Sea level extremes

Francisco M. Calafat
National Oceanography Centre, UK

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

Sea Level Training Course, St Lucia | 17-21 October 2016

What we will cover

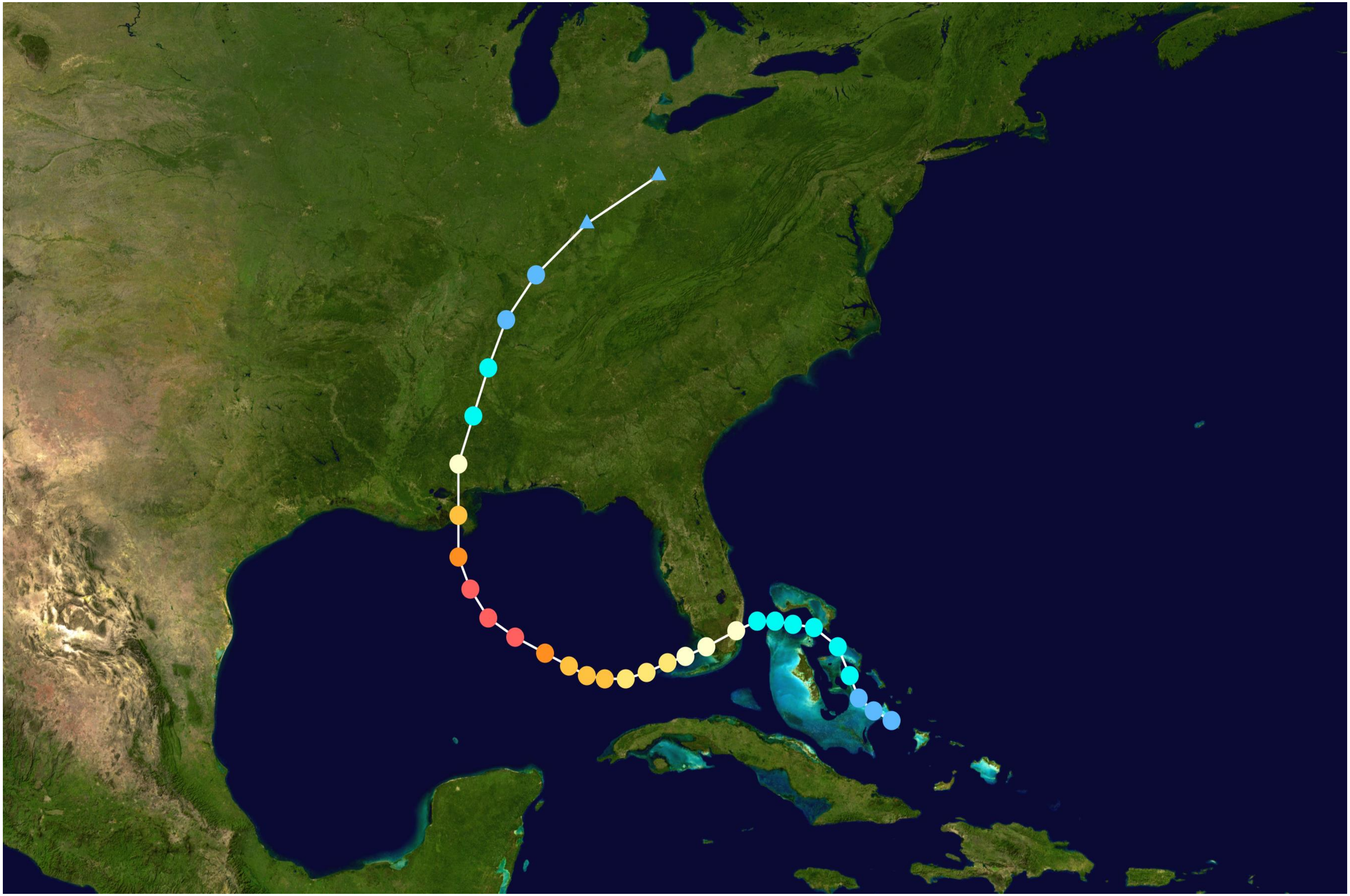
- The practical issue
- Introduction to storm surges
- Analysis of sea level extremes
- Trends in sea level extremes
- Decadal variations in sea level extremes
- Future changes in MSL
- Conclusions

The practical issue

- Coastal zones have changed profoundly during the 20th century with increasing populations, economies and urbanization
- About 600 million people live within 10 m of present day sea level
- Coastal areas below 10 m elevation generate 10% of the world's GDP
- Data for 136 of the world's largest cities indicate a factor of 3 increase in population numbers exposed to flooding risk by the 2070s and a ten-fold increase in asset exposure relative to present levels

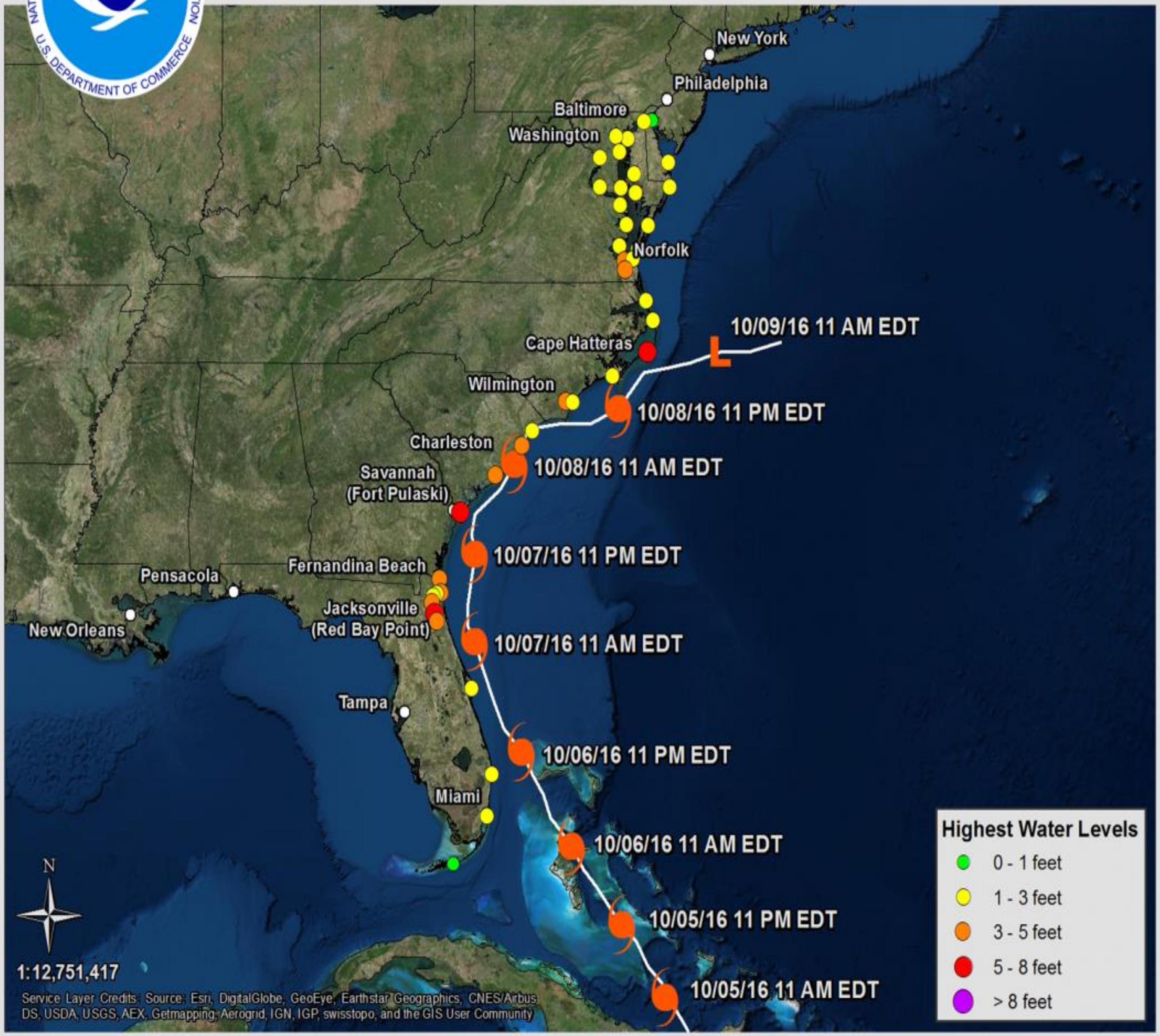
New Orleans after Hurricane Katrina (2005)

Hurricane Katrina track




North Norfolk 1953

Highest Water Levels During Hurricane Matthew



Highest Water Levels

(*ft. above MHHW/Inundation)

- Hatteras, NC (***5.8 feet)***
- Red Bay Point, FL (***5.5 feet)***
- Fort Pulaski, GA ***(5.1 feet)***
- Oyster Landing, SC ***(4.7 feet)***
- Fernandina Beach, FL ***(4.2 feet)***
- Charleston, SC ***(3.5 feet)***

Water at seven stations exceeded historical maximum levels, including Mayport, FL, Fort Pulaski, GA Wilmington, NC and Hatteras, NC.

Water levels at Fort Pulaski far exceeded the prior record of 3.4 feet established during the Cape Sable Hurricane in October 1947.

****Mean Higher High Water (MHHW) is defined as the average daily highest tide. Inundation typically begins when water levels reach above MHHW. These values are based on preliminary observed water levels from NOAA and partner tide stations.***

tidesandcurrents.noaa.gov

D Depression **Tropical Storm** **Hurricane** **L Post-Tropical / Extratropical Low**

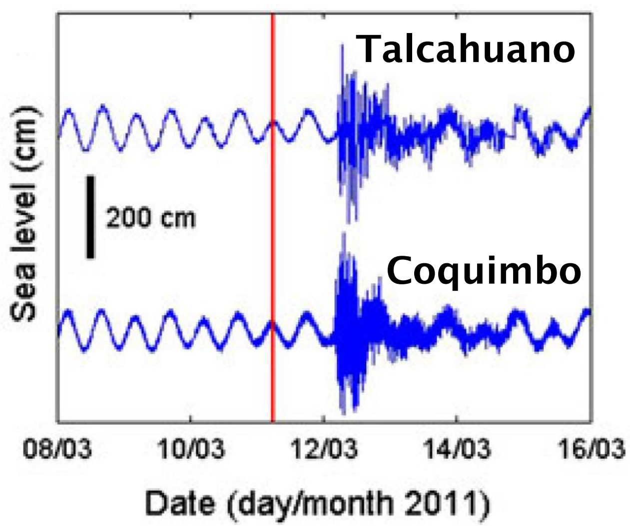
Mean sea level rise will result in more severe episodic events and events of a given height will occur more often

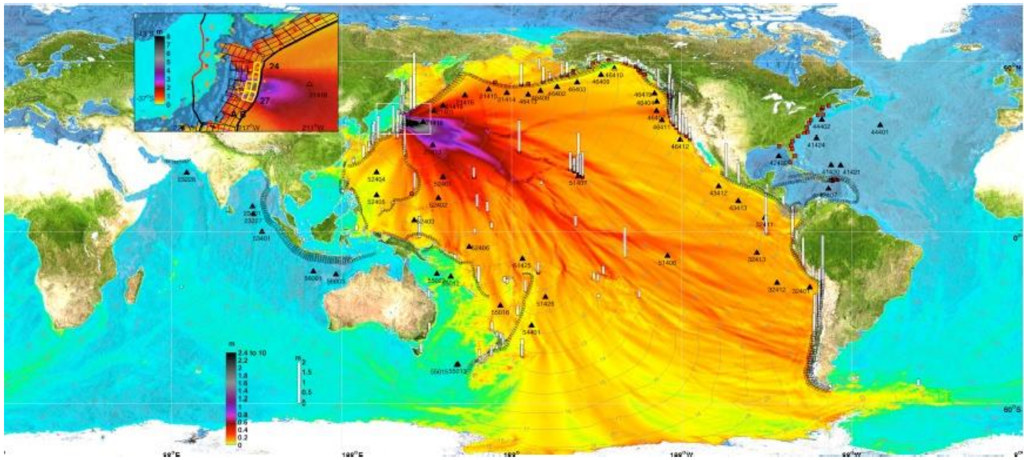
Causes of sea level extremes

There are many processes that can produce sea level extremes:

- **Storm surges**
- **Seiches due to resonant behaviour of harbours and bays (caused by many things, often wind)**
- **Tsunamis caused by earthquakes, landslides, etc.**

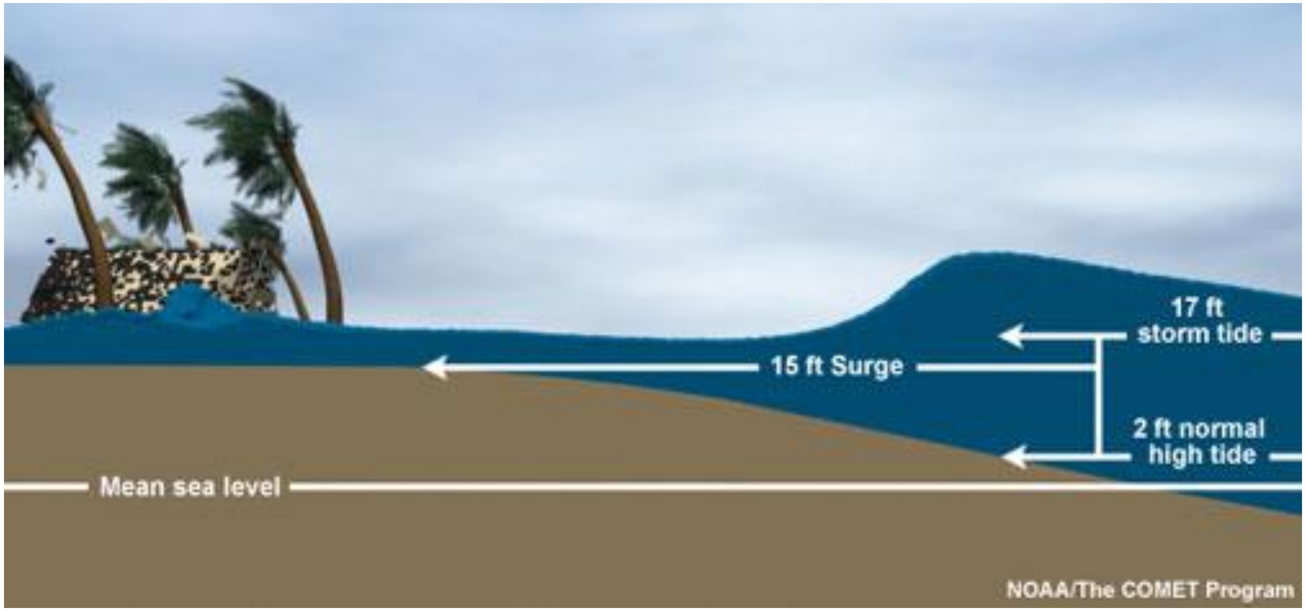
11 March 2011 Tōhoku tsunami





What is a storm surge?

- A storm surge refers to an abnormally high sea level (above the tide and the MSL) induced by a storm
- The storm tide is the combination of the storm surge and the tide
- The total water envelope is the sum of the storm surge, the tide, waves, and the MSL



High water marks are lines found on trees and structures marking the highest elevation of the water surface following hurricane Katrina (2005)

~8 m

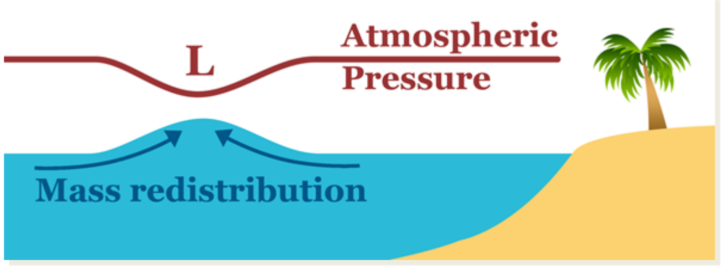
The highest high water mark was almost 2 m above the storm tide due to the large waves on top of it

Mechanisms of a storm surge

A storm surge can be viewed as the sum of two contributions:

1) The effect of the wind piling up water against the coast

2) The low atmospheric pressure associated with the storm sucking water from the surroundings (inverse barometer effect)



Waves forming on top of the storm surge will result in greater impact

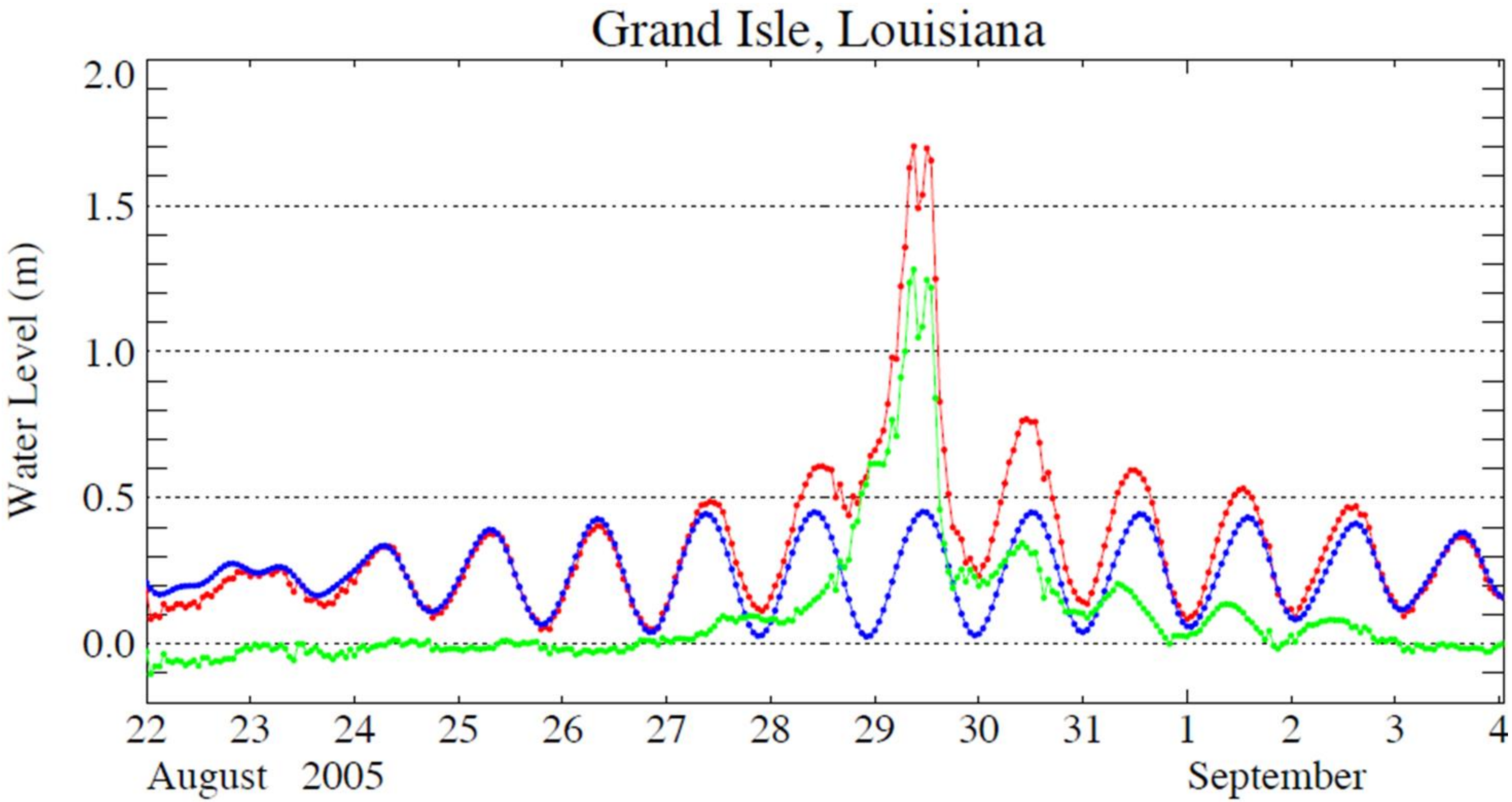
Wind and Pressure Components of Hurricane Storm Surge

Features of a storm surge

- A larger storm will produce greater surges
- Stronger winds will produce higher surges
- Fast moving storms induce high surges on open coastlines and lower in narrow seas and bays
- The bathymetry plays also an important role: wide and shallow shelves will produce greater surges but smaller waves
- A storm approaching the coast perpendicularly is more likely to produce greater surges
- Timing is crucial! If the storm surge coincides with high tide the impact will be much greater

Observing and forecasting storm surges

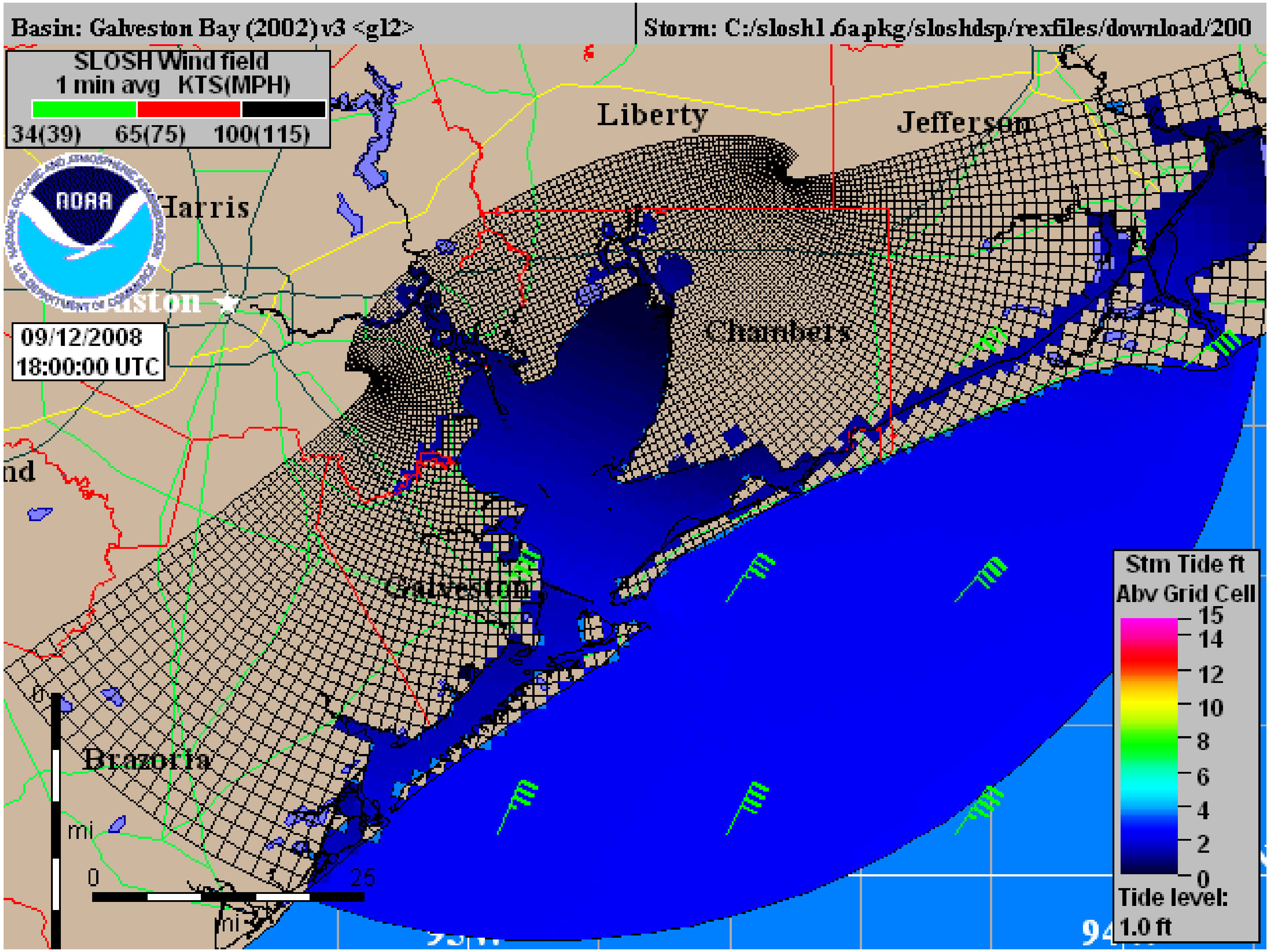
- Tide gauges are the most reliable way of measuring the storm surge (without waves)
- However, their distribution along the coast is sparse and often no station exists at the location where a storm makes landfall
- Higher water marks such as the marks found in trees and structures (they represent the combination of the tide surge and the waves).
- Numerical 2D barotropic models are typically used to forecast storm surges along the coast.



