Atlantic Hurricane Surge Threat

Tide gauge records and a projection

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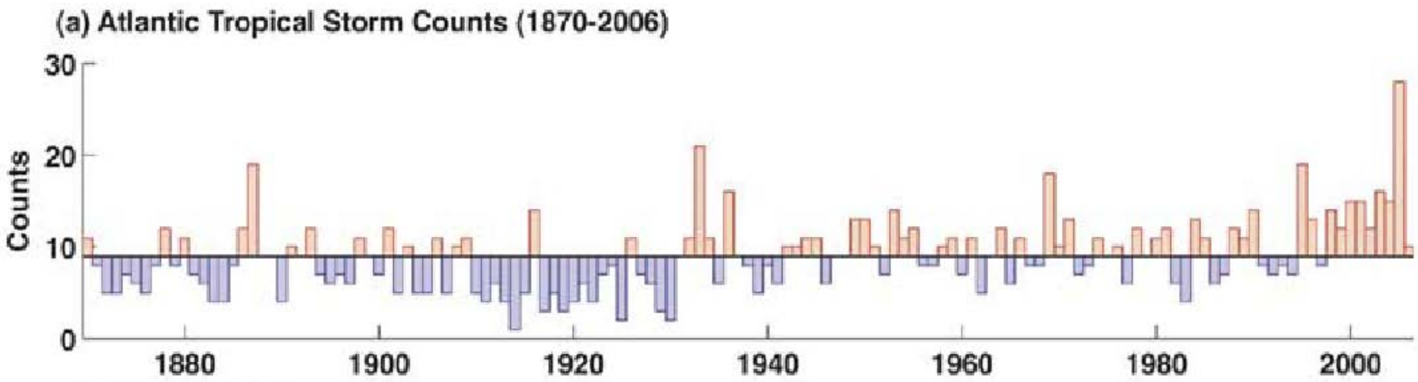
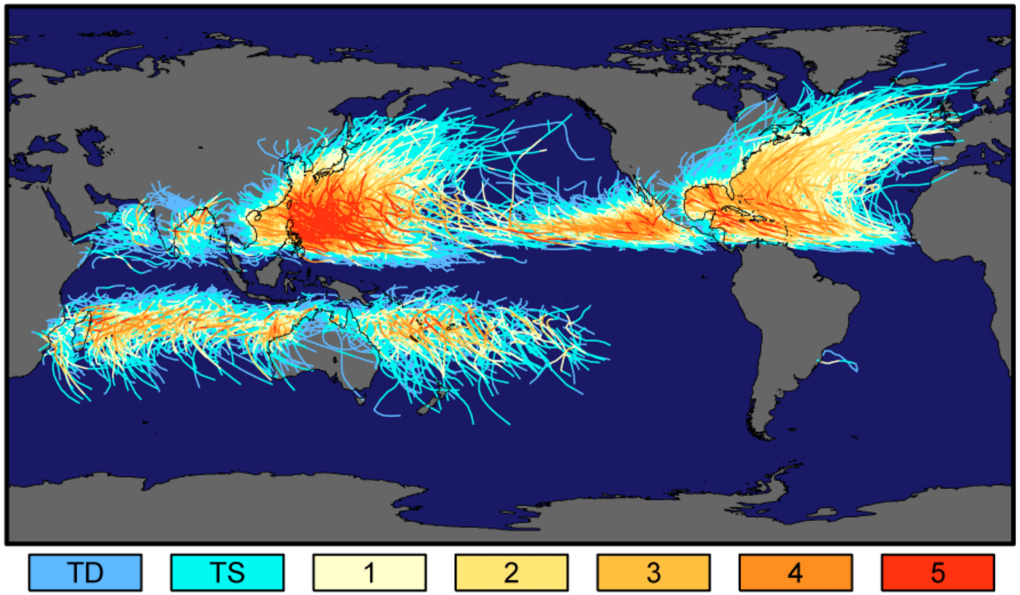
Motivation: trend in counts



