The Effects of Natural Structure on Extreme Storm Surge Statistics

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Motivation for Study

- Often “state-of-the-art” practices evolve from applications that must be performed under severe time and funding constraints
- Many assumptions in extremal statistics are either not recognized or just neglected
- We know from atmospheric-oceanic downscaling studies that larger scale circulation patterns dramatically affect synoptic-scale behavior
- How might natural structure in our samples affect our estimates of extremes?
- How does this impact the response that we really care about (inundation, threshold exceedance, etc.)?

Outline

- Basic assumptions in analyses of extremes
- Motivation to move from Return Period and/or Annual Exceedance probabilities to expected failure over a “life-time”
- Examine real-world applications that “bend” basic assumptions used in many studies today
- Conclusions

Inherent Assumptions

- A sample is drawn from a **homogeneous (time and/or space) population – for both GEV and GPD**

$$AEP(x) = \lambda(1 - F(x))$$

or

$$T = \frac{1}{AEP(x)} = \frac{1}{\lambda(1 - F(x))}$$

and over N years

$$P(x > threshold) = 1 - \prod_{i=1}^{N} F^{n}(x > threshold)$$

- Where AEP is annual exceedance probability, F(x) is the cumulative distribution function, λ is the Poisson frequency, T is return period and N is the number of years in the sample.

Not-So-Inherent Assumptions

- Directional probabilities and storm intensities can be treated as independent: $p(c_p,\theta)=p(c_p)p(\theta)$
- Stochastic-deterministic methods can be used over the entire Atlantic Ocean Basin to extend the sampling length of our record
- Since the population is homogeneous, λ and $F(x)$ can be treated as fixed over the sample interval
- We can use a simple method to move from multivariate distributions to response probabilities

Before moving on to threshold exceedance ……

- Coastal structures provide some of the longest lasting life-times of functionality (Dikes, Levees, Ports, etc.)
- Given this perspective, what does a “100-year design” really mean?
- How often do we want a major city to be inundated? The probability of exceedance of 100-year design in 50 years: 39.5%

It seems more logical to use a combination of Return Period and "Planned Life-Time" to define the context for risk of failure?

- In this context, if you want your design to last 100 years with a 0.01 probability of failure you would have $1\text{-}F(x_{100})^{100} < 0.01$ or:

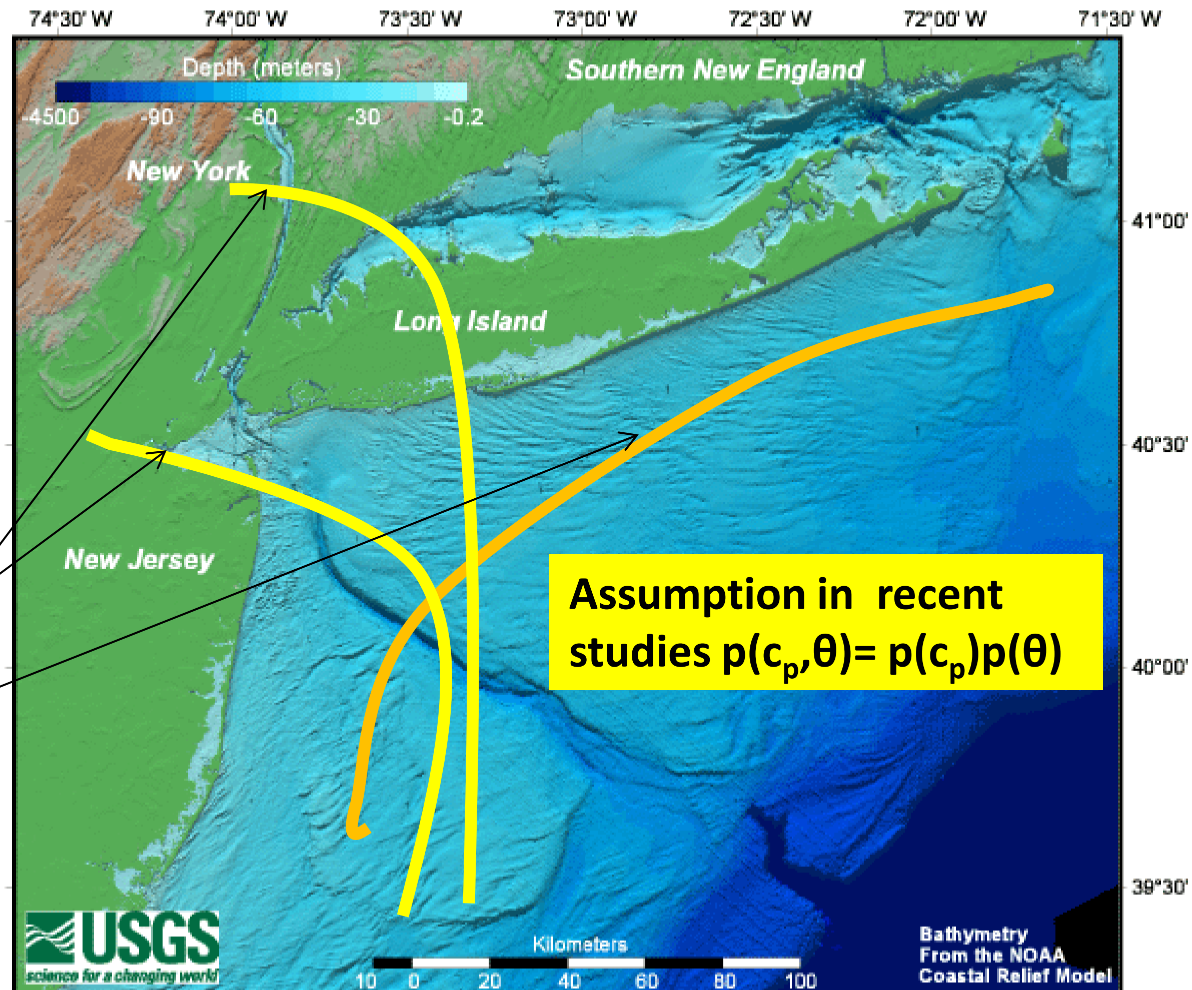
  $F(x_{100} | \text{Lifetime}=100 \text{ years}) = .9999$

- This means that the **design return period** for such a critical structures might be **10,000 years**
- Note: this would not affect insurance decision-making but would play a large role in design and planning

Example 1: Independence of: Directions and Intensities

Tropical storms in the New York Bight are treated as having direction and intensity attributes that are independent in recent flood studies.