A tide gauge near New Orleans during Hurricane Katrina

Storm surge animation from NOAA's SLOSH model

Hurricane Ike (2008)



Storm surge simulated by NOAA's SLOSH model

Hurricane Dennis (2005)

Storm surges are often found to move along the coast in the form of coastal Kelvin waves

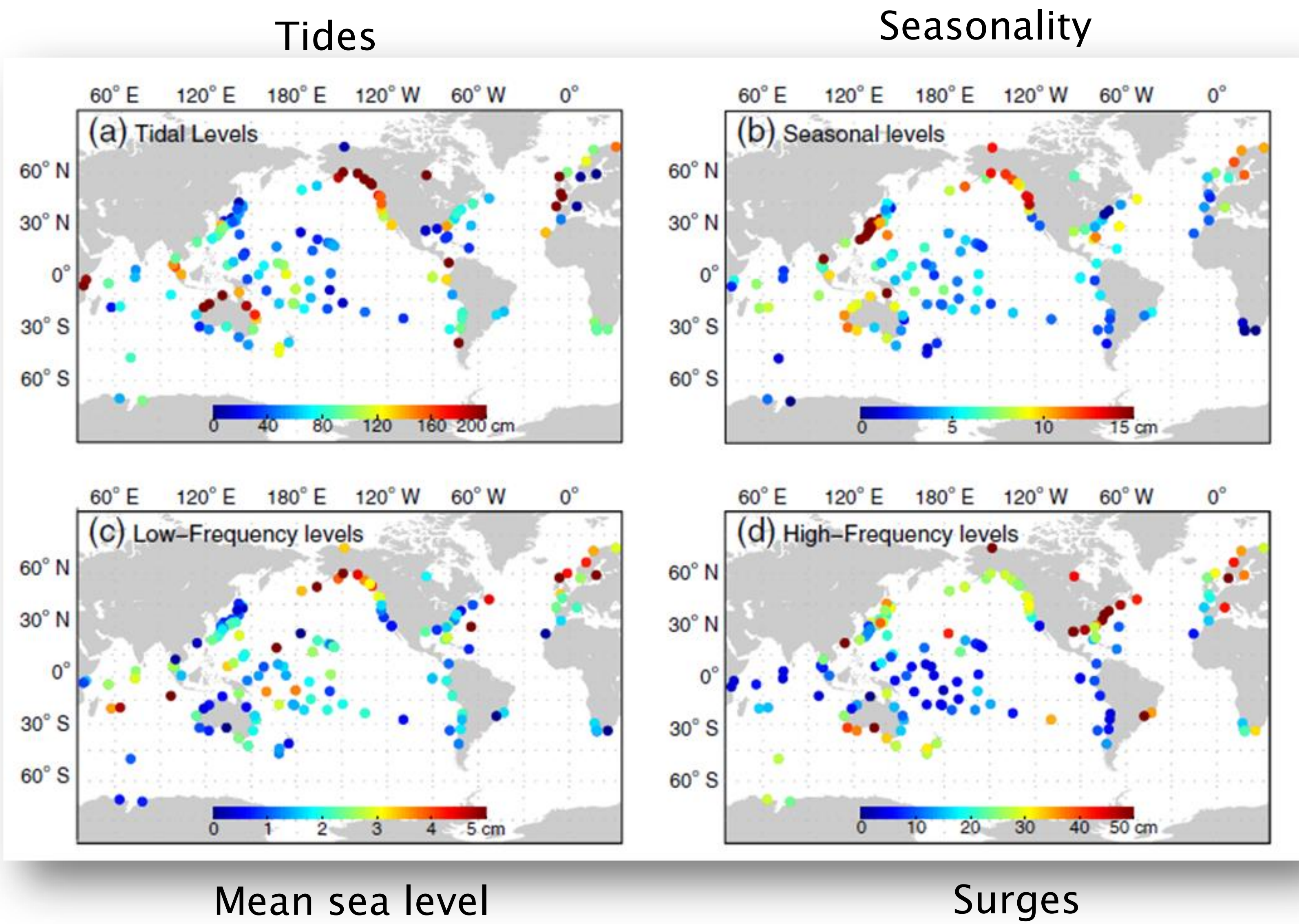
In the Northern Hemisphere, Kelvin waves always travel with the coast to the right

Why to study sea level extremes?

Sea level extremes are rare by definition, so why bother to study them?

- **When they happen they cause extreme damage**
- **To estimate flooding risk and understand how this might change in the future**
- **Estimates of flooding risk can be included into coastal planning and design**
- **A risk assessment enables coastal planners to make more effective decision, which results in direct savings.**
- **If the risks are unknown, decision-making is not much different from gambling**

Contribution to extreme sea levels



Merrifield et al. (2013)

Selection of sea level extreme events

We would typically perform extreme value analysis on hourly tide gauge observations or numerical model output

The first step is to separate the observed sea level into three components: (1) tidal levels; (2) MSL; and (3) surge levels

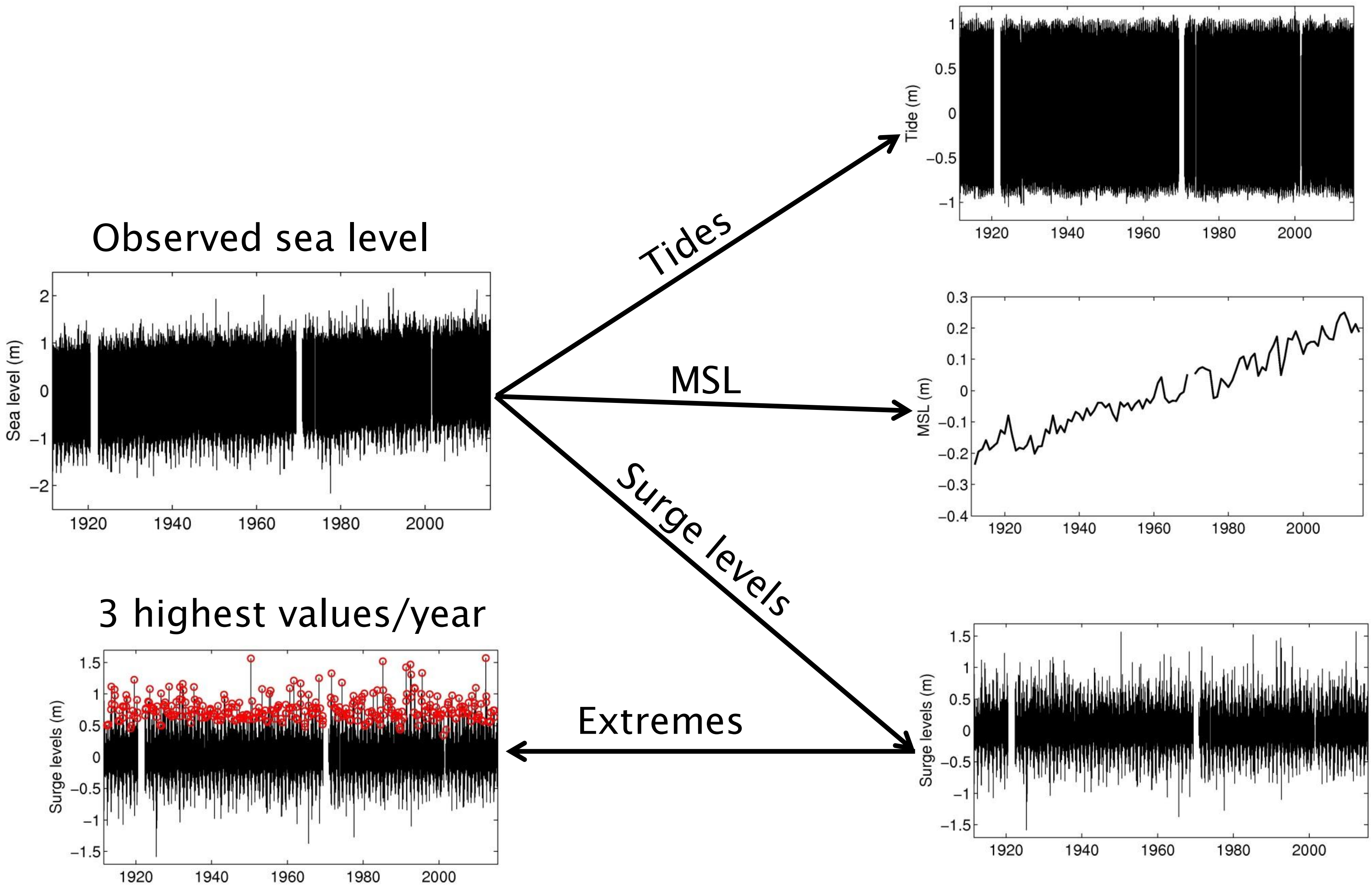
The MSL can be computed by low-pass filtering the nontidal residuals (MSL + surges) or simply as the annual median of the hourly nontidal residuals.

The surge levels are then simply computed by subtracting the MSL from the nontidal residuals.

There is no universally accepted definition of sea level extreme. One can use high annual percentiles, the *n* highest values per year, values over a certain period, etc. Moreover, this selection can be performed on the total sea level, nontidal residuals (MSL + surges), or the surges, depending on what our interest is.

Selection of sea level extreme events

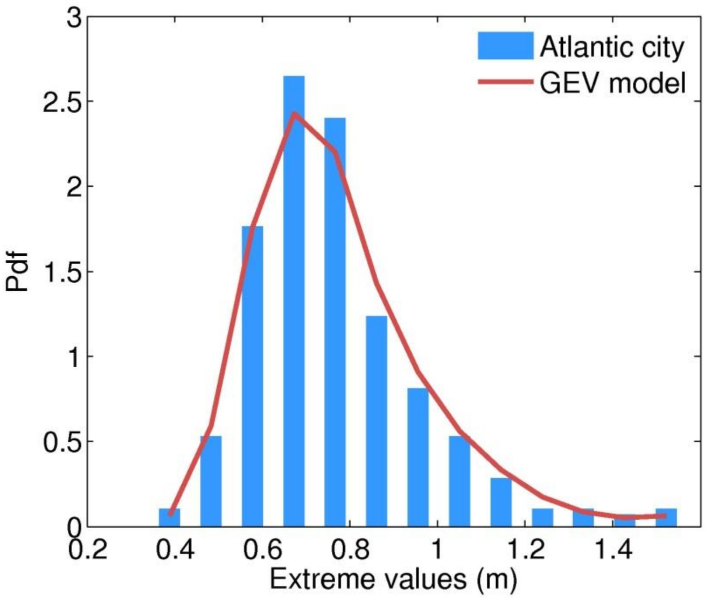
Let's use tide gauge data from Atlantic city as an example



Analysis of sea level extremes

Our goal is to characterize the intensity and frequency of extreme events. We are also interested in long-term variations (decadal, trends, etc.) in the extremes.