Tracks and Intensity of All Tropical Storms



- Apparent trend in storm counts

Motivation: observational Bias

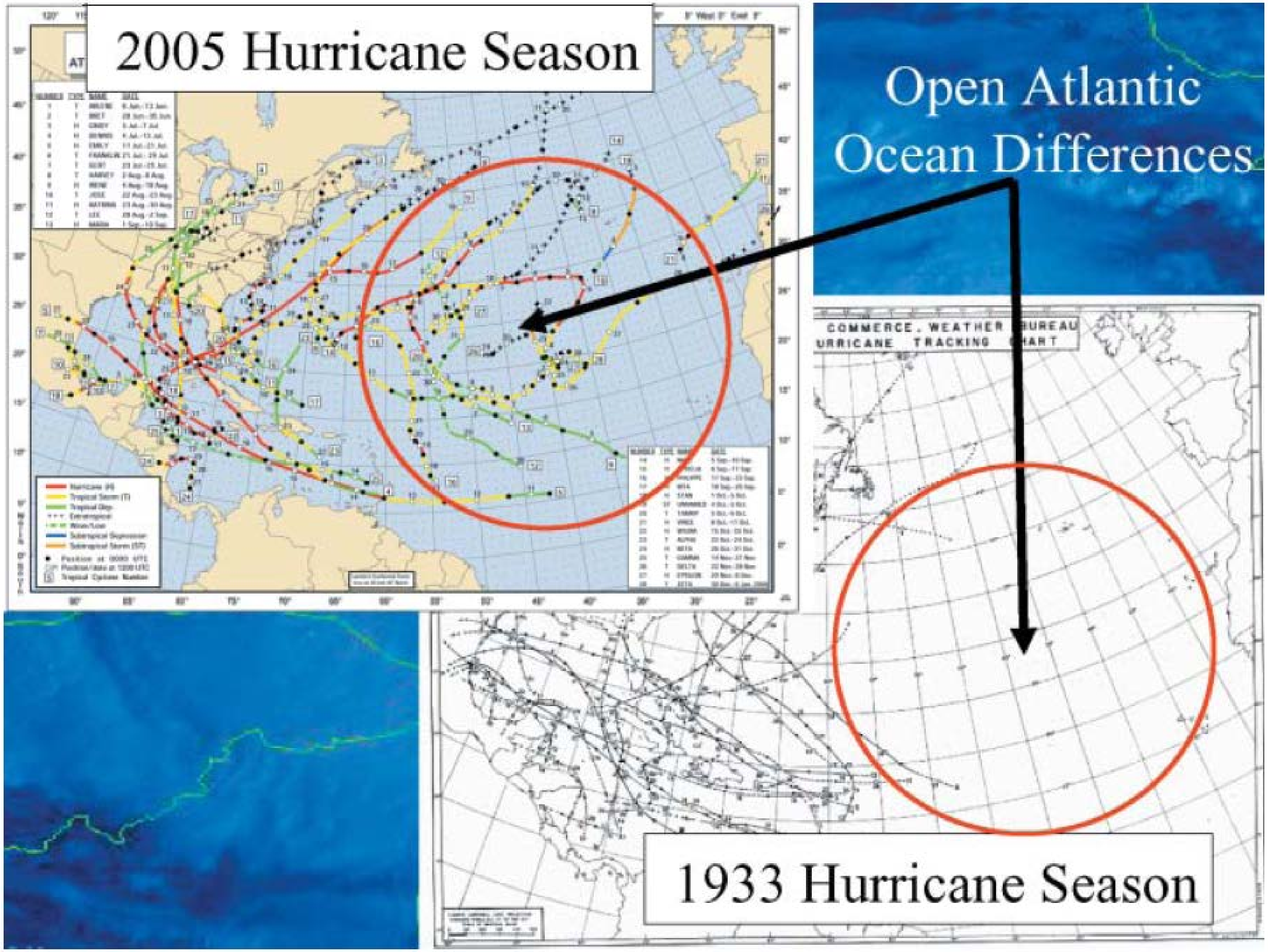


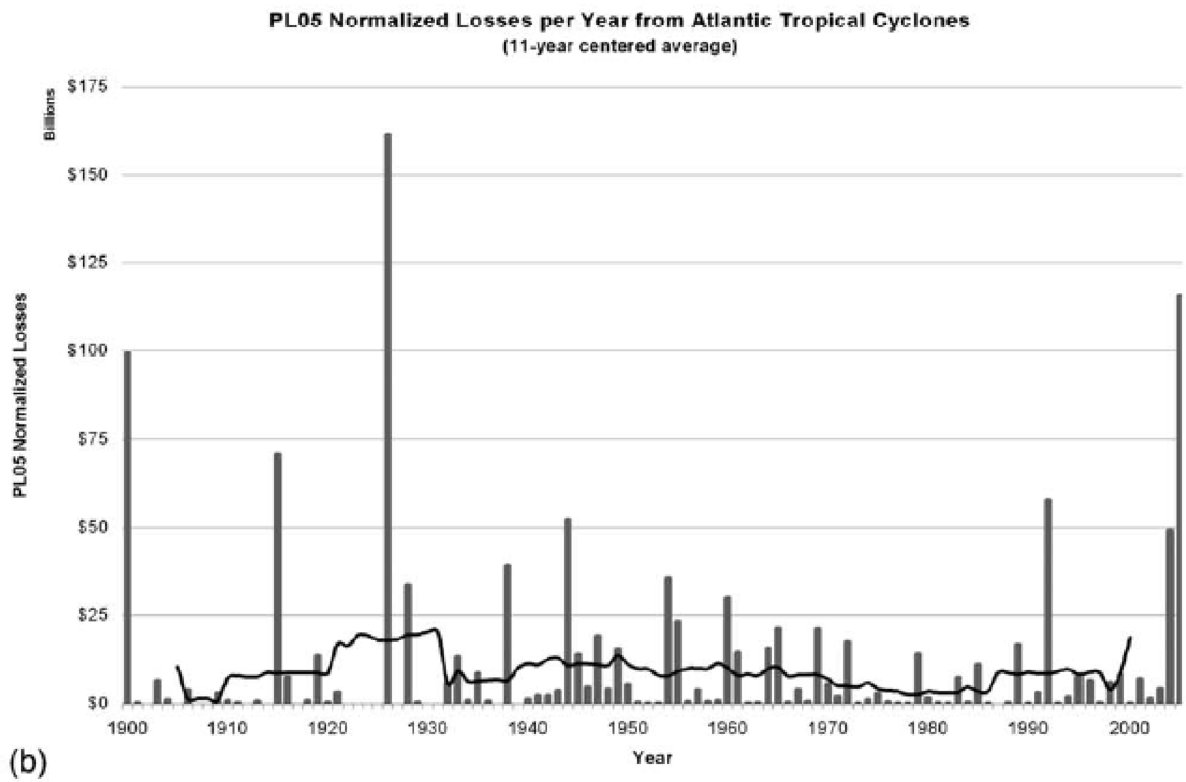
Fig. 1. Track maps of the Atlantic hurricane seasons of 2005 and 1933, the two busiest hurricane years on record for tropical cyclone frequency. The circles highlight large differences in activity that occurred over the open Atlantic Ocean.

Landsea, EOS2007

Danish National Research Foundation

Motivation:
Normalized Hurricane Damage (NHD)

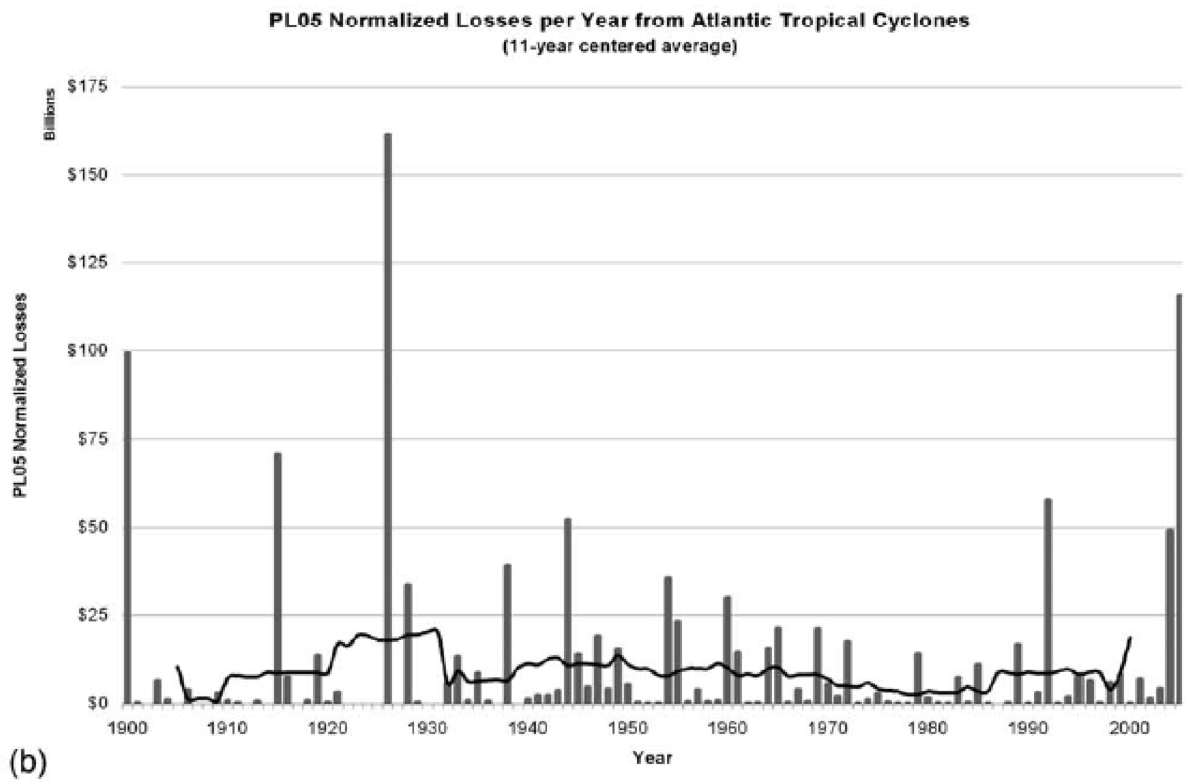
CENTRE FOR ICE AND CLIMATE



Avg:
14bn$/yr
(2013$)