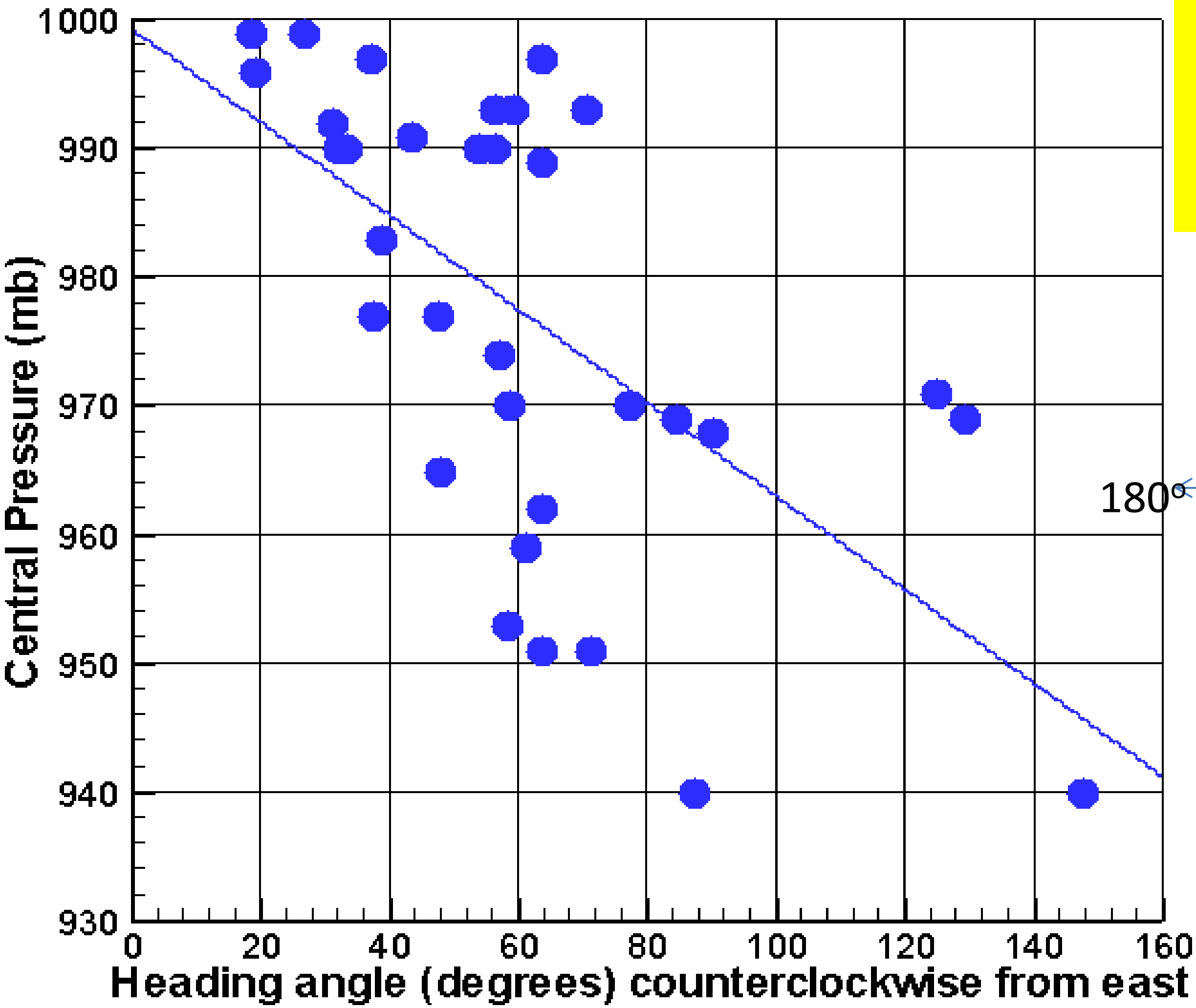
Non-recurring storms and recurring storms present very different surge hazards the NY/NJ vicinity of New York



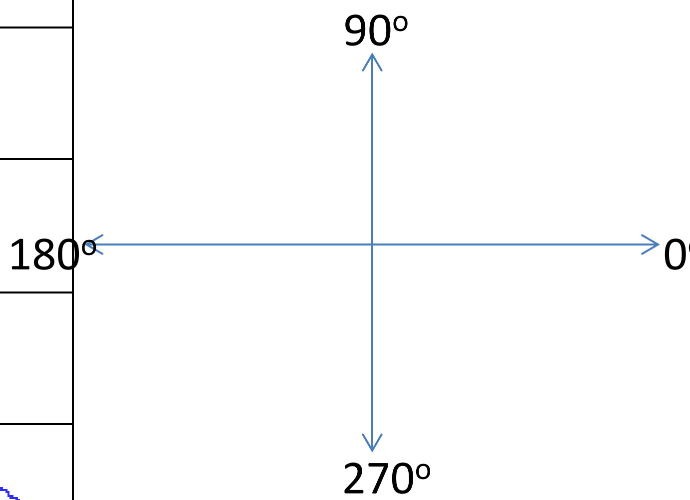
Assumption in recent studies $p(c_p,\theta)= p(c_p)p(\theta)$

Plot of storm intensity versus heading directions: Correlation – 0.66: Significant at 0.01 level

(From: Resio and Irish , 2015)



What impact might a violation of this assumption have on estimated surges??