Return levels or other quantities of interest are derived by modeling the series of extreme values using a particular probability distribution (usually a GEV or a GDP). The parameters of the distributions (i.e., scale, shape, location) are typically estimated by MLE.



To test if our extreme data comes from the assumed probability distribution we can compare the histograms. In this case we see that the surge levels from Atlantic City follow a GEV distribution quite closely

Analysis of sea level extremes

Several quantities may be used to asses flooding risk, but often we are interested in knowing the likelihood of an event of a certain height. The return period and level provide an estimate of such likelihood.

For instance, if the level *z* has a 0.01 probability of being exceeded in a year, then we would say that such level has a return period of 1/0.01 = 100 years

The *N*-year return level (RL_N) is the level that is expected to be crossed on average once every *N* years, and it can be calculated as follows (Assuming that we model the extremes using a GEV):

1) Compute the GEV parameters by MLE: $\mu\,(\text{location}), \sigma\,(\text{scale}), \xi\,(\text{shape})$

2) Compute the RL_N using the inverse cdf: $\boldsymbol{RL_N} = GEV^{-1}\left(1-\frac{1}{\lambda N}; \mu, \sigma, \xi\right)$

Where λ is the number of extremes that we use per year

Analysis of sea level extremes

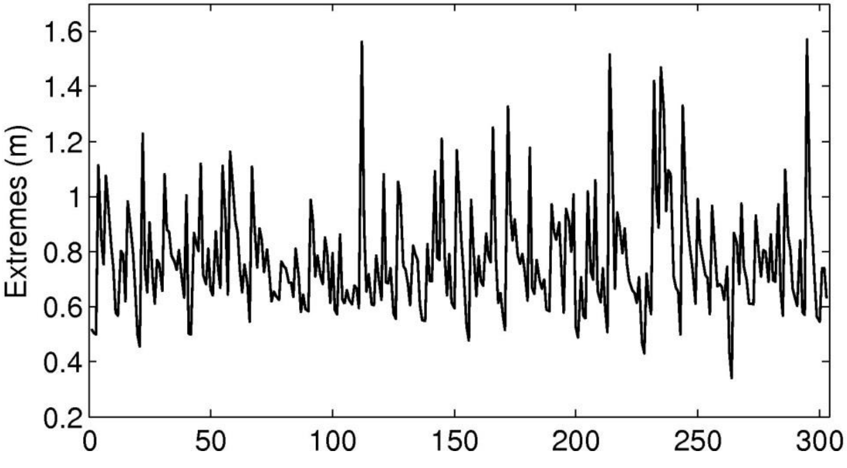
In Matlab:

```
[par, parci] = gevfit(x);  % x : our extremes data
RL100 = gevinv(1-1/(lambda*100), par(1), par(2), par(3));
```

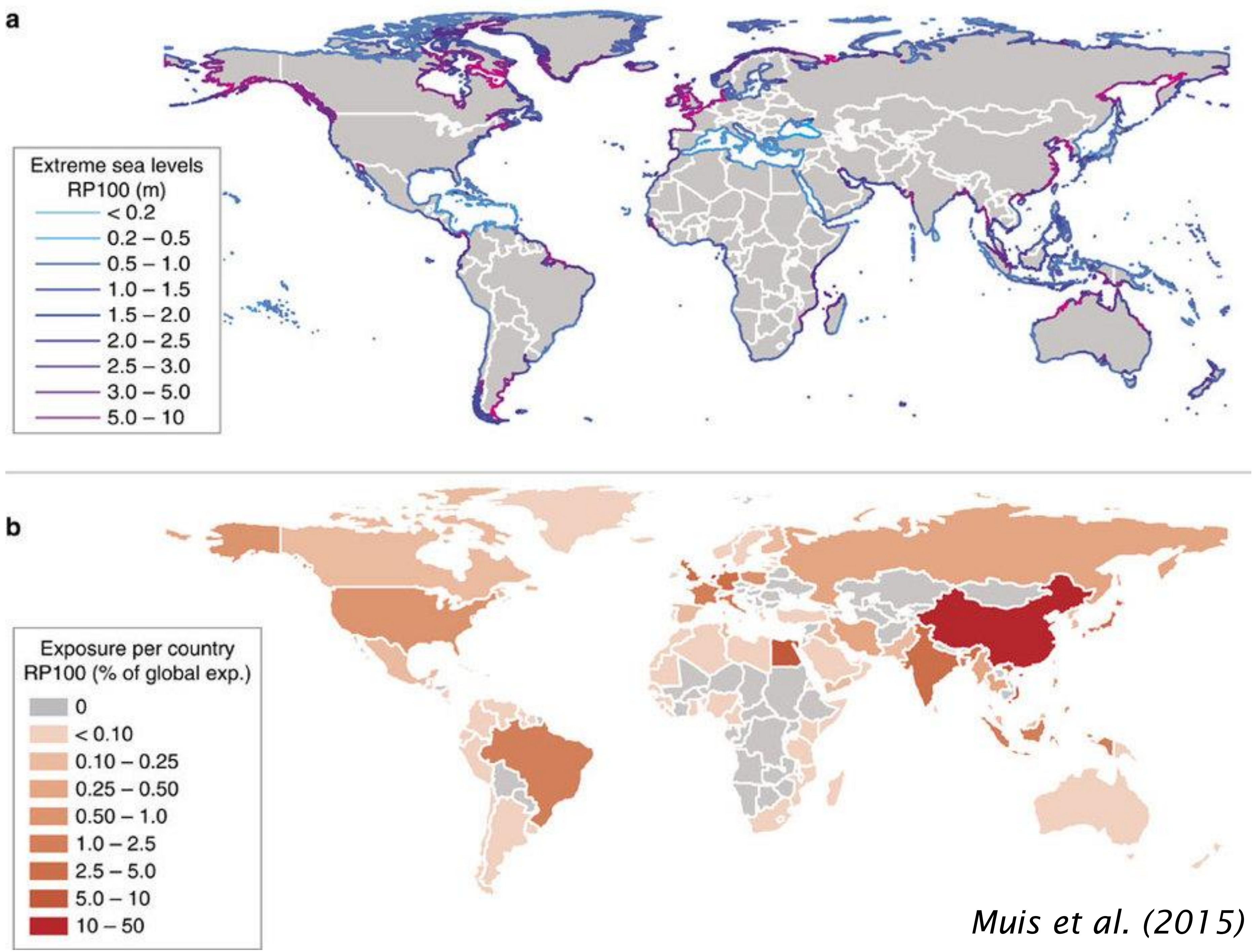
In Python:

```
from scipy.stats import genextreme
s, m, k = genextreme.fit(x)  # x : our extremes data
RL100 = genextreme.ppf(1-1/(lambda*100), s, m, k)
```

3 highest values/year



If we do that using surge levels from Atlantic city we obtain:
RL_{100} = 1.55 m



Muis et al. (2015)

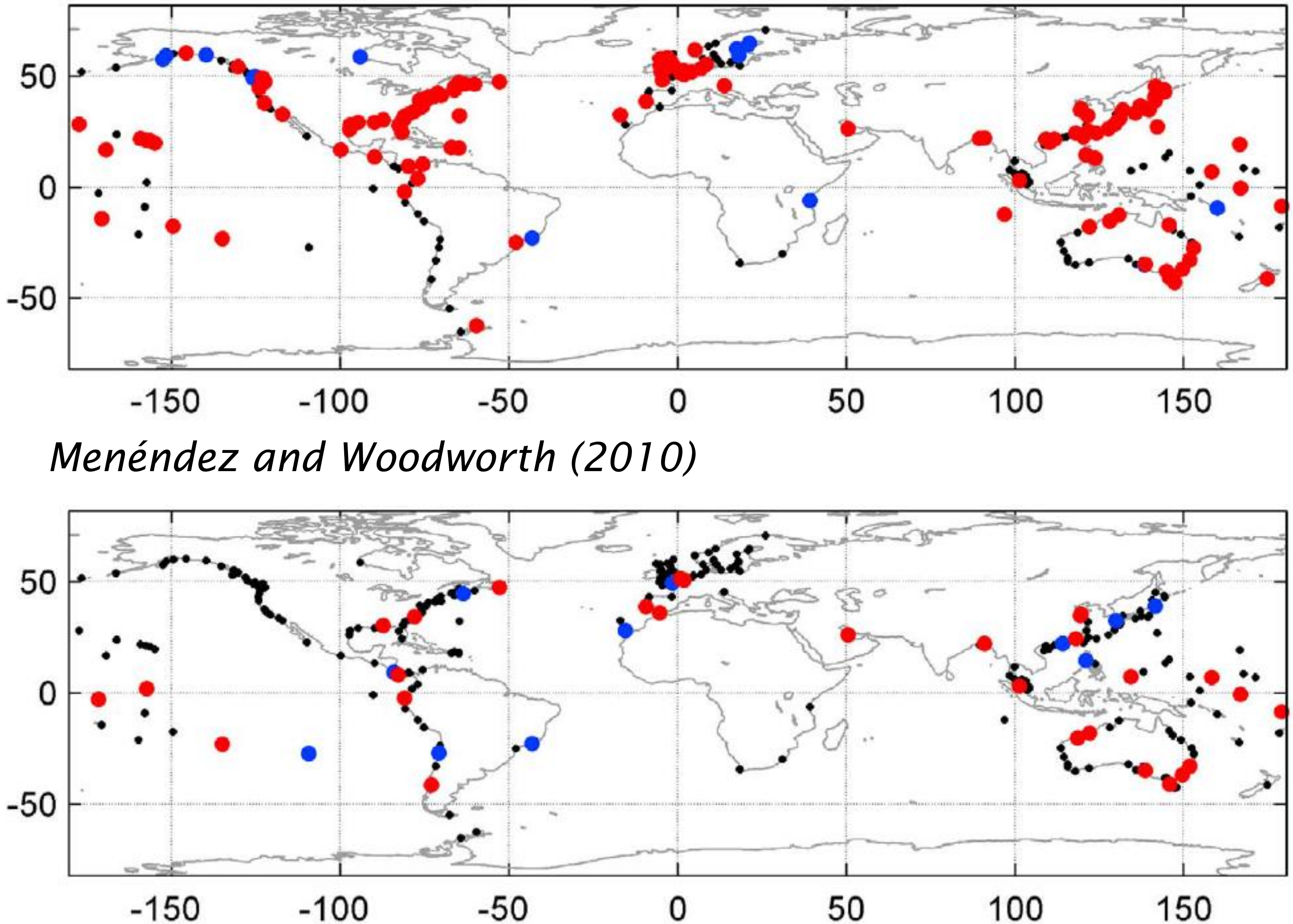
Analysis of sea level extremes

The analysis of return periods and levels assumes that the probability of an event occurring is constant in time. However, sea level extremes are highly non-stationary, caution!

Long-term variations in sea level extremes can be due to changes in: (1) tides; (2) MSL; and (3) storminess. MSL, for instance, has been rising significantly for the last several decades.

The obvious question is, have extreme sea levels increased differently from what you would expect from a rise in MSL?