Fig. 3. U.S. Gulf and Atlantic hurricane damage 1900–2005 adjusted for inflation. Total United States tropical cyclone losses adjusted only for inflation to 2005 dollars. Upward trend in damages is clearly evident, but this is misleading since increased wealth, population, and housing units are not taken into account.

Motivation:
Normalized Hurricane Damage (NHD)



(b)

Avg:
14bn$/yr
(2013$)

Fig. 3. U.S. Gulf and Atlantic hurrican ... cal cyclone losses adjusted only for inflation to 2005 dollars. Upward trend ... ealth, population, and housing units are not taken into account.

Corrected for "wealth at risk"

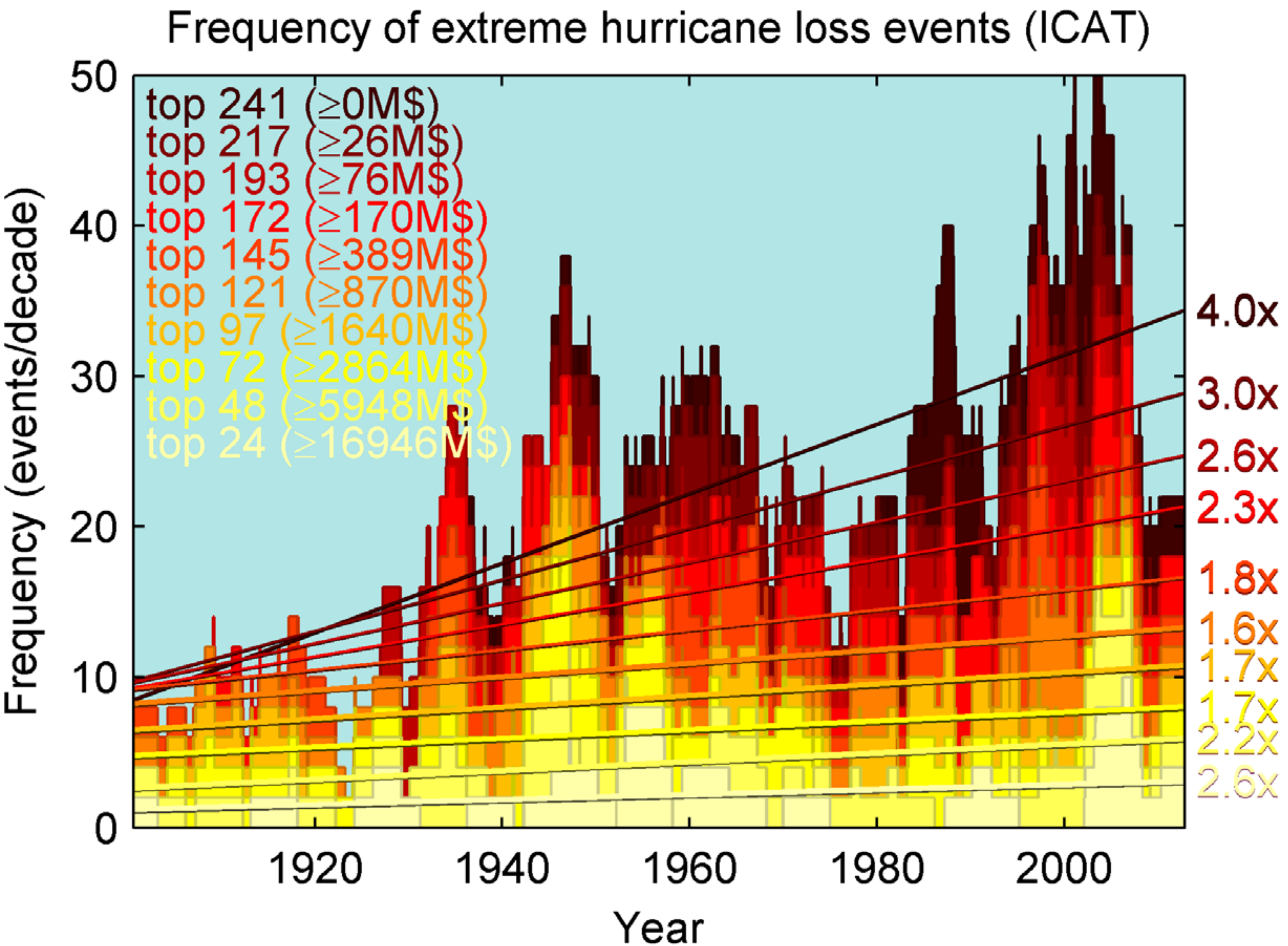
$$D_{2005} = D_y \times I_y \times \mathrm{RWPC}_y \times P_{2005/y} \qquad (1)$$

where D_{2005}=normalized damages in 2005 dollars; D_y=reported damages in current-year dollars; I_y=inflation adjustment; RWPC_y=real wealth per capita adjustment; and $P_{2005/y}$=coastal county population adjustment.