Vector-Heading coordinate system

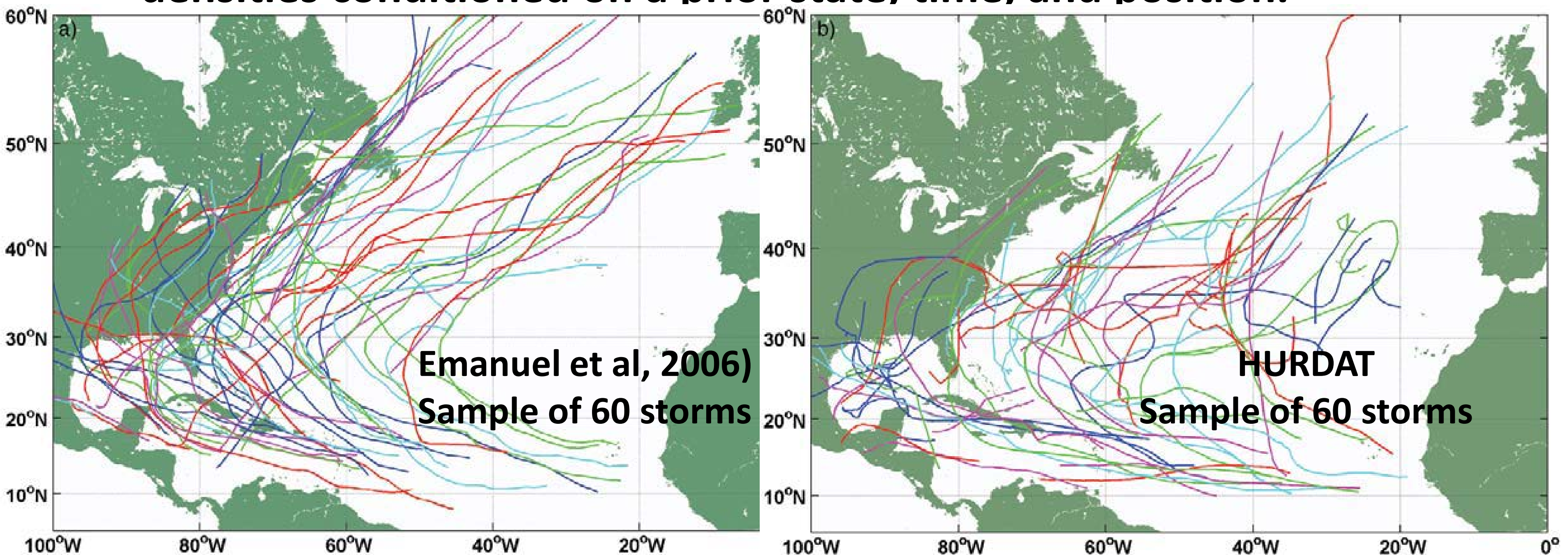
Differences in Estimated C_p for storms heading at angles ≥ 85° with and without considering correlation

Return Period (years_	C_p (mb) (No Correlation)	C_p (mb) (With Correlation)
100	955	939
500	951	931
1000	949	927

Note: Estimates based on 22 degree mean angle and 11-degree standard deviation. **This problem is exacerbated by the use of omnidirectional sampling over a broad spatial region which captures many more bypassing storms**

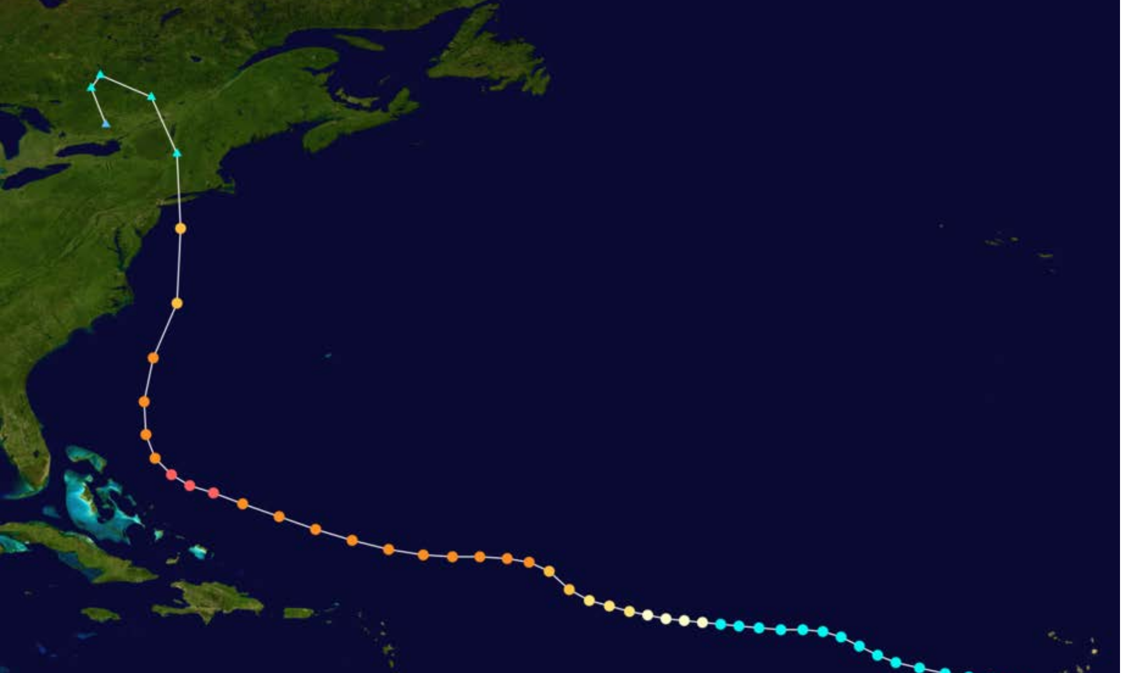
Case 2: Stochastic-Deterministic Models

- **First, a smooth, discrete space–time genesis probability distribution is constructed from the HURDAT track database and genesis events are sampled from this distribution.**
- **Each sample is then integrated forward in 6-h steps as a Markov chain (Lange 2003), using translation speed and direction and their rates of change as state variables.**
- **Transition probabilities for the Markov chain are constructed using variable-resolution, kernel-smoothed nonparametric densities conditioned on a prior state, time, and position.**



How well are these known?

- Epistemic Variability in Markov chain is untested and **baroclinic energy source to storms is neglected**
- Aleatory Variability is related to the sampling time and the spatial inhomogeneity of the sample – How well can we know multivariate structure as a function of location?



The vast majority of storms passing into the New York Bight recurve toward the east, which strongly influences directional statistics.