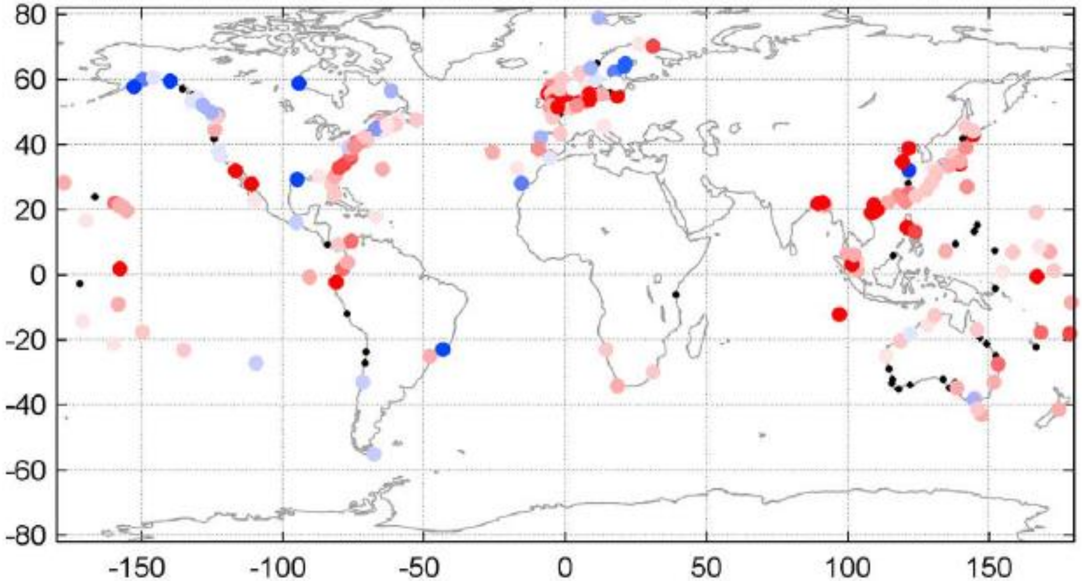
Trends in sea level extremes



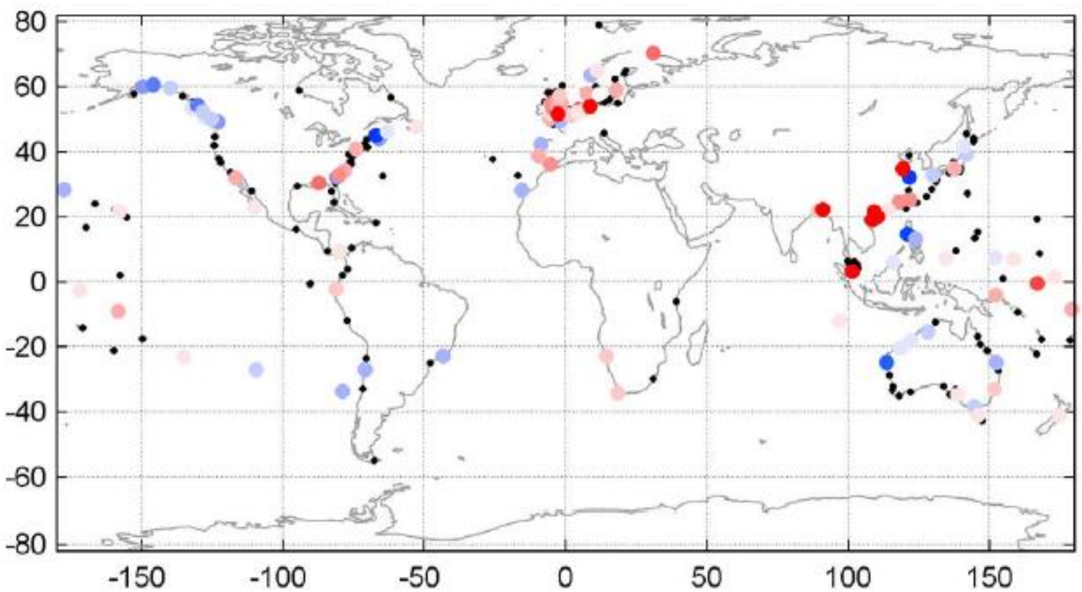
Menéndez and Woodworth (2010)

Trends in annual 99 percentile observed sea levels (top) and sea levels reduced to their annual medians (bottom).

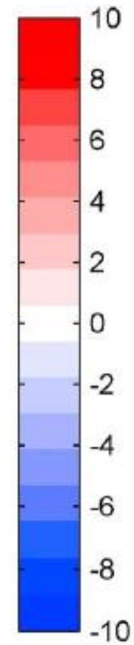
Trends in sea level extremes



Menéndez and Woodworth (2010)

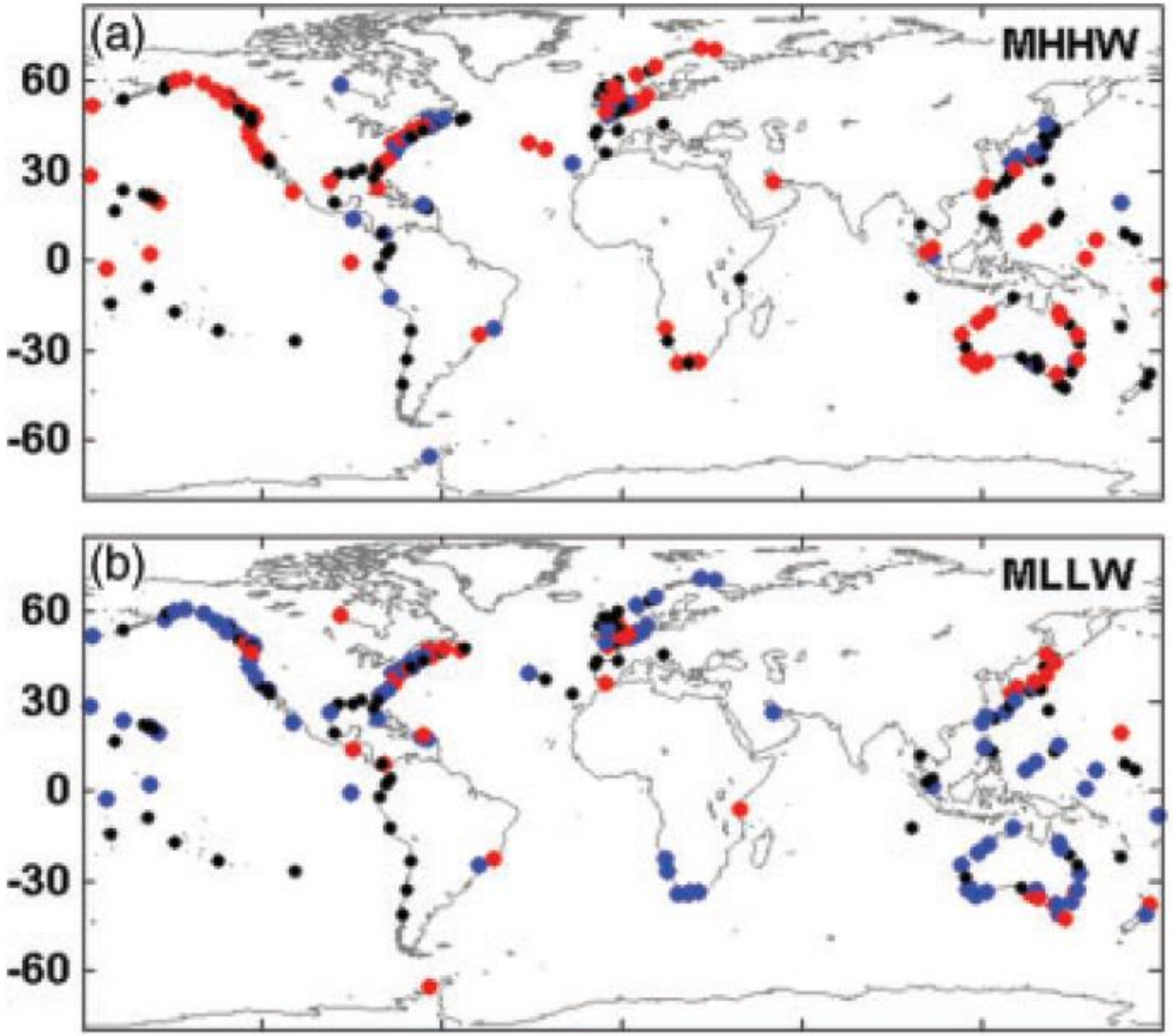


Trends (cm/10yr) in the 50-year return level from total elevations (top) and total elevations after removal of annual medians (bottom).



Trends in tides

Trends: positive significant (red), negative significant (blue) and nonsignificant (black)

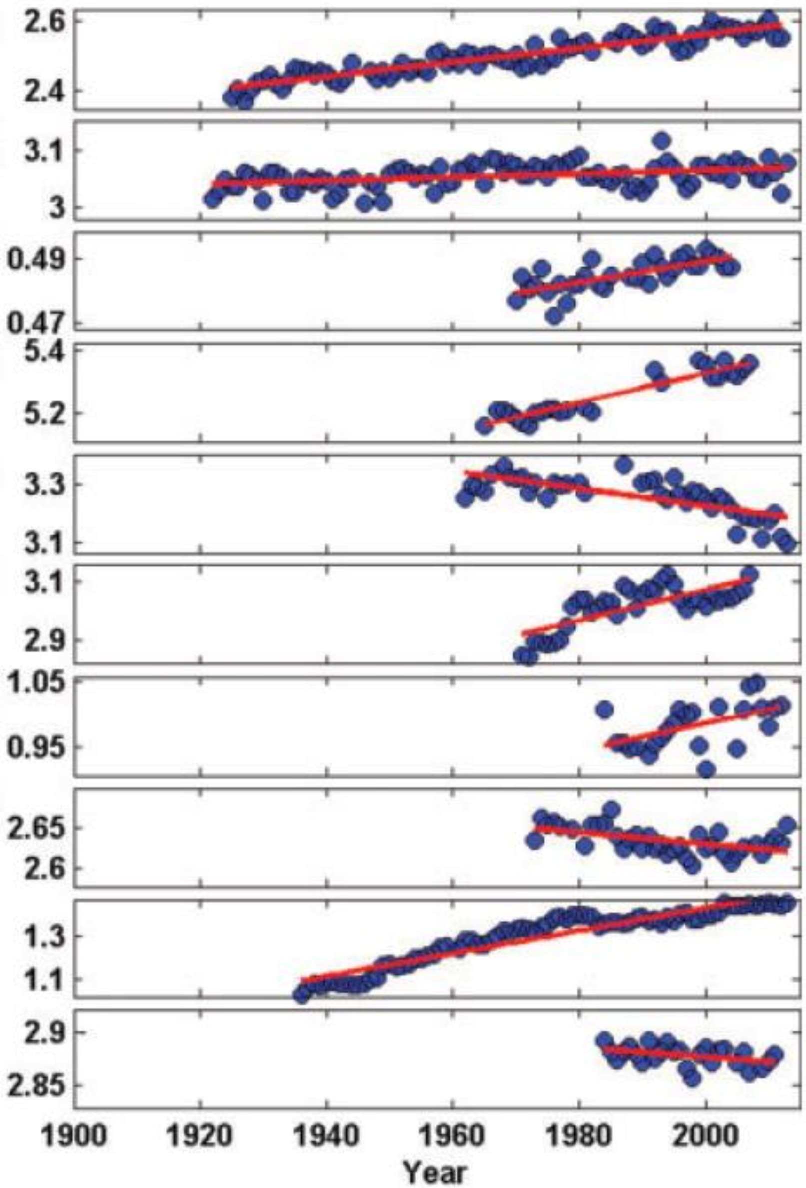


Mean higher high water

Mean lower low water

Mawdsley et al. (2015)