Danish National Research Foundation

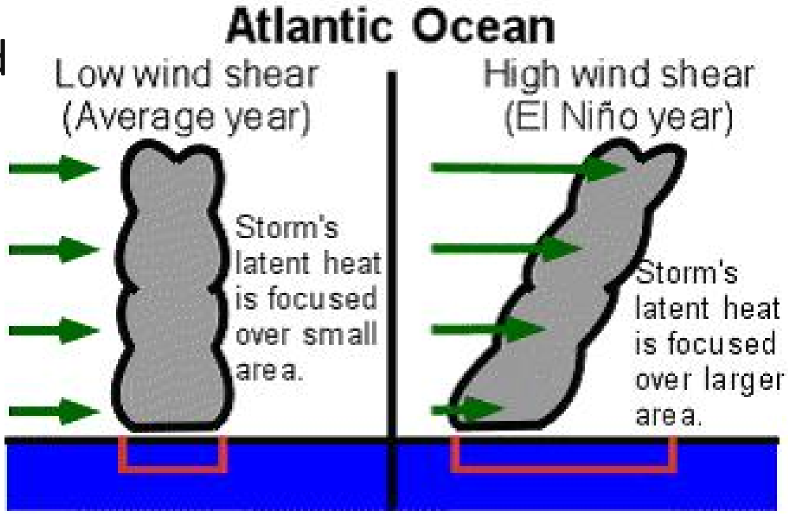
Motivation: Hurricane damages
(corrected for societal changes)

CENTRE FOR ICE AND CLIMATE

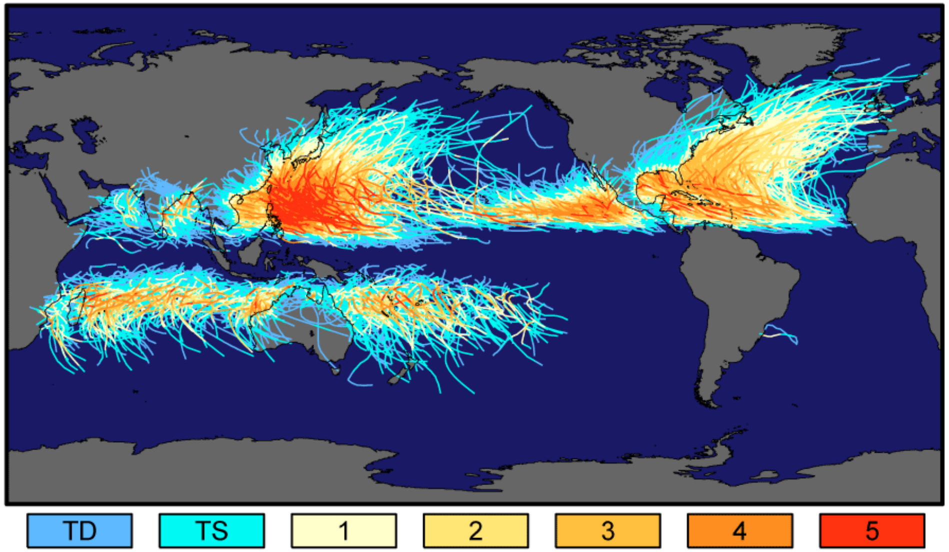


Background

- Warmer sea surface temperatures (SST) are favourable to tropical cyclones.
- But warming may also increase vertical wind shear, which would be unfavourable.
- **Relationship to warming is not trivial.**



Tracks and Intensity of All Tropical Storms



Saffir-Simpson Hurricane Intensity Scale

REVIEW ARTICLE

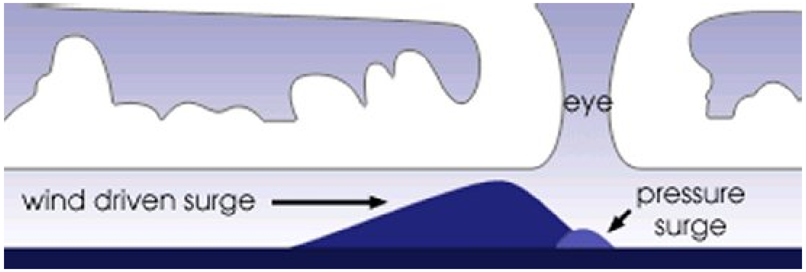
Box 1 | Summary of detection, attribution and projection assessmen

Detection and attribution

It remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, and so on) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities.

IDEA: Use tide gauge records of storm surges

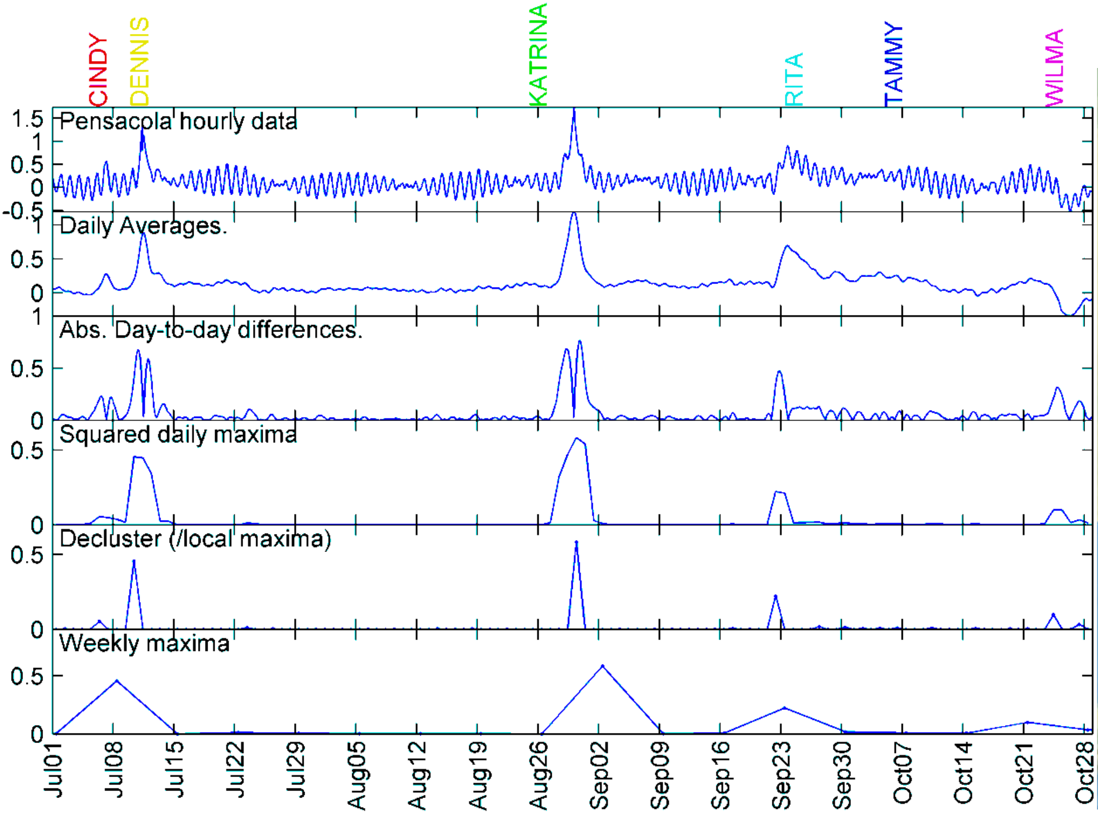
- The strong winds and intense low pressure associated with tropical **cyclones generate storm surges**.
- wherever tropical cyclones prevail they are **the primary cause of storm surges**.