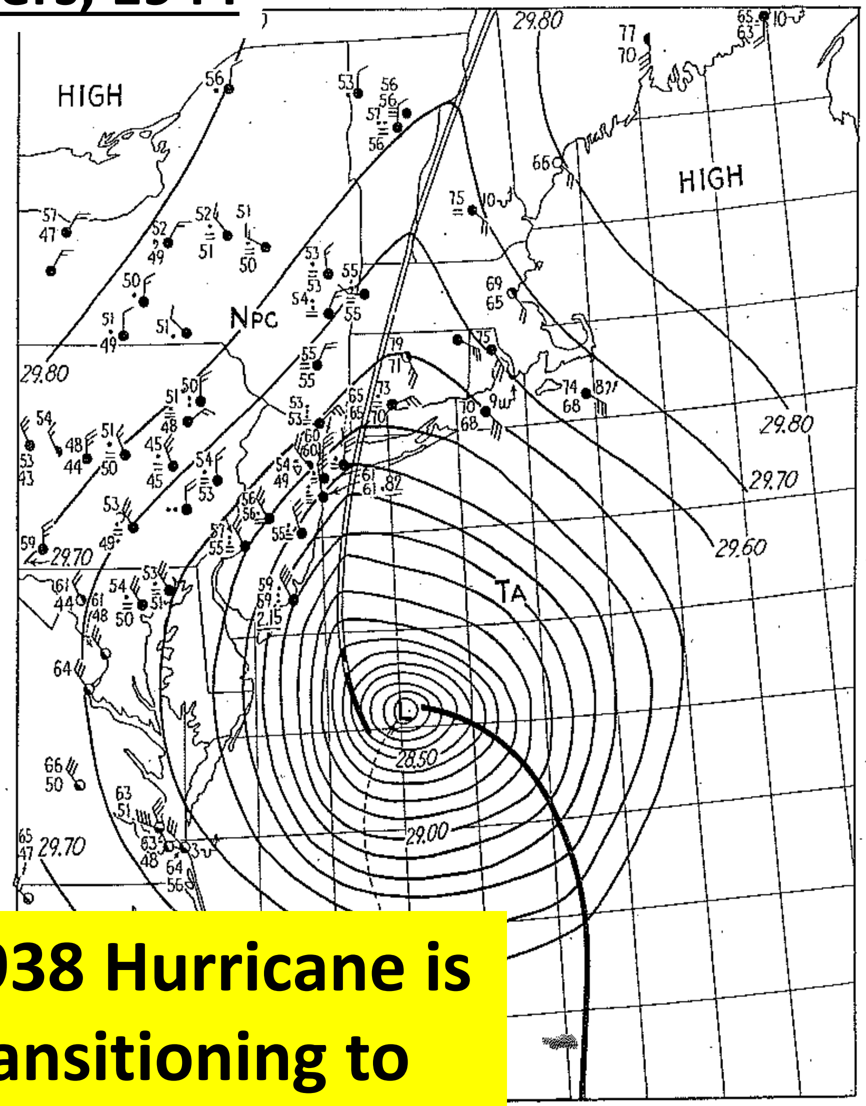
Both the 1938 Hurricane and Hurricane Sandy did not recurve and were caught up in extratropical steering effects. **Recall the earlier correlation between heading and intensity.**

So what could the impact of this be?

Intensity Distribution of 7555 Simulated TCs NY Bight

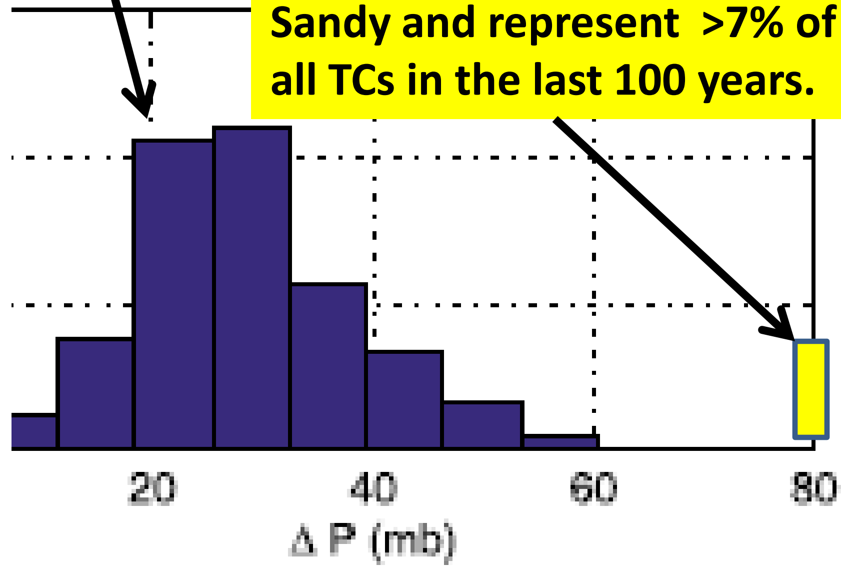
(Lin et al. 2010)

Byers, 1944



...rricane, as shown in the synoptic cha...
...e, Sept. 21, 1938.

