Viewer**
  - –Passive model, hydrological connectivity
  - –Tides only (MHHW)
  - –Excellent elevation data, datum control
  - –Wetland migration model, socioeconomic impacts
  - –'1st order screening tool'



http://www.coast.noaa.gov/slr/

- **DYNAMIC: CoSMoS (also ART Project, FEMA CCAMP)**
  - –GCM ensemble forcing
  - –Includes wind, waves, sediment transport, fluvial discharge, and vertical land movement rates
  - –Range of SLR and storm scenarios
  - –Flooding extent explicitly modeled, hydrological connectivity



Our Coast Our Future: *www.prbo.org/ocof*

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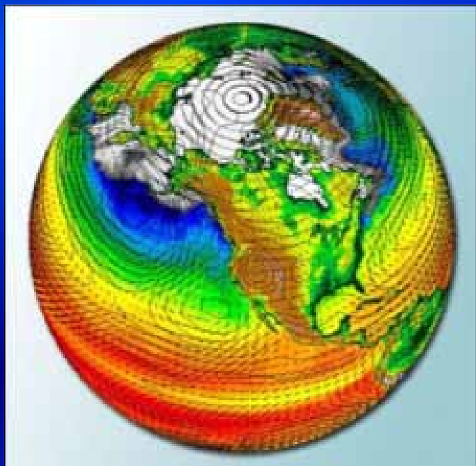
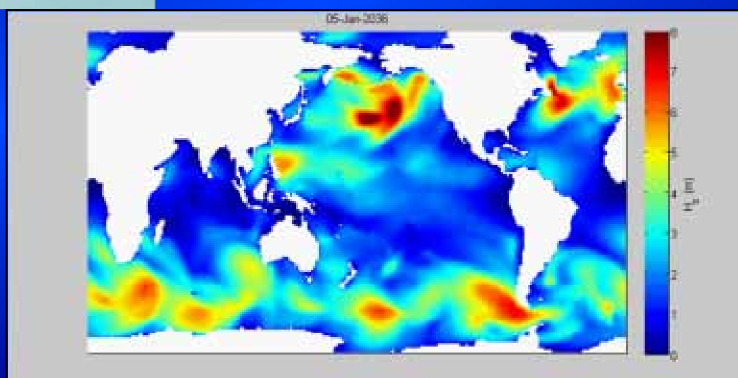
Identifying Future Risk with CoSMoS