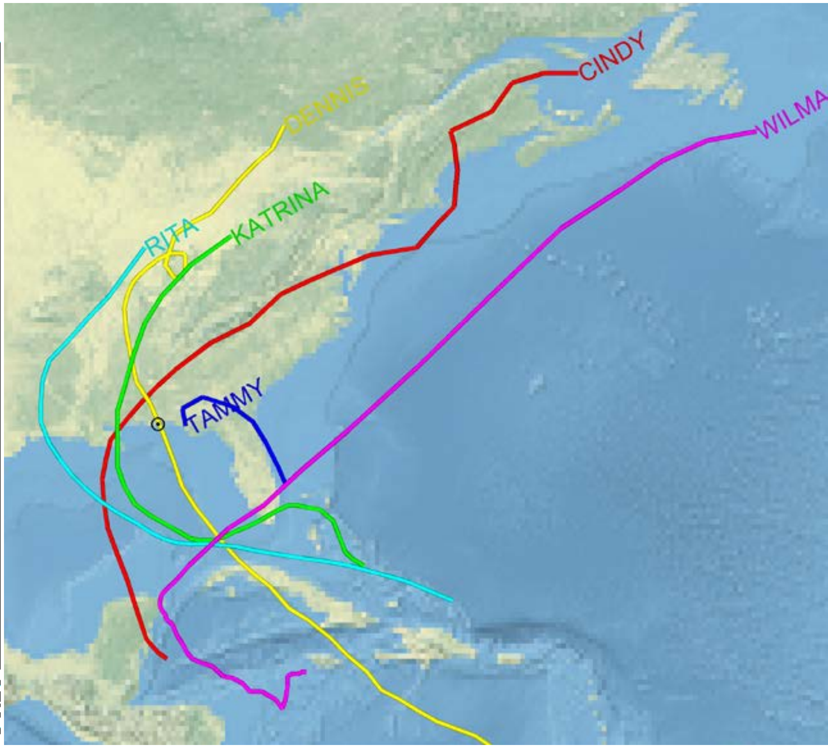


- Storm surges are the **most harmful aspect of tropical cyclones** in the current climate

- A record of storm surge intensity would therefore be a useful measure of a major part of hurricane threat.

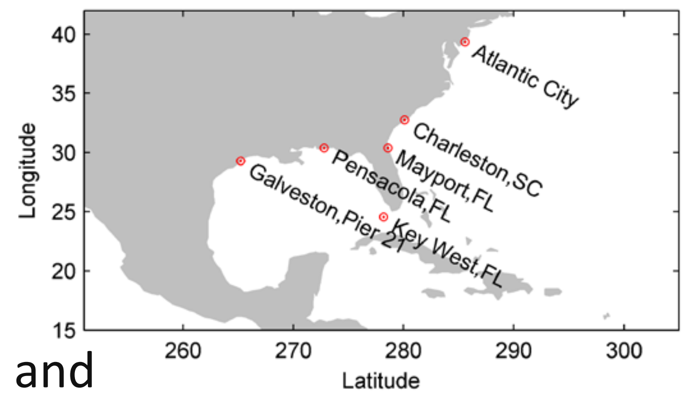
Pre-Processing: Extracting the hurricane surge



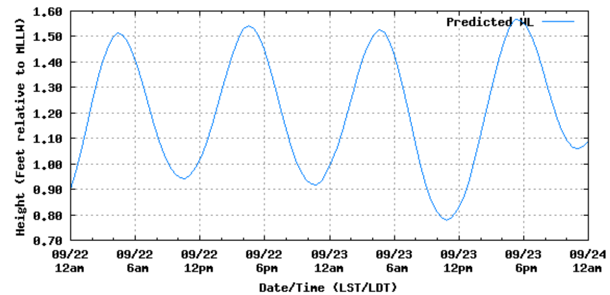


Constructing an independent & **homogeneous** regional **Surge Index**

- We use 6 **long tide gauge records** in the tropical atlantic. (1923 onwards)
- **Daily averages** to minimize influence of wave dynamics, and instrument changes (incl. harbour development).
- **Day to day differencing** to remove the tidal signal and the influence from global sea level rise.
- **Squared**: The potential energy stored in a sea level perturbation is related to the square of the vertical displacement of the sea surface
- **Normalize + Remove seasonal cycle** from each record to make them comparable. (Local bathymetry may make some locations particular sensitive to storm surge).
- **For each day choose the maximum squared-change from each of the records.**