1938 Hurricane is transitioning to Extratropical.

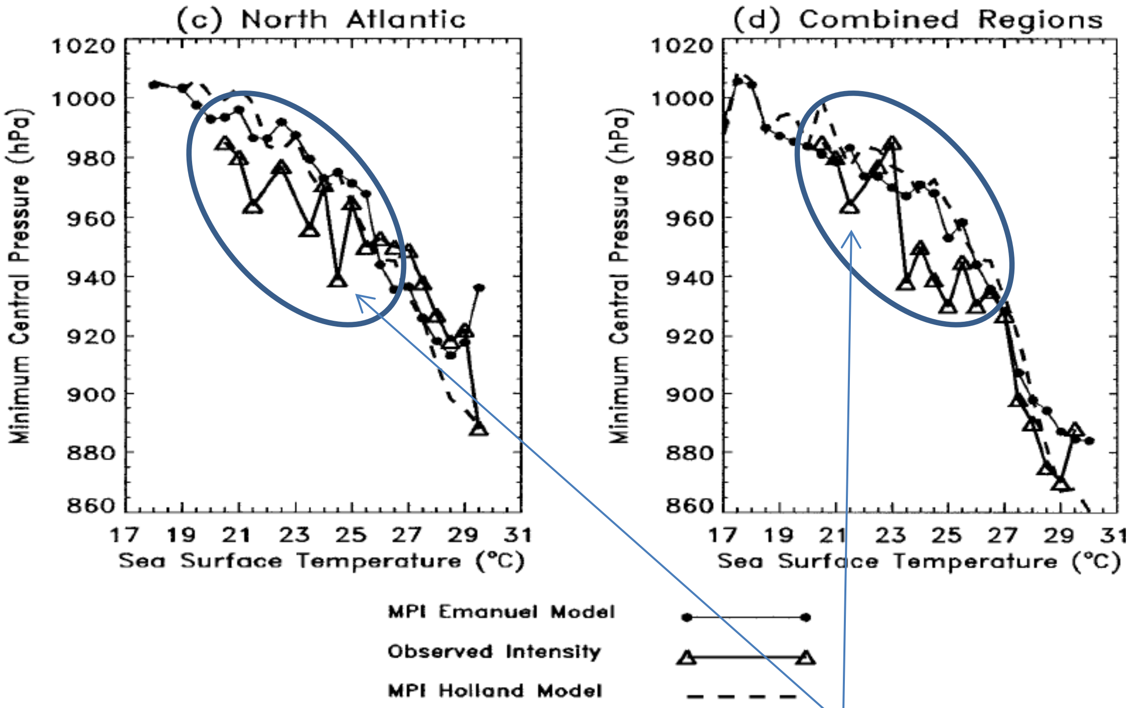


The 1938 Hurricanes and Sandy and represent >7% of all TCs in the last 100 years.

Maximum ΔP →60mb, but Sandy, a transitioning TC had a ΔP value of 78 mb.

Was Sandy unique? No, many TCs in this region undergo transition here as shown in the weather map for the 1938 "hurricane" (ΔP=80 mb).

(Jones et al. 2003)



Comparison of Envelope of Minimum Central Pressures and Idealized Models

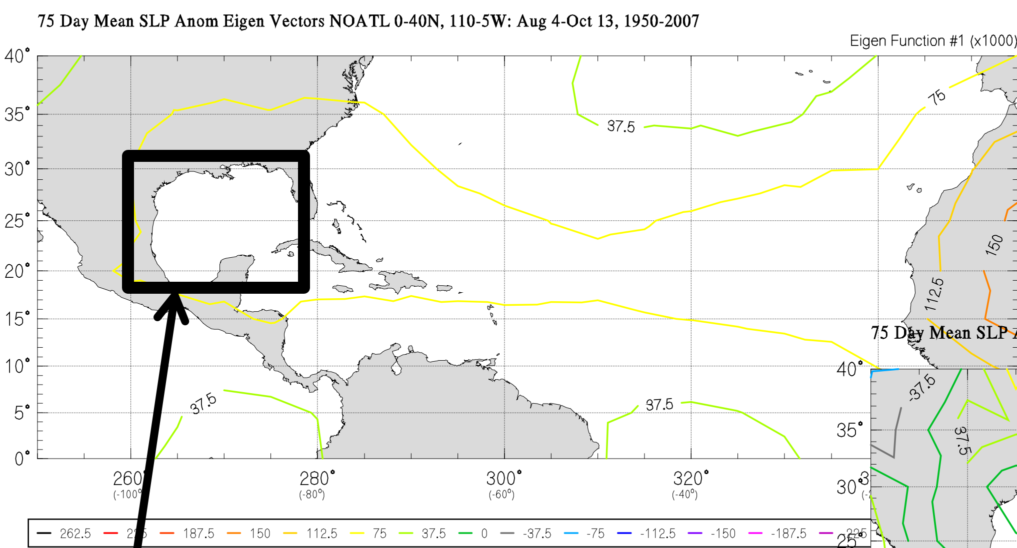
(Tonkin et al, 2000)

Note the two regions of central pressures significantly below the TC models – due most likely to their lack of baroclinic energy source.

Storms heading more westerly are able to tap into this energy more effectively

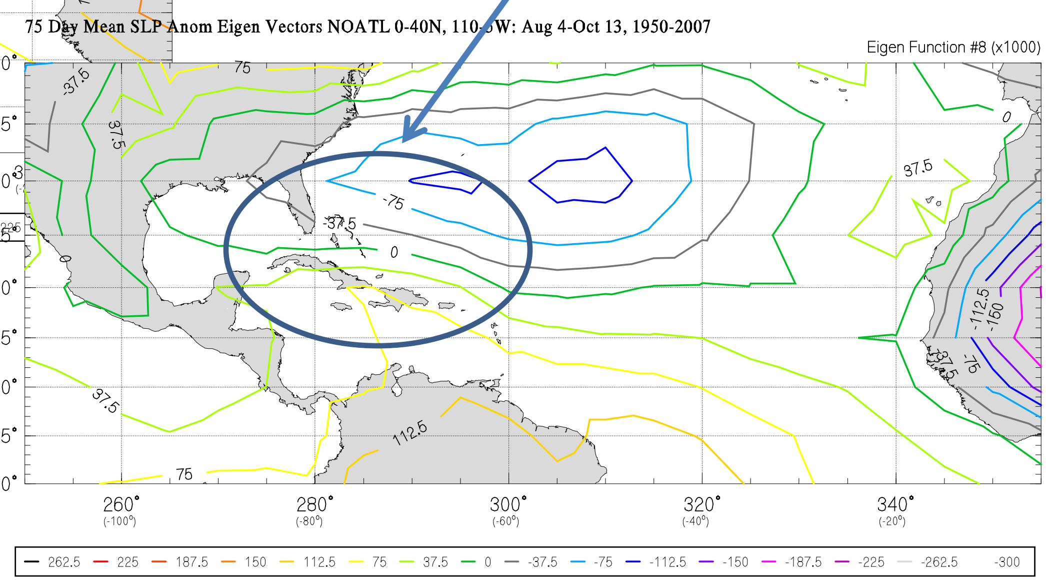
Case 3: Are λ and F(x) independent and homogeneous over a sample?