1. Global forcing using the latest climate models



2. Drives global and regional wind/wave models

3. Scaled down to local hazards projections

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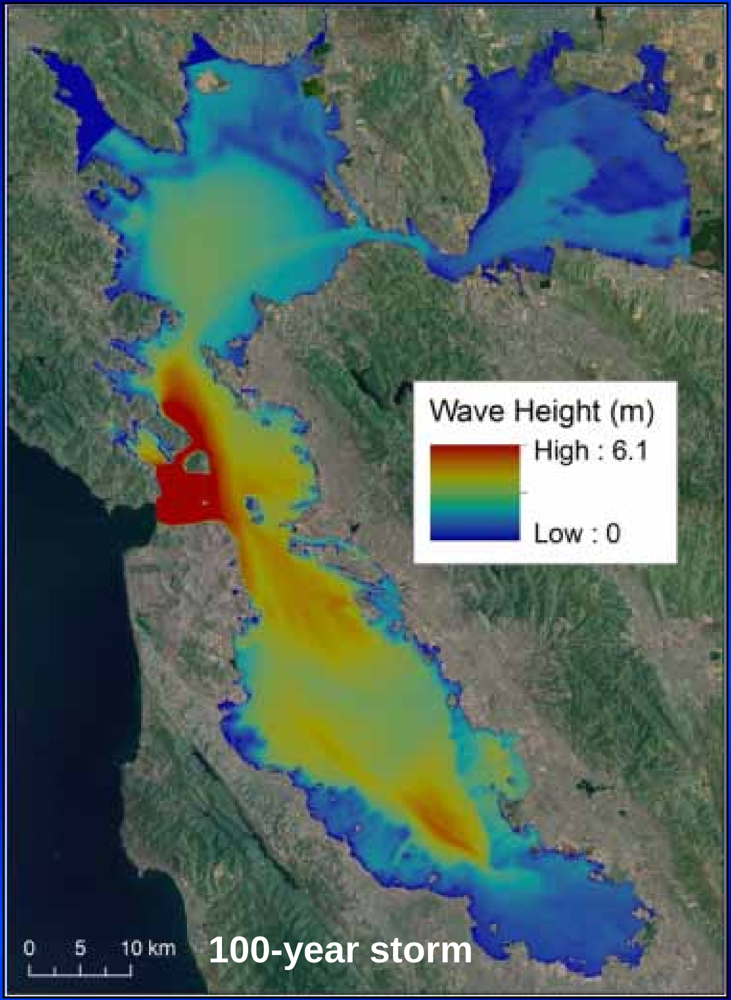
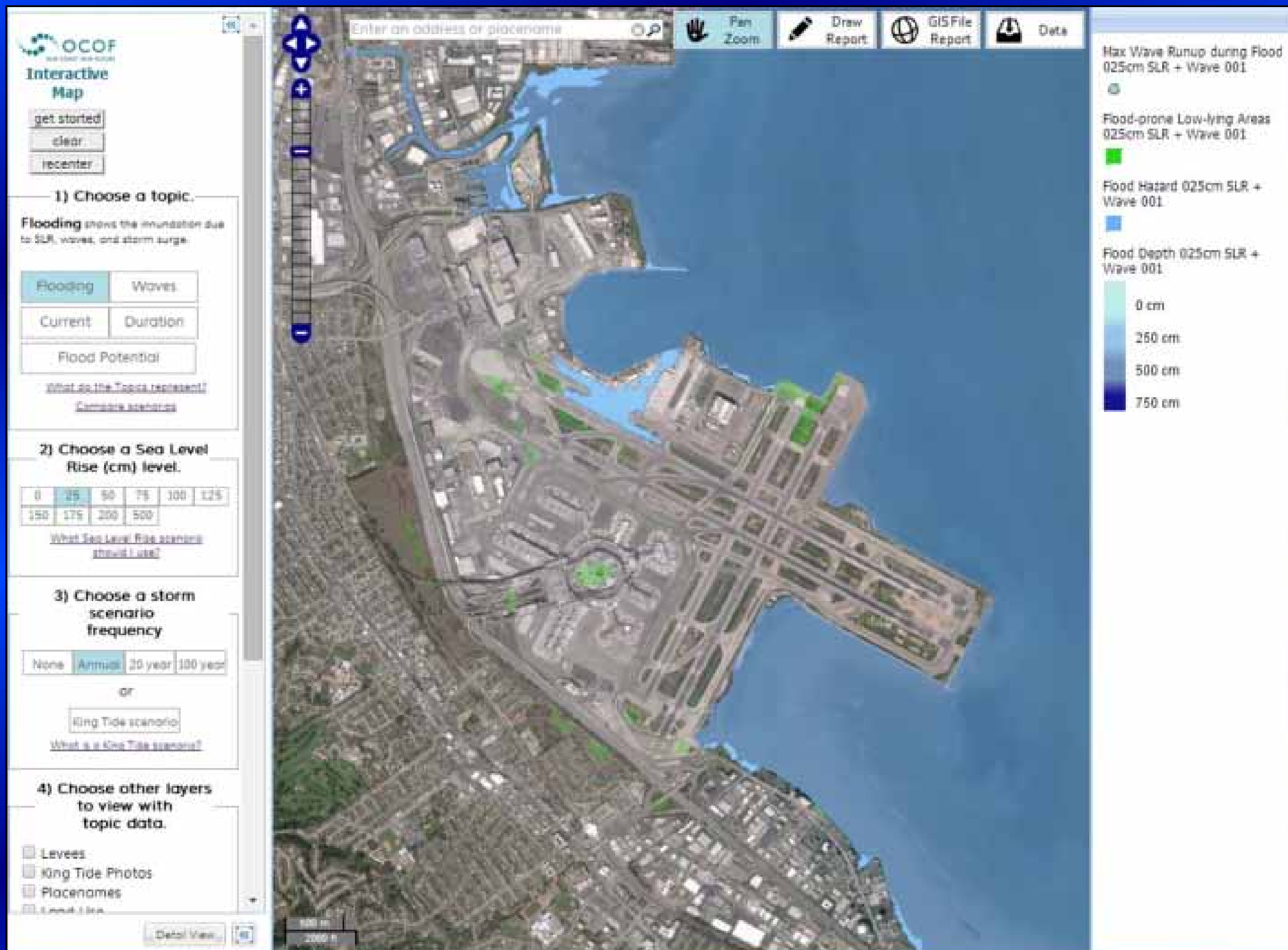
CoSMoS SF Bay