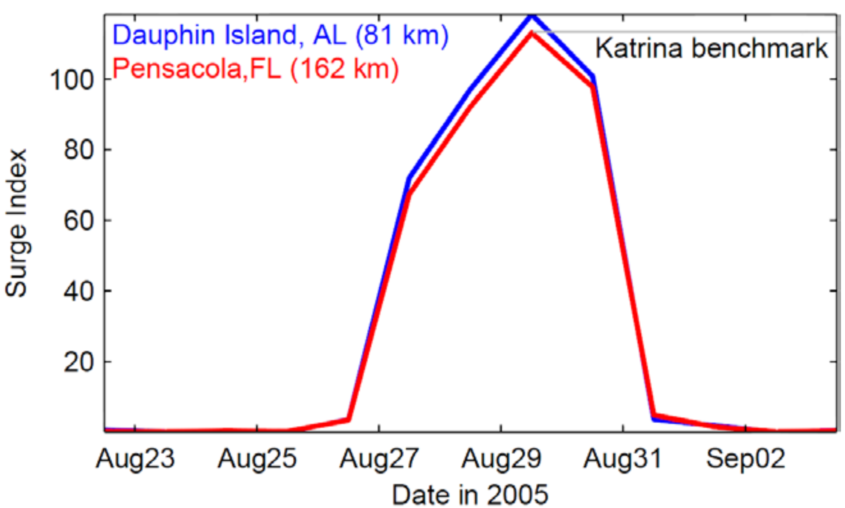


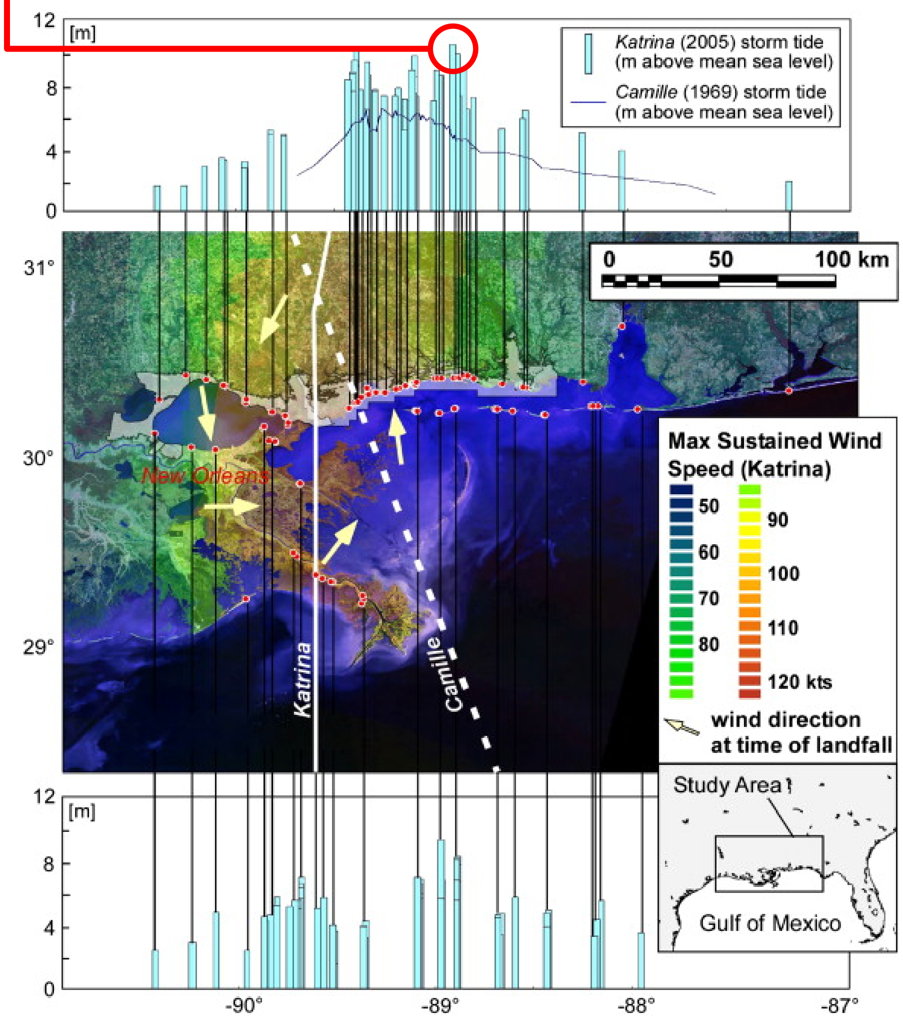
Tide prediction



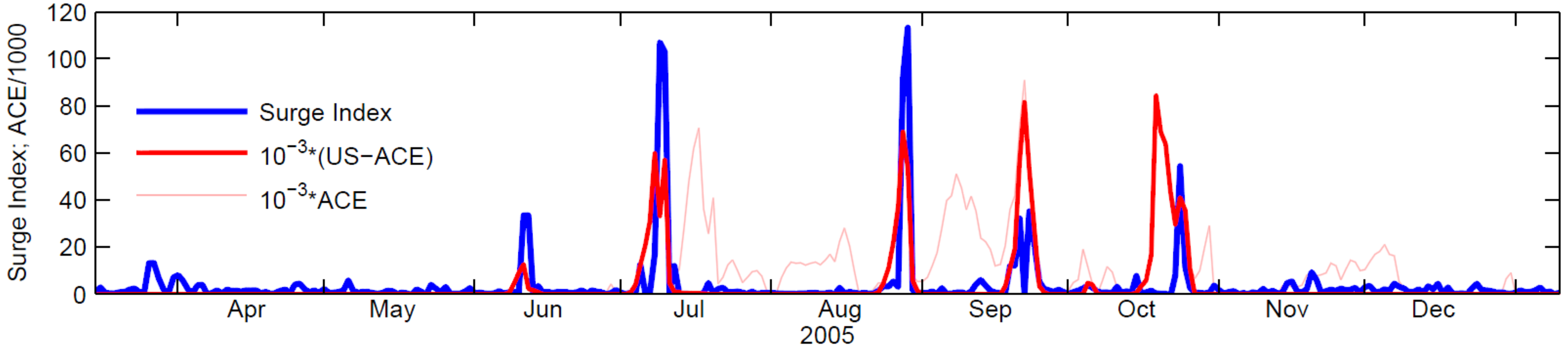
Criteria: long & almost complete

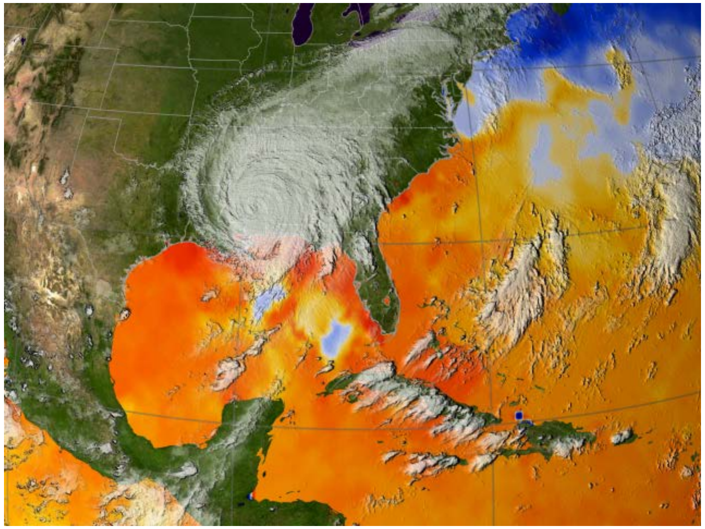
The definition of a Katrina Benchmark





Does the surge index really respond to hurricanes?





ACE: Accumulated Cyclone Energy (Wind^2)
US-prefix: calculation restricted to storms that made US-landfall.

The surge index is a proxy for cyclone activity!

Table S2. 50 greatest events

Rank	Event date	Candidate storm (category)	Surge index	ACE	US-ACE	Wind,
1	Sept. 20, 1926	“Great Miami hurricane” (4)	283	422,098	228,174	125
2	July 25, 1934	Not named (1)	153	39,450	39,450	65
3	Sept. 19, 1947	Not named (5)	139	223,806	223,806	130
4	Sept. 10, 1961	Carla (5)	114	588,267	312,007	125
5	Aug. 30, 2005	Katrina (5)	113	189,274	167,424	110
6	July 10, 2005	Dennis (4)	107	207,799	188,024	120
7	Sept. 12, 2008	Ike (4)	104	146,499	143,599	100
8	Sept. 10, 1965	Betsy (4)	94	169,699	169,699	135
9	Sept. 1, 1932	Not named (1)	89	172,324	65,775	70
10	June 28, 1957	Audrey (4)	86	79,474	79,474	125
11	Sept. 27, 1998	Georges (4)	85	463,173	155,699	95
12	Sept. 1, 2008	Gustav (4)	70	326,423	300,849	125
13	Oct. 6, 1995	Opal (4)	59	180,099	91,975	110
14	Aug. 5, 1940	Not named (1)	57	117,449	117,449	70
15	Aug. 18, 1969	Camille (5)	57	362,419	217,996	165
16	Aug. 13, 1932	Not named (4)	55	64,600	64,600	125
17	Oct. 25, 2005	Wilma (5)	55	190,674	161,224	110
18	July 15, 2003	Claudette (1)	55	81,050	56,875	75
19	Oct. 4, 1964	Hilda (4)	53	166,994	166,994	83
20	Sept. 15, 2004	Ivan (5)	53	406,723	364,298	105
21	Aug. 17, 1983	Alicia (3)	52	68,500	68,500	100
22	Aug. 31, 1942	Not named (3)	49	162,324	93,275	70
23	Aug. 26, 1926	Not named (3)	48	110,974	110,974	95
24	Sept. 27, 2002	Isidore (3)	47	180,174	180,174	110
25	8-Sep-1974	Carmen (4)	47	168,899	124,474	120
26	Sept. 12, 1979	Frederic (4)	42	272,524	134,274	115
27	Sept. 25, 1941	Not named (1)	40	229,774	57,725	70
28	April 8, 1938		39			
29	Sept. 19, 1928	Not named (5)	39	152,974	152,974	140
30	Feb. 27, 1984		39			