Trends in tides

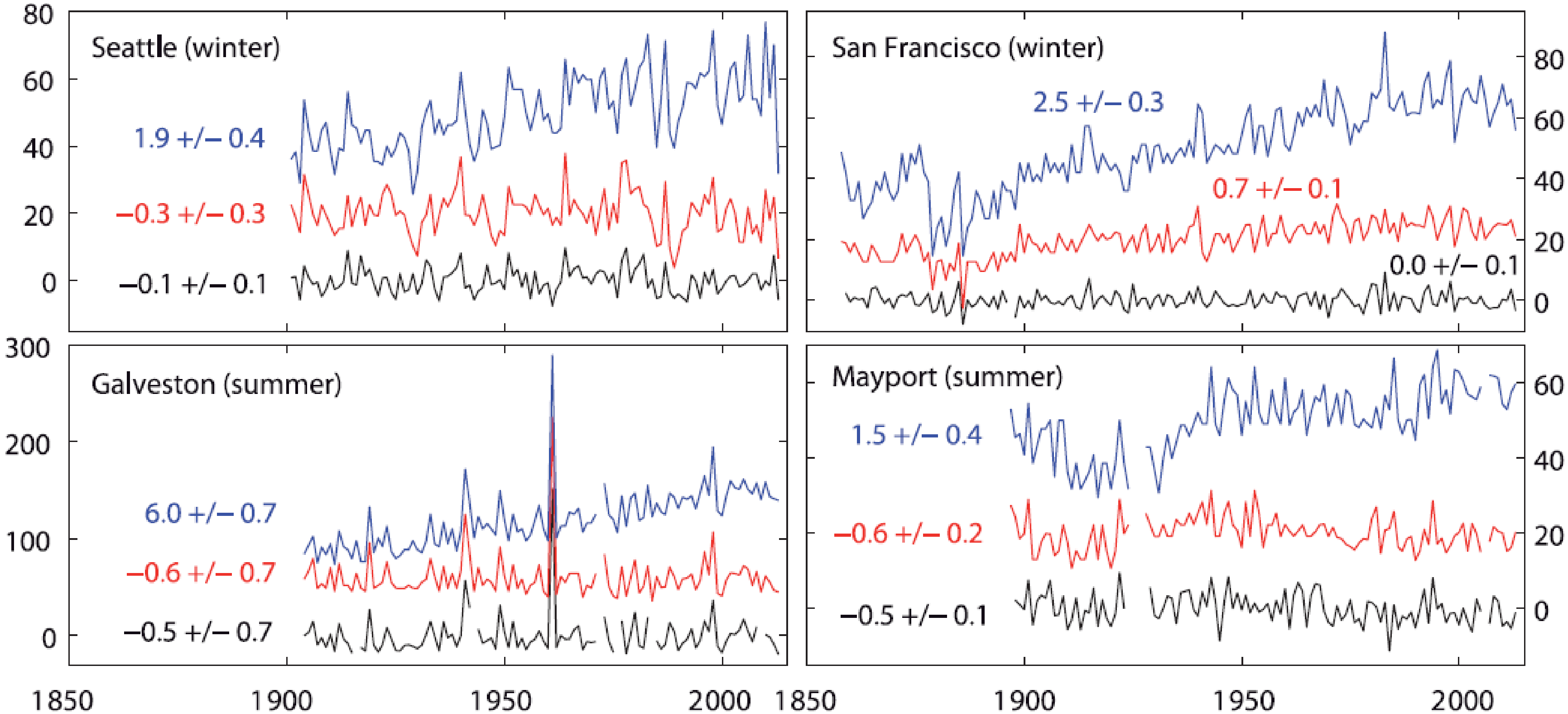


Mawdsley et al. (2015)

Time series of annual greater diurnal tidal range values (in meters) without nodal component.

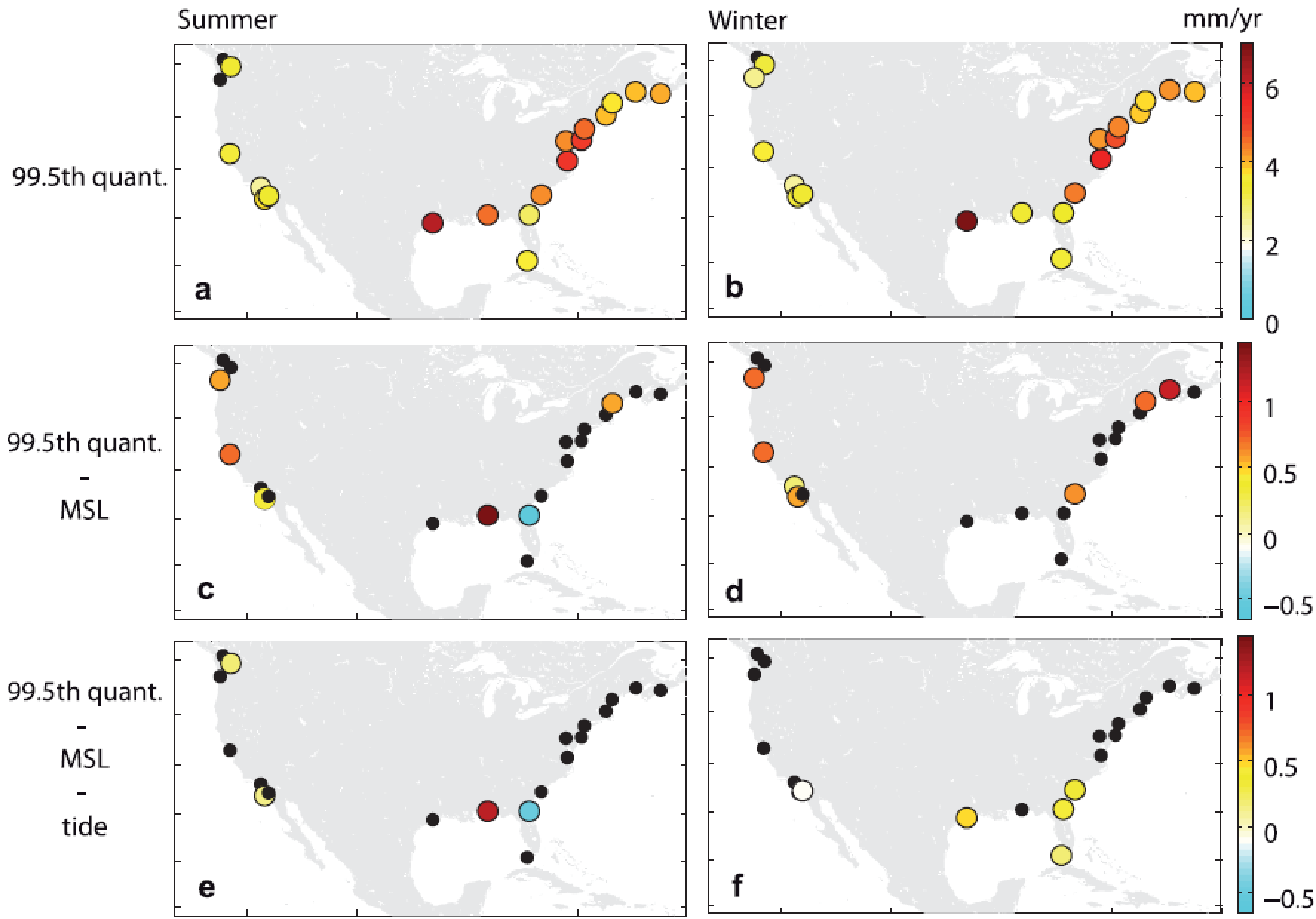
Contribution to trends in extremes

Time series of the 99.5th percentiles (seasonal) from observed sea level (blue), after the annual media has been removed (red), and after both the annual media and tidal influence have been removed (black)



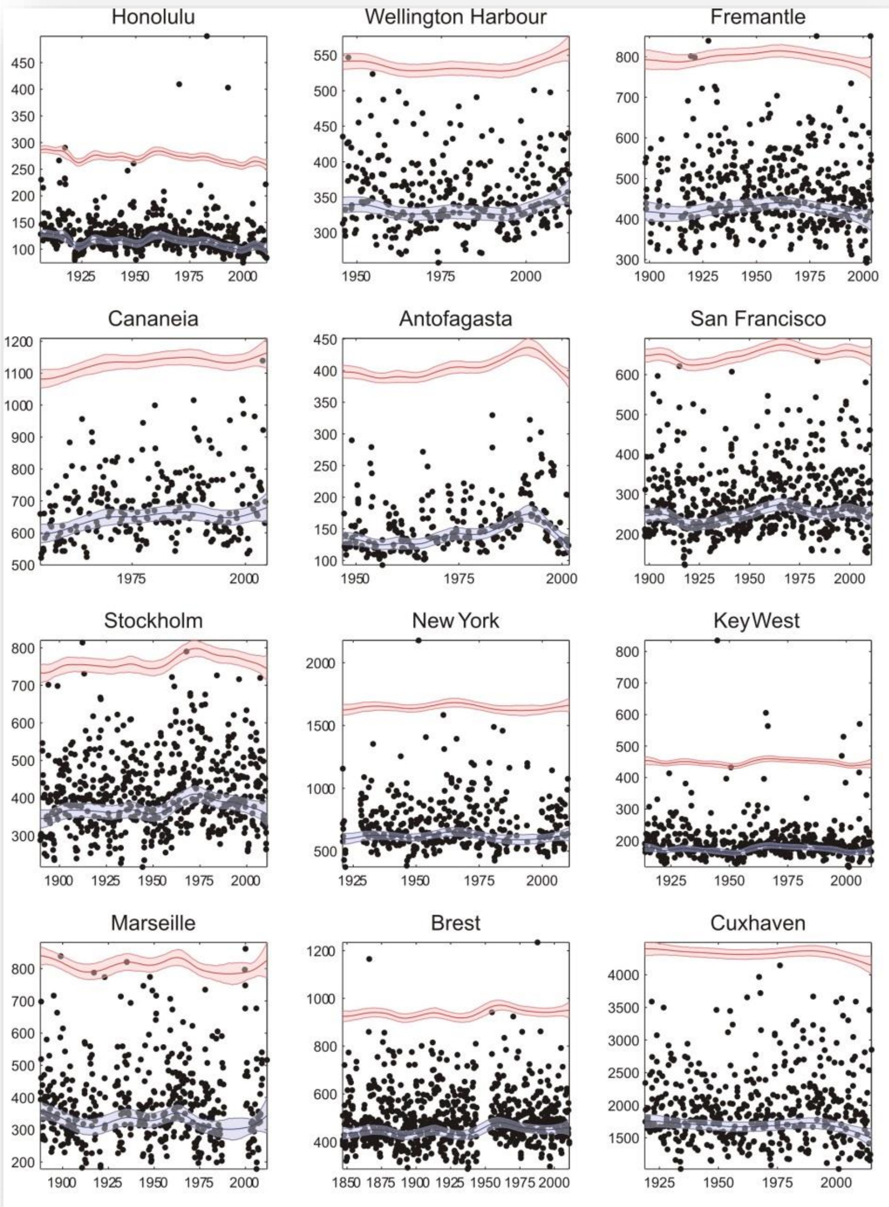
Wahl and Chambers (2015)

Contributions to extreme trends



Wahl and Chambers (2015)