- **In-bay generated waves and outer coast swell penetration**
- **River discharge, incl. 21st century delta discharge projections**
- **Hydrological connectivity**
- **Levees (100s of km)**
- **Vertical land motion, incl. projections of tidal marsh accretion and land uplift/subsidence**



Flooding



Our Coast Our Future
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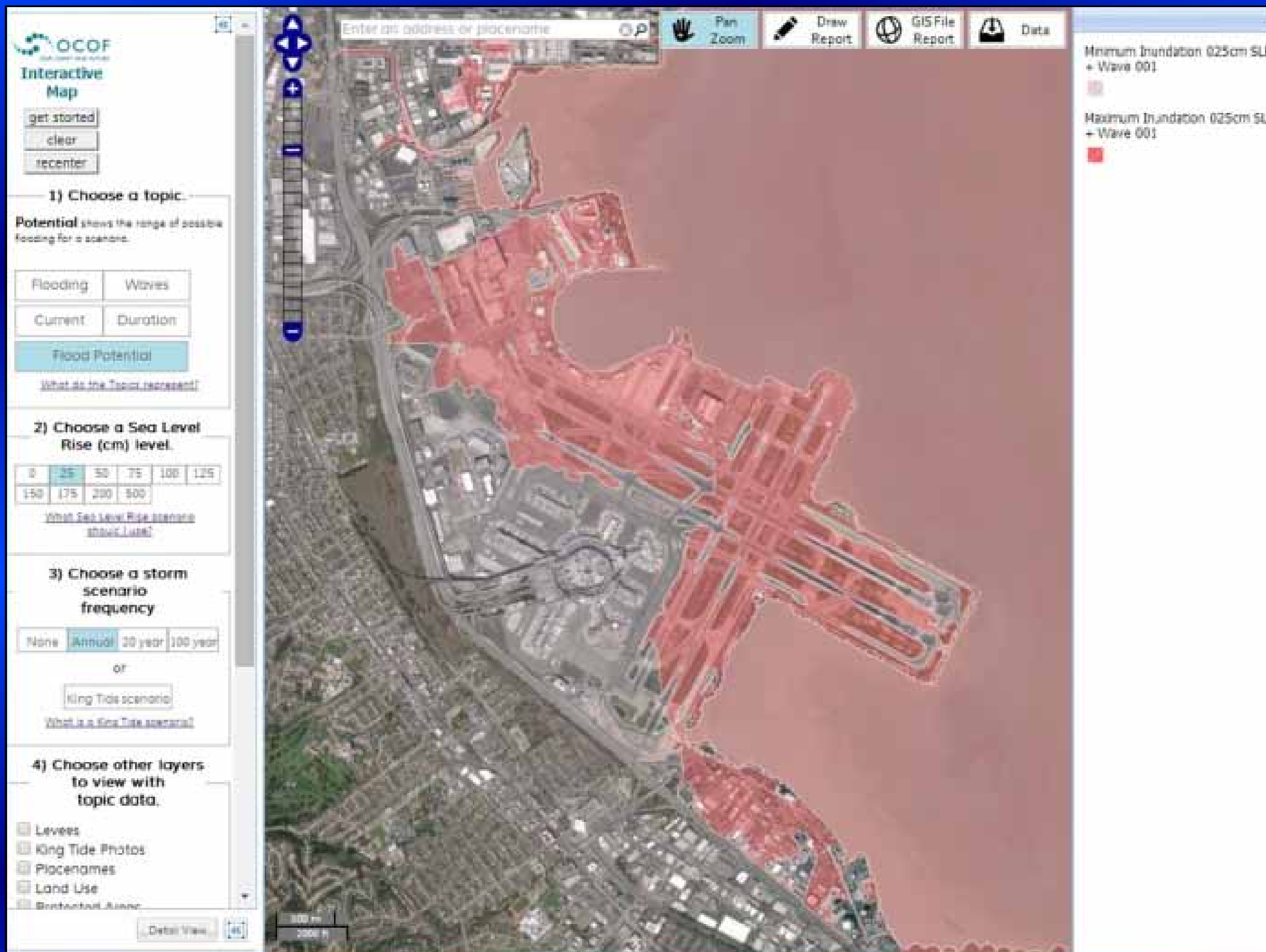
science for a changing world