The surge index is a proxy for cyclone activity!

42 of top-50:
known tropical storms

remainder primarily
severe winter storms.

Table S2 50 greatest events

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		(1)	153	39,450	39,450	65
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						100
						135
						70
						125
						95
						125
						110
						70
15	Aug. [illegible], 1969	Camil				165
16	Aug. 13, 1932	Not na				125
17	Oct. 25, 2005	Wilma				110
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3 Storm of the Centur...

en.wikipedia.org/wiki/1993_Storm_of_the_Century

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1993 Storm of the Century

From Wikipedia, the free encyclopedia

The **Storm of the Century**, also known as the **'93 Superstorm**, or the (**Great**) **Blizzard of 1993**, was a large cyclonic storm that occurred on March 12–13, 1993, on the East Coast of North America. It is unique for its intensity, massive size and wide-reaching effect. At its height the storm stretched from Canada to Central America, but its main impact was on the Eastern United States and Cuba. Areas as far south as central Alabama and Georgia received 6 to 8 inches (15 to 20 cm) of snow and areas such as Birmingham, Alabama, received up to 12 inches (30 cm) with isolated reports of 16 inches (41 cm). Even the Florida Panhandle reported up to 4 inches (10 cm)[2], with hurricane-force wind gusts and record low barometric pressures. Between Louisiana and Cuba, hurricane-force winds produced high storm surges in the Gulf of Mexico, which along with scattered tornadoes killed dozens of people.

Contents [hide]

1 Formation
1.1 Forecasting
2 Storm progression
2.1 The blizzard
2.2 Subtropical derecho
2.3 Tornadoes spawned by the storm
3 Impact
4 Storm amounts
5 See also
6 References
7 External links

Storm of the Century (1993)

Satellite image by NASA of the superstorm on March 13, 1993, at 10:01 UTC.

Storm type: Cyclonic blizzard, Nor'easter
Formed: March 11, 1993

Comparisons with other measures of cyclone activity

Table 1. Correlations between July–November surge index and other measures of cyclone activity

Series	Period of overlap	Correlation full period	Correlation 1950–2005	High-frequency correlation	Low-frequency correlation
Cat 0–5	1923–2008	0.56	0.65	0.51	0.64
Cat 1–5	1923–2008	0.55	0.57	0.54	0.56
Cat 2–5	1923–2008	0.50	0.42	0.51	0.50
Cat 3–5	1923–2008	0.51	0.47	0.42	0.58
Cat 4–5	1923–2008	0.53	0.50	0.46	0.62
Cat 5	1923–2008	0.38	0.61	0.41	0.48
US cat 0–5	1923–2008	0.54	0.55	0.55	0.56
US cat 1–5	1923–2008	0.57	0.57	0.55	0.67
US cat 2–5	1923–2008	0.55	0.56	0.51	0.66
US cat 3–5	1923–2008	0.57	0.60	0.55	0.67
US cat 4–5	1923–2008	0.61	0.70	0.57	0.74
US cat 5	1923–2008	0.38	0.62	0.38	0.46
ACE	1923–2008	0.61	0.58	0.54	0.72
US ACE	1923–2008	0.58	0.58	0.51	0.77
NTC	1923–2006	0.58	0.55	0.48	0.54
PDI	1923–2008	0.60	0.58	0.53	0.73
US PDI	1923–2008	0.58	0.61	0.52	0.75
NHD	1923–2005	0.65	0.66	0.59	0.38

Low-frequency correlation is the correlation of the two series after a 5-y moving average. High-frequency correlation is the correlation of the residuals after subtracting this moving average. A US prefix indicates that the metric has been restricted to US-landfalling storms only. Cat, category.

Very good agreement with many other measures of cyclone activity.

Especially measures which emphasize large land-falling hurricanes.

Only notable exception is trend of Normalized Hurricane Damages (NHD) which has been subjected to heavy trend corrections.