Changes in the intensity of extremes

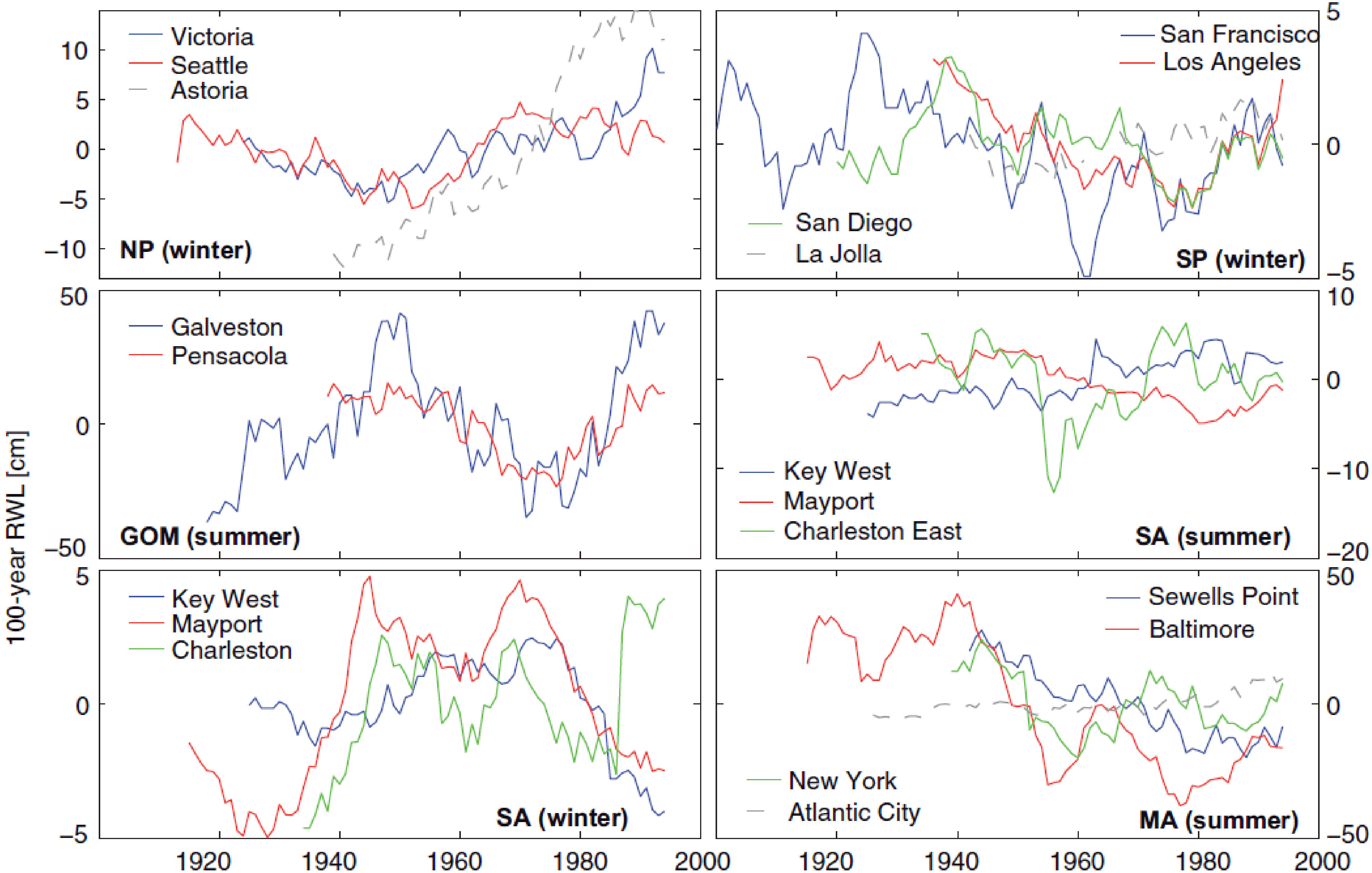


$$y_t|\mu_t \sim GEV(\mu_t, \sigma, \varsigma)$$

Surge levels (black dots) and time-varying location parameter (blue curve) and 50-year return level (red curve).

Marcos et al. (2015)

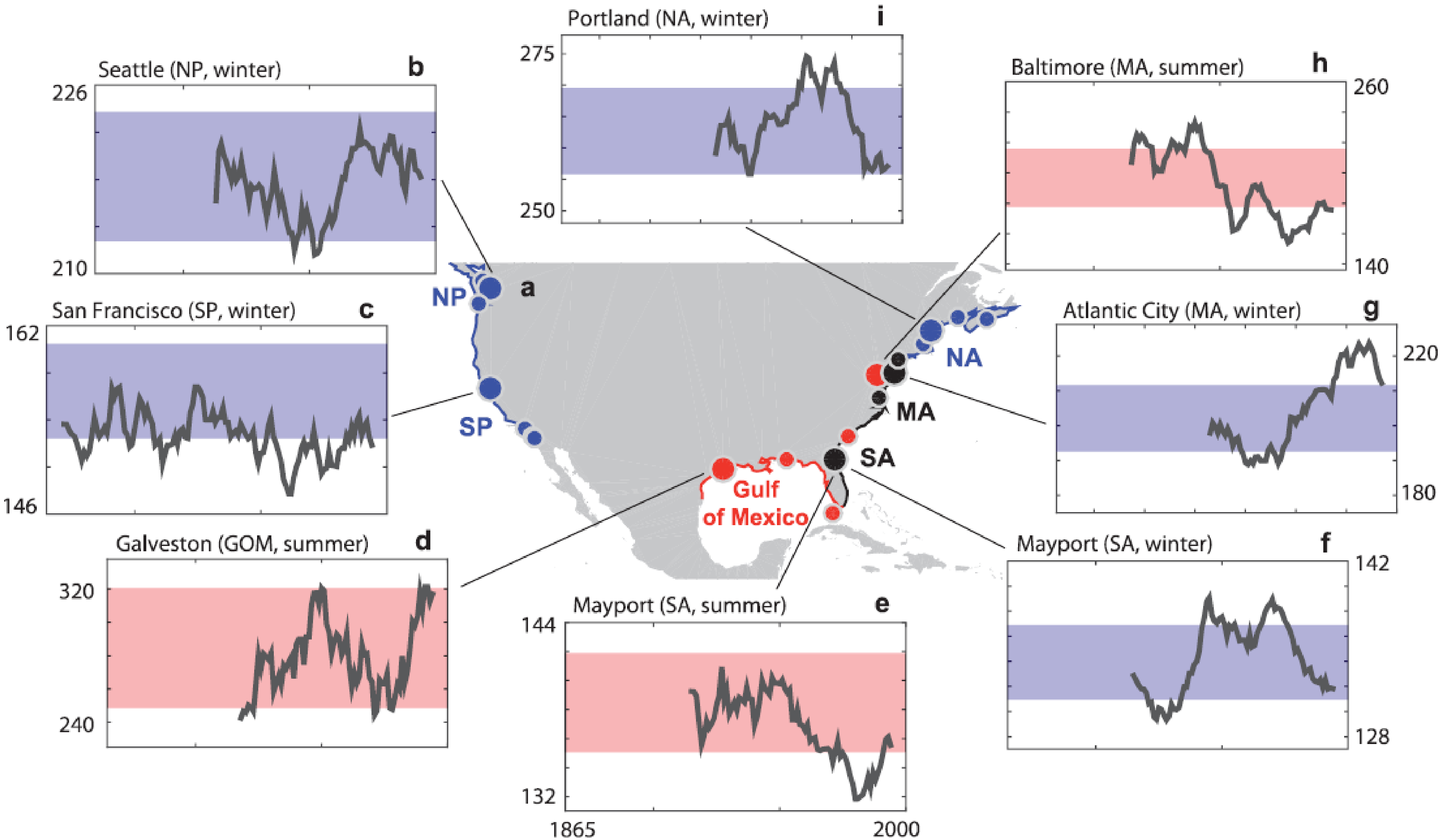
Changes in the intensity of extremes



Wahl and Chambers (2015)

Changes in the intensity of extremes

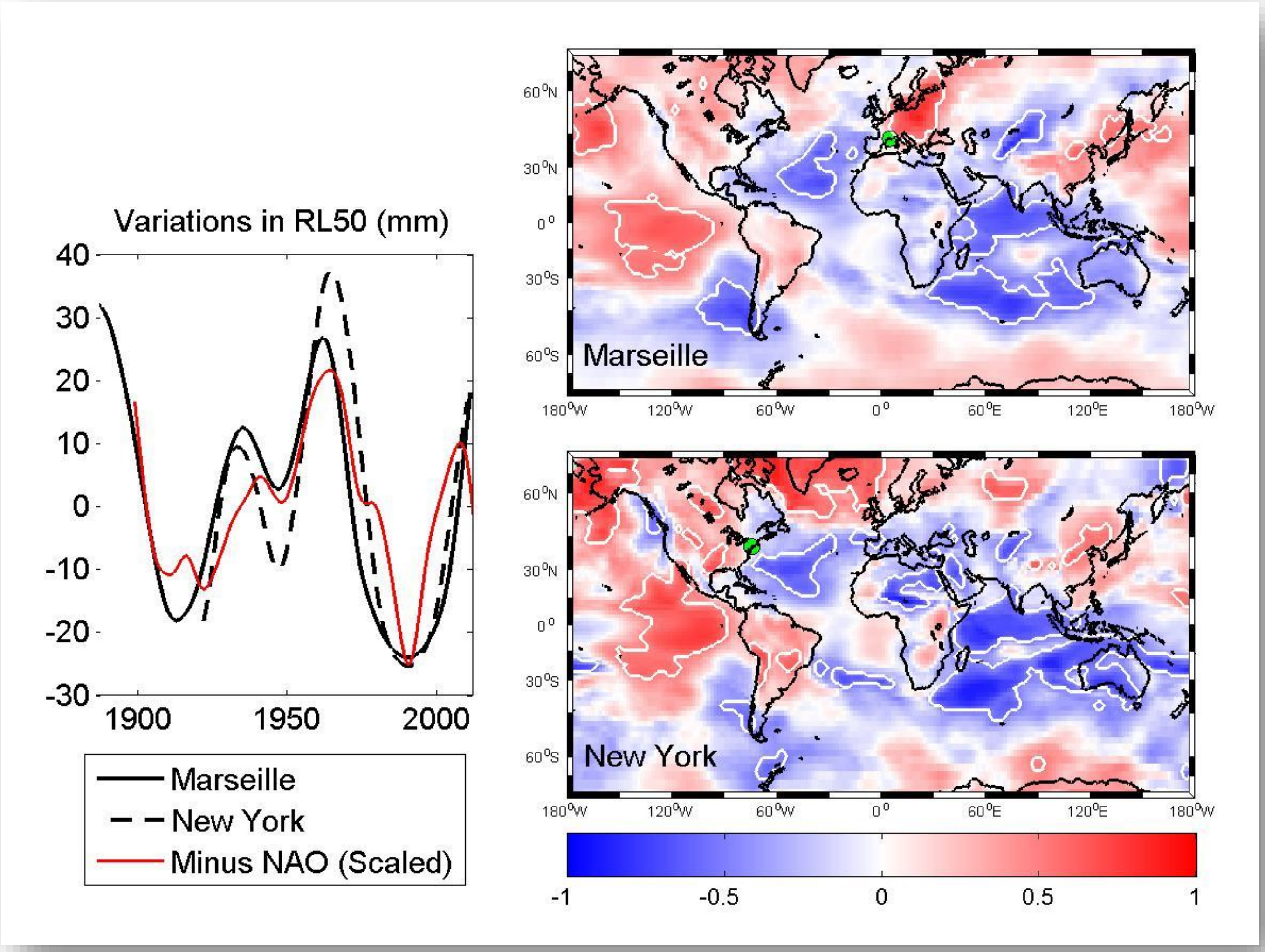
Changes in extremes deviate significantly from the stationary assumption



Wahl and Chambers (2016)