- **Using EOFs (PCA) to isolate the major organized modes of variations, we find that two of the eigenfunctions are:**



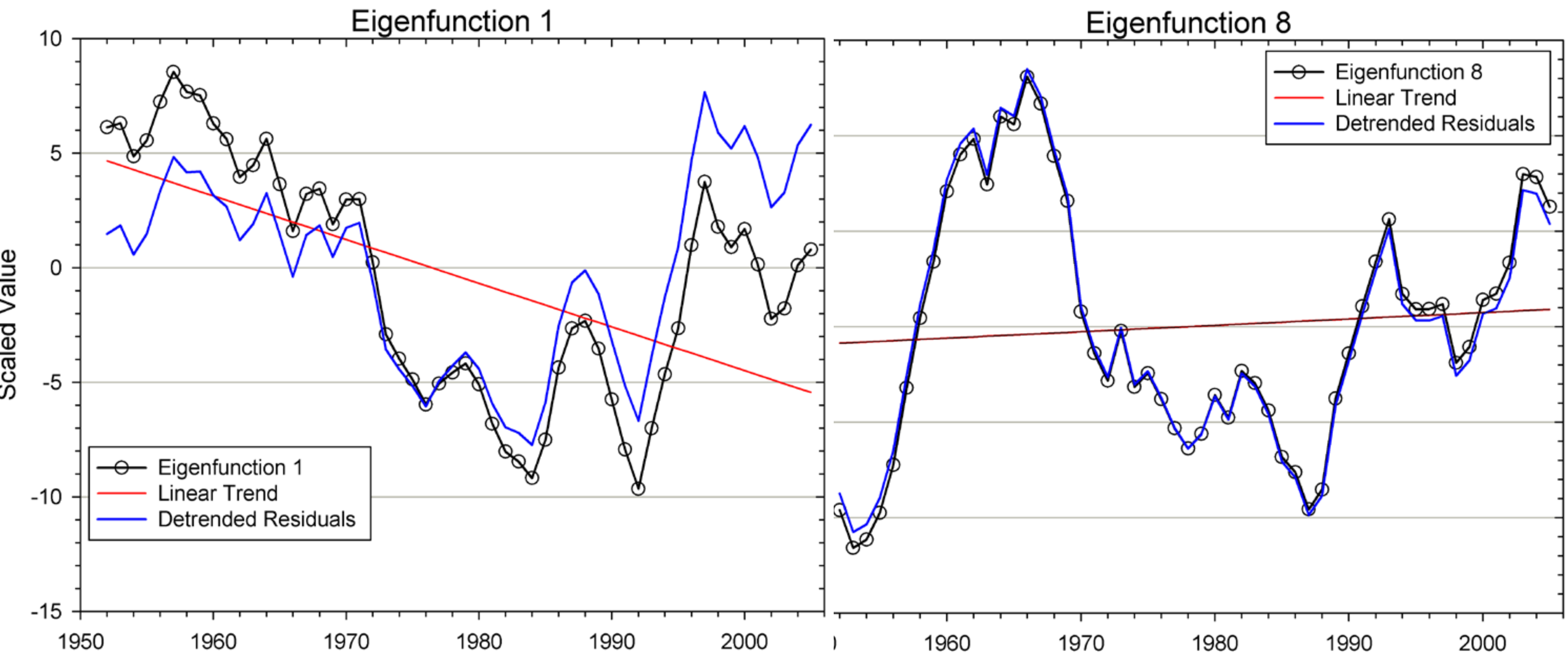
Area of interest: Gulf of Mexico

Over 15% of variance contained in area affecting hurricane tracks.



We can form a time series of weightings on an E-function as:

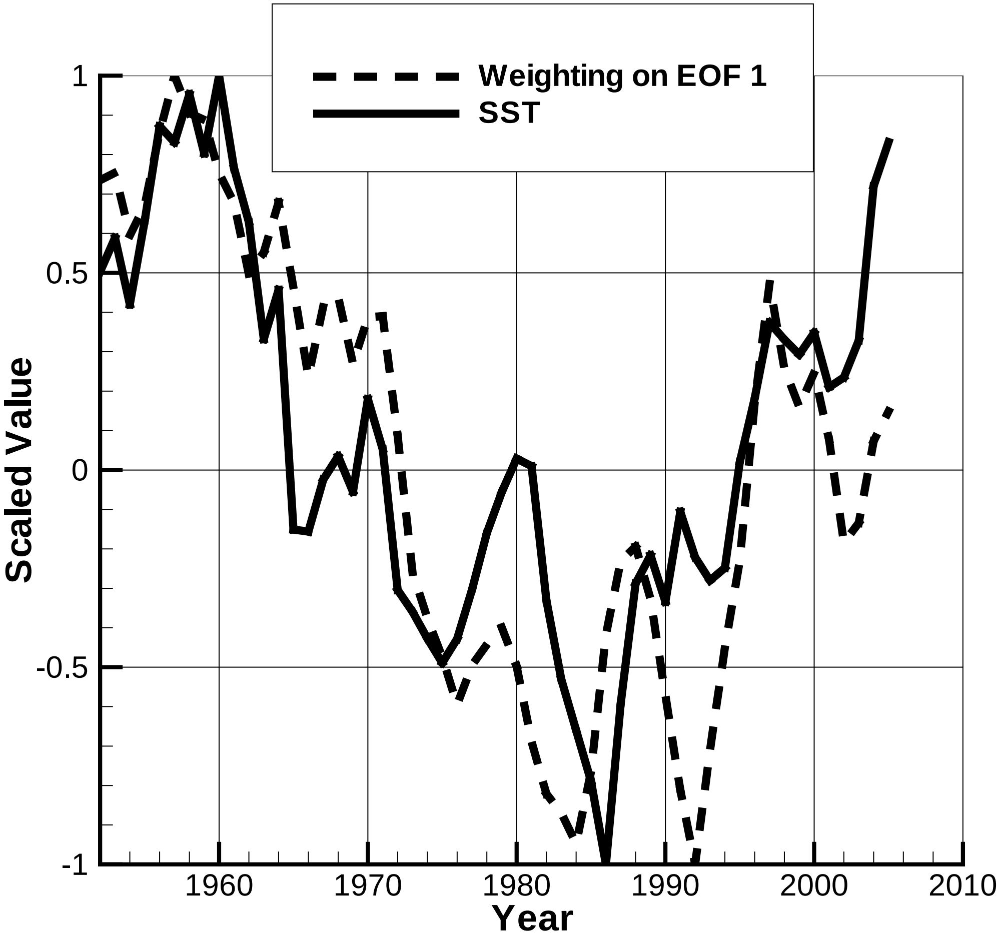
$$W_{i,k} = \sum_{j=1}^{N} O_{i,j} E_{k,j}$$



Relatively long-interval cycles, but do they have physical significance?

Weightings on EOF 1 are correlated above 0.8 level with SST but out of phase with H.I.