CoSMoS Coastal Storm Modeling System USGS

Flooding Uncertainty



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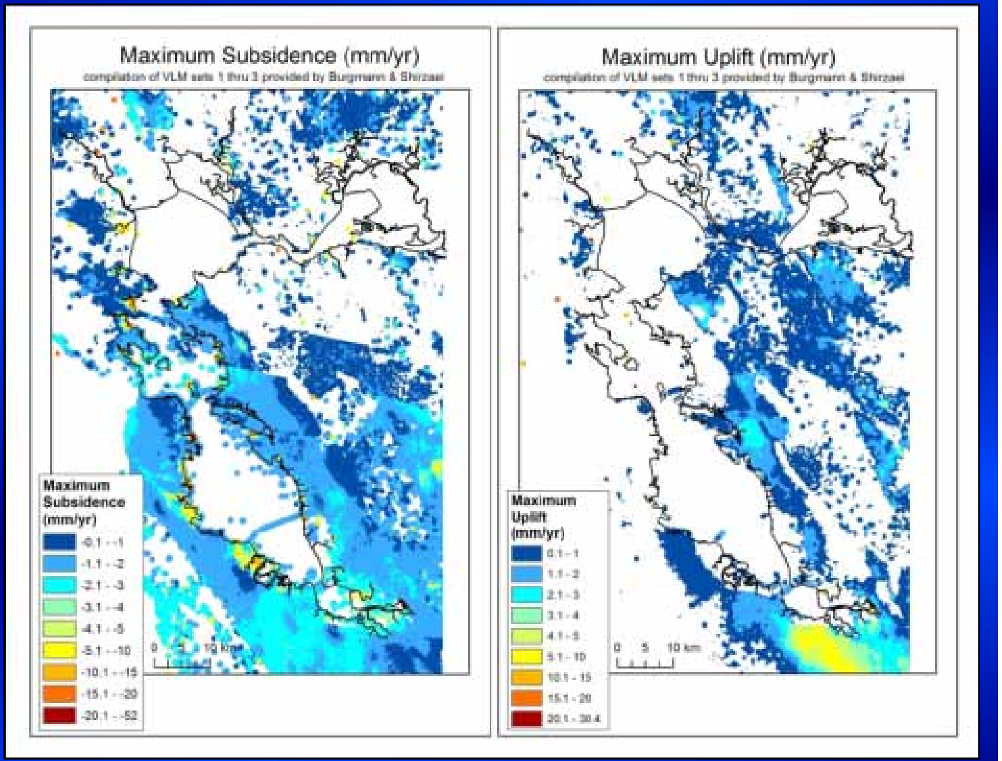
Uncertainty

- **Modeling uncertainty (10 – 50 cm)**

- **LiDAR uncertainty (± 9 cm vertical RMSE)**
  - **known issues with tidal marsh vegetation, biased high ~20 cm but not systematic**

- **Vertical land motion (varies by 4 mm/yr)**
  - **High spatial variability, unknown temporal variability**
  - **Max subsidence = 5 cm/yr**
  - **Max uplift = 3 cm/yr**
  - **Average VLM= ~ -1 mm/yr (subsidence)**

- **Tidal high marsh accretion rates (up to 4-7 cm/yr)**
  - **Based on wide range of sediment supply and production rates**



Burgmann & Shirzaei (InSAR, 1992-2012)

Big Questions for San Francisco Bay

- What will the 21st century SLR curve actually look like?
- How can we better predict storms and impacts? *(M. Ralph, L. Johnson, K. May)*
- Will marshes keep up with SLR? (J. Lowe)
- How will the shoreline evolve?
- How will management decisions (e.g., levees, tidal marsh restoration) affect the dynamics of Bay flooding? *(M. Gerhart, M. Stacey, K. Schaefer, J. Lowe)*

*For more information, contact Patrick Barnard: pbarnard@usgs.gov

USGS CoSMoS website: http://walrus.wr.usgs.gov/coastal_processes/cosmos/index.html

Our Coast- Our Future tool: *www.prbo.org/ocof*

Image courtesy of A. Louie

Crissy Field NPS Interpretive Display

How high the sea?

What the balls on the pole at right represent:

19 feet, 8 inches
Sea level if Greenland Ice Cap melts (if the ice at both poles melted, the ocean would reach the road deck of the Golden Gate Bridge)

9 feet, 6 inches
100-year flood level with a 4-foot, 6-inch rise in sea level and a storm surge

4 feet, 7 inches
High end of predicted sea level rise by 2100

3 feet, 3 inches
Moderate estimate of predicted sea level rise by 2100 (approximately today's 100-year flood level)

1 foot, 8 inches
Low end of predicted sea level rise by 2100

Source: March 2009, Pacific Institute study