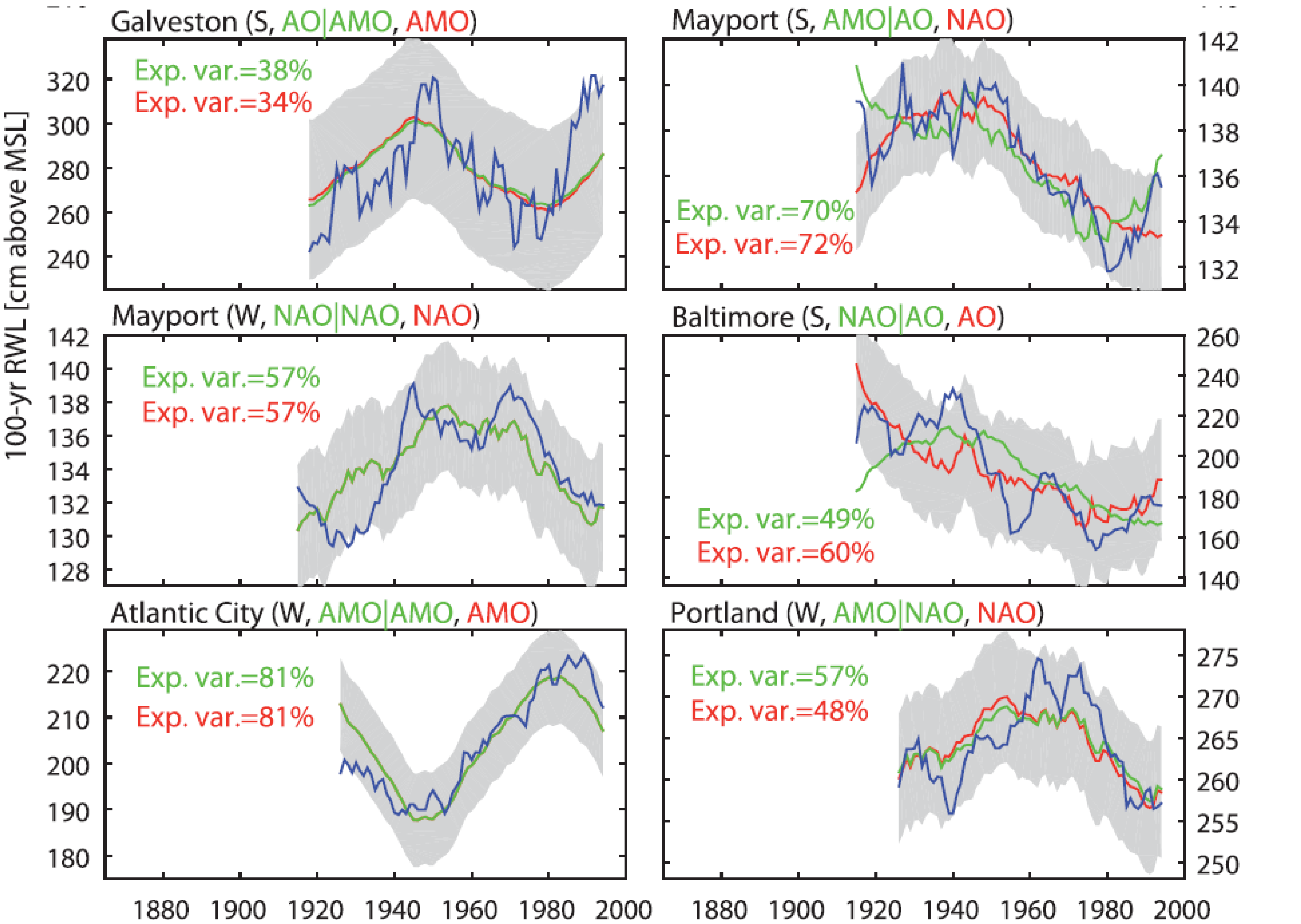
Drivers of long-term extreme changes

Sea level extremes in Marseille and New York and their relationship with the NAO



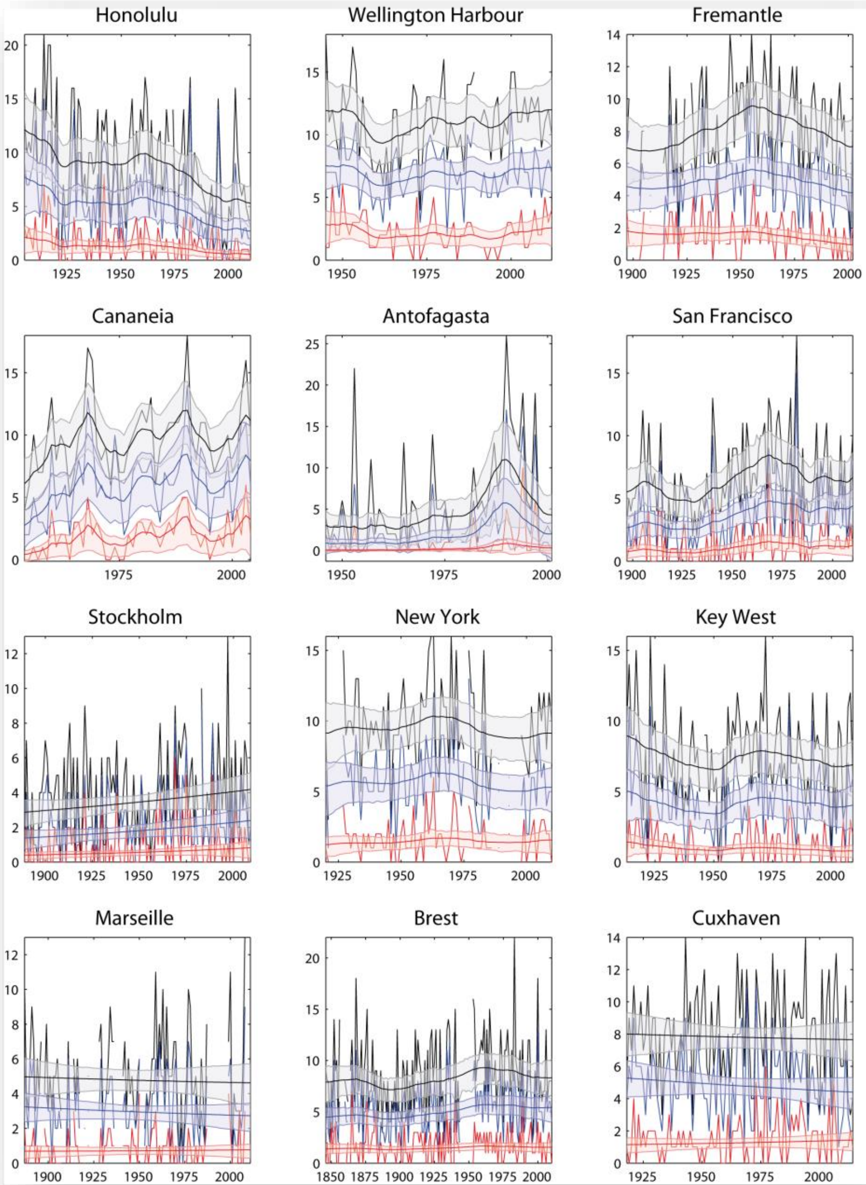
Marcos et al. (2015)

Drivers of long-term extreme changes



Wahl and Chambers (2016)

Changes in the frequency of extremes



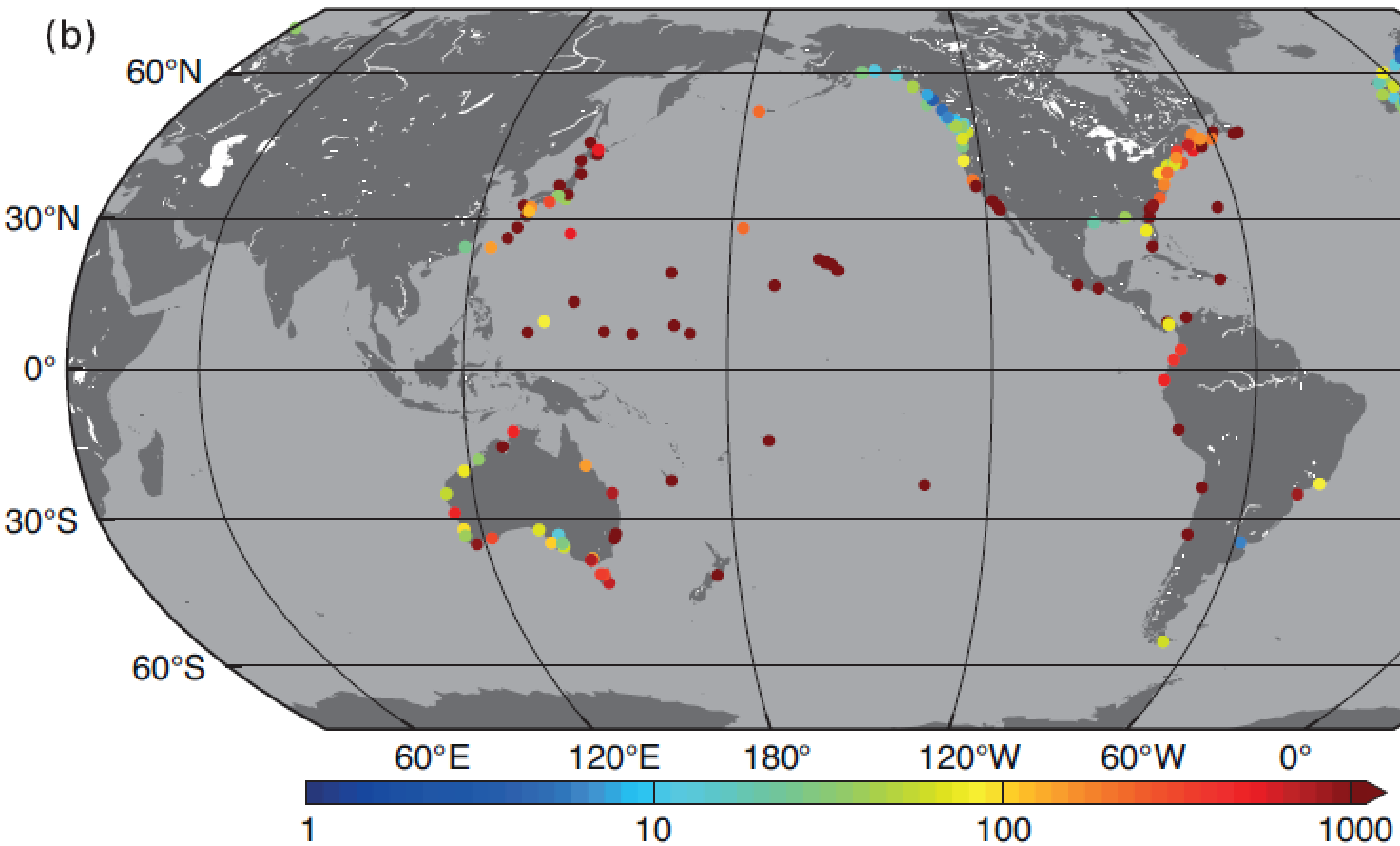
$$y_t|\theta_t \sim Poisson(Ue^{\theta_t})$$

Extreme occurrences (in number per year) above the 99th (black), 99.5th (blue), and 99.9th (red) percentiles.

Marcos et al. (2015)

Future changes in sea level extremes

Multiplication factor by which the frequency of flooding events of a given height will increase for the projected MSL rise under the RCP 4.5.



IPCC AR5

Warning about the methods

- **It is important to visually inspect the time series of extremes for outliers since these have a large effect on the analysis. One needs to decide whether they are a true geophysical signal or they are result of instrument malfunction.**

- **It is a good idea to analyse separately surges due to tropical and winter storms since they are likely to follow different probability distributions.**

- **When analysing sea level extremes from either tide gauges or numerical models, one should consider the possibility of tide-surge interactions.**

Conclusions

- **It is the combined effect of MSL rise and storm surges that do the greatest damage .**
- **It is important to include estimates of flooding risk in coastal planning so that an appropriate level of protection can be implemented.**
- **Return periods are decreasing mainly due to MSL rise. It is important to account for this when trying to predict flooding risk**
- **Note however, that significant trends have also been observed in the tides.**
- **There is also significant decadal variability in the return levels, which should be included in impact assessments**

Thank you for listening!

Questions?