Using the zero-crossing point for stratifying the hurricane population, we get at landfall:



1974	Carmen	937
1979	Frederic	946
1980	Allen	945
1998	Earl	987
1996	Opal	942
2002	Lili	963

← **Negative wts**

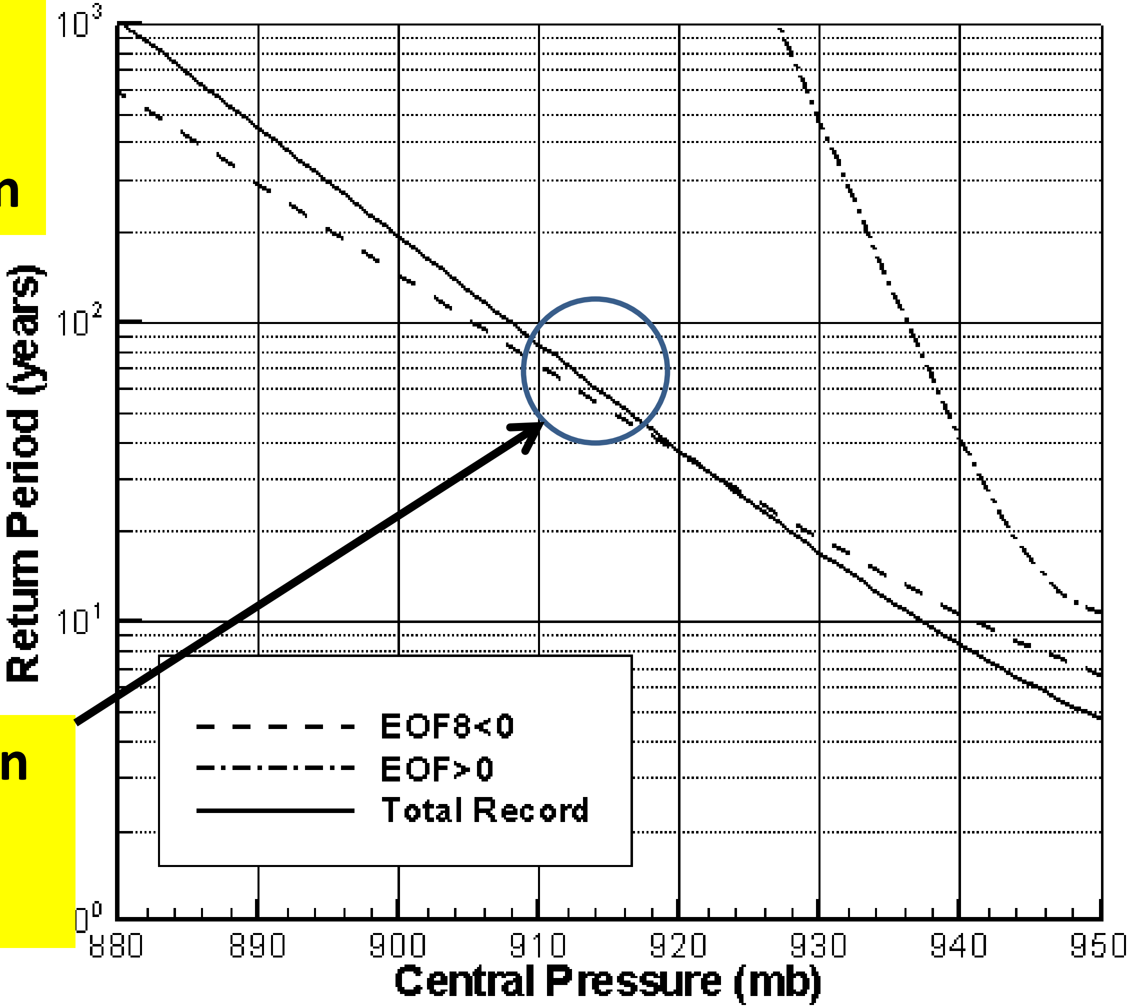
Positive wts →

Stratification on magnitude alone would not separate these .

1957	Audrey	945
1961	Carla	931
1964	Hilda	950
1965	Betsy	948
1967	Beulah	950
1969	Camille	900
1970	Celia	945
1992	Andrew	945
2004	Charley	941
2004	Ivan	946
2005	Dennis	946
2005	Katrina	920
2005	Rita	937
2005	Wilma	959
2008	Gustav	954
2008	Ike	950

Years with positive EOF 8 weighting have more storms and they are more intense (two populations) based on best-fit Poisson-Gumbel distributions

Error Increases With Extrapolation



Not too bad in the range of the record

Moving from multivariate to scalar extreme estimates: the cumulative distribution function for a (scalar) Response of interest (inundation level, wave height above a threshold, etc.) can be written as:

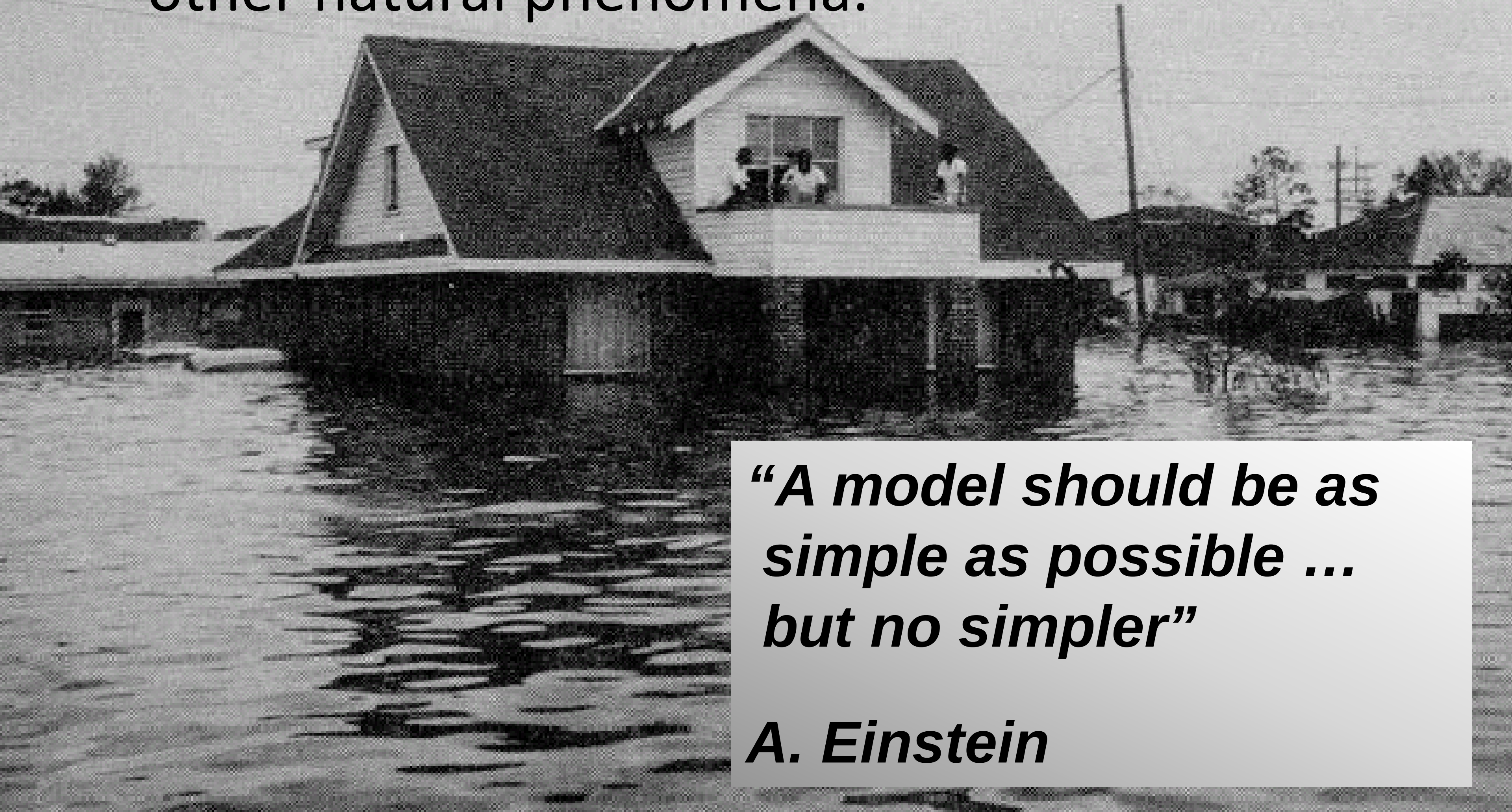
$$F(R) = \int_0^\infty \cdots \int_0^\infty P(X_1,\ldots,X_n) H[R - R(X_1,\ldots,X_n)] dX_1,\ldots,X_n$$

Where, the X parameters denote all the different factors that go into a model to estimate R and H(.) represents the Heaviside function =1 if R≥1 and =0 if R<1.

But, the multivariate, possibly multi-population used in this estimate should be carefully considered in light of the influence of natural structure within the sample!!

Conclusion

- Statistics-only approach to extremes can lead you quite astray in surges and probably most other natural phenomena.

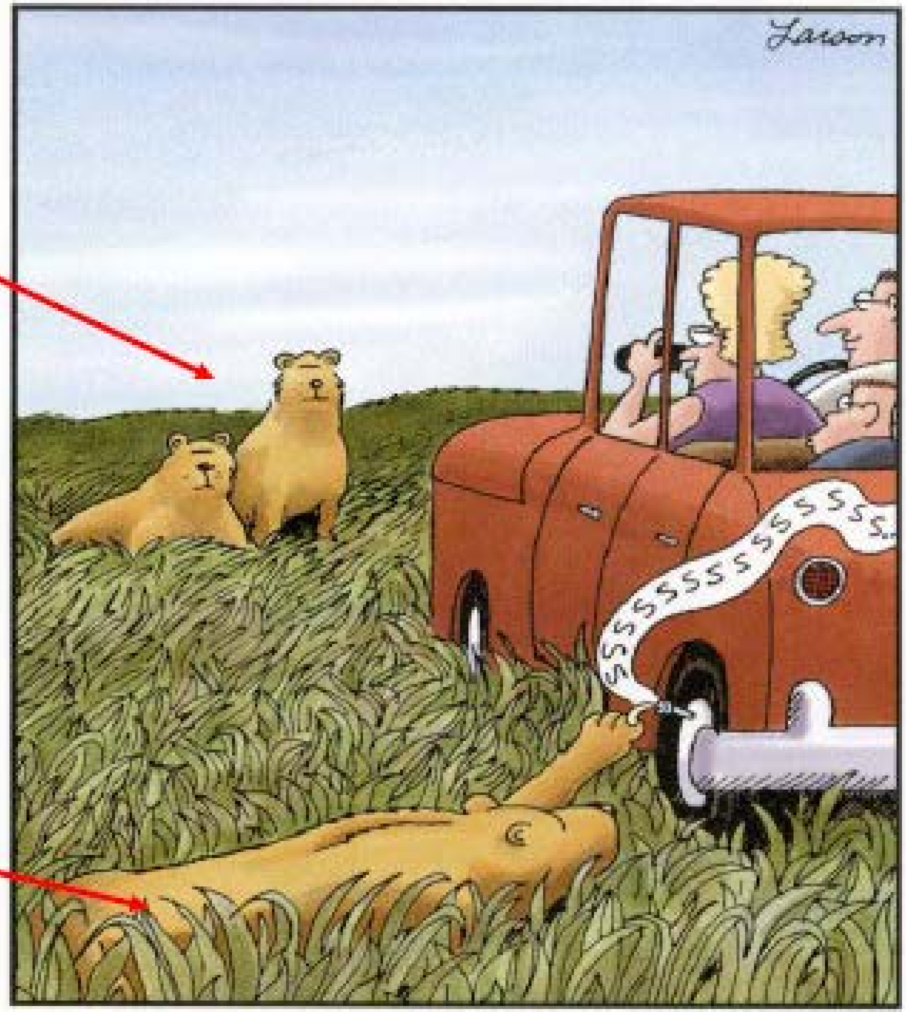


"A model should be as simple as possible … but no simpler"

A. Einstein

QUESTIONS??????

Known threat –
Dangerous but can
be analyzed and
risk can be understood



Unknown threat –
Not recognized as
a problem, but can
significantly affect
the actual risk level

Acknowledging Sverre Haver, who is missed this year.