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Cat 5	1923–2008	0.38	0.61	0.41	0.48
US cat 0–5	1923–2008	0.54	0.55	0.55	0.56
US cat 1–5	1923–2008	0.57	0.57	0.55	0.67
US cat 2–5	1923–2008	0.55	0.56	0.51	0.66
US cat 3–5	1923–2008	0.57	0.60	0.55	0.67
US cat 4–5	1923–2008	0.61	0.70	0.57	0.74
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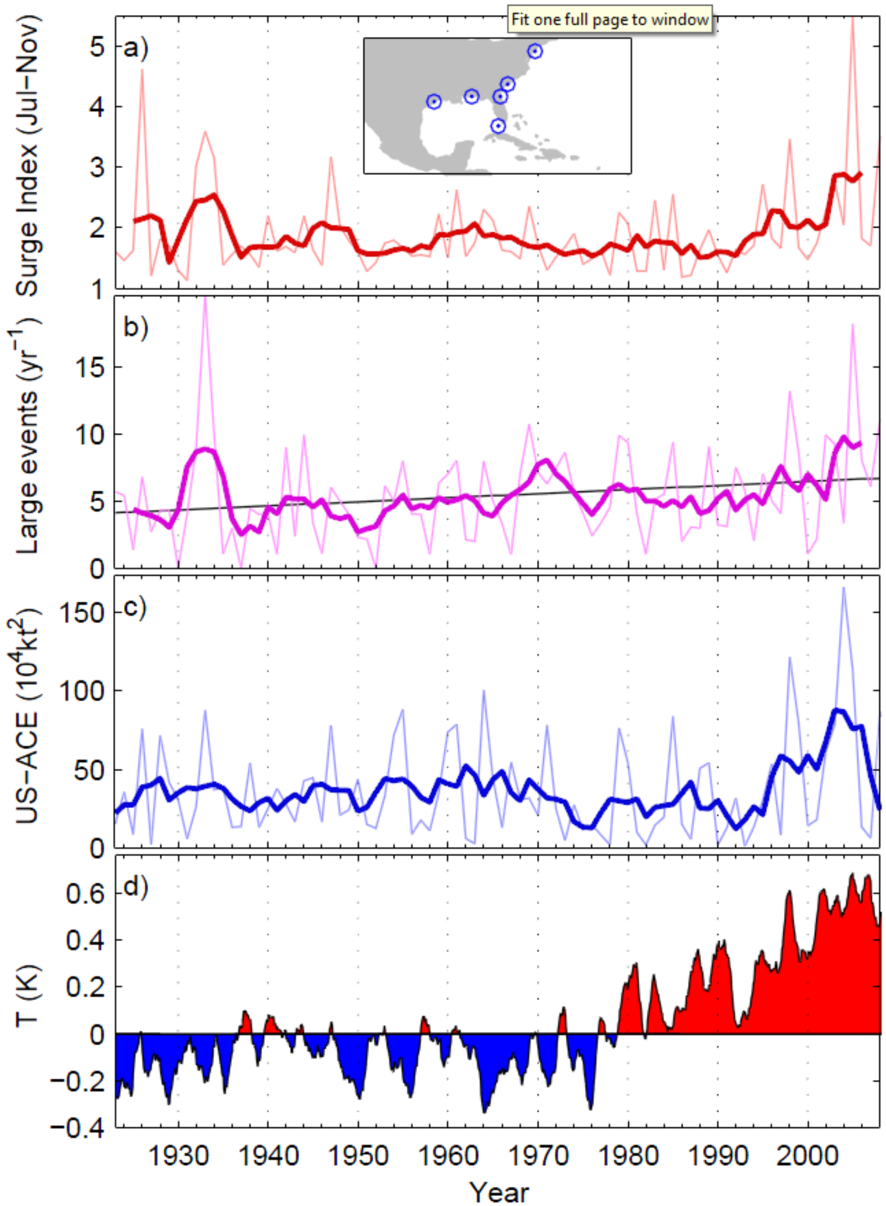
Low-frequency correlation is the correlation of the two series after a 5-y moving average. High-frequency correlation is the correlation of the residuals after subtracting this moving average. A US prefix indicates that the metric has been restricted to US landfalling storms only. Cat, category.

Very good agreement with many other measures of

Especially measures which emphasize large land-fallin

Only notable exception is trend of Normalized Hurrican
which has been subjected to heavy trend corrections.

Interpretation:
this is a record of
Hurricane surge threat



Mean surge index over season

Frequency above surge index threshold

“accumulated cyclone energy” of landfalling cyclones

Global temperature (gistemp)

Grouping according to global temperature...

$$F(x;\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

ξ: shape
σ: scale
μ: location.

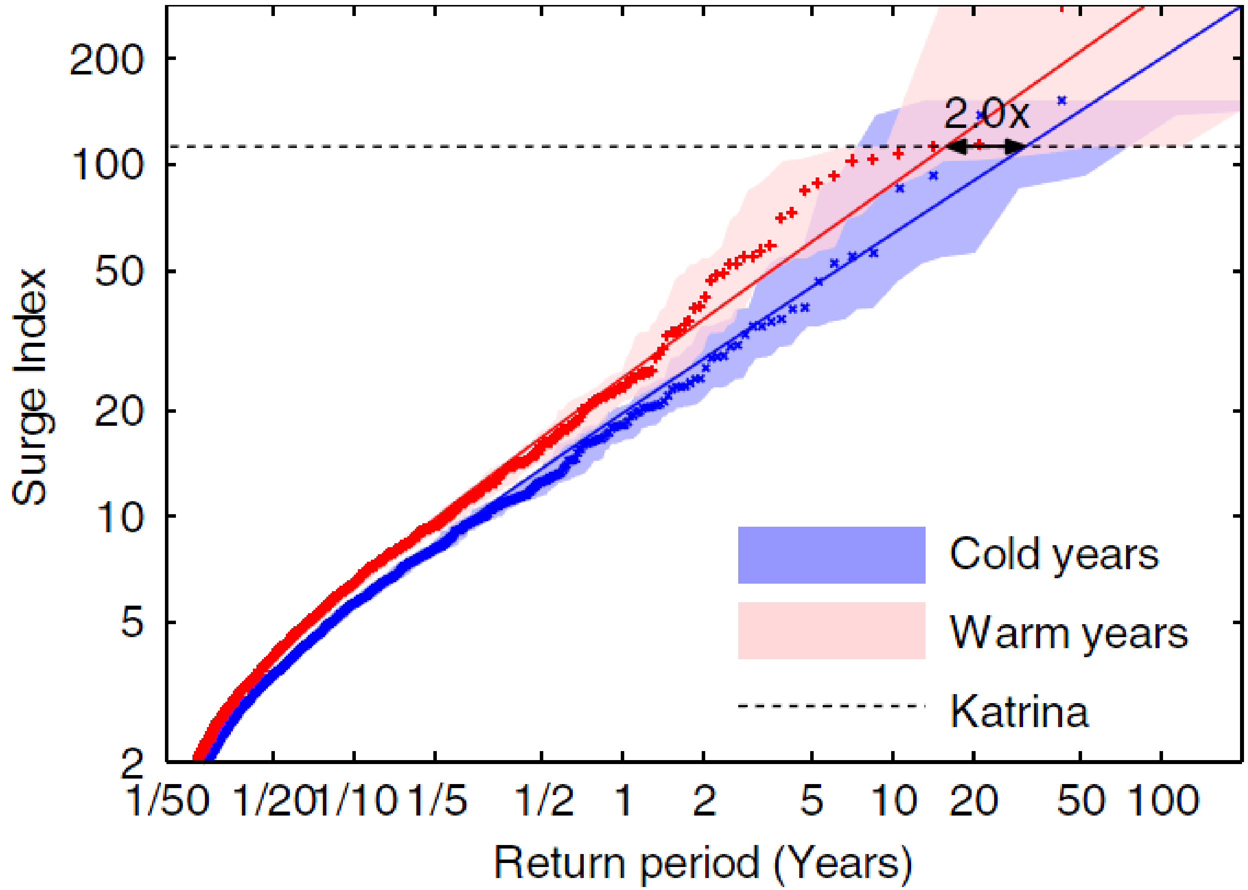


Fig. 3. Return period plot of surge index distribution for cold (blue) and warm (red) years separately (Fig. 1*D*). The crosses and shaded bands show return periods and confidence intervals estimated from the empirical cdf (*Methods*). Solid lines show best-fitting GEV distributions (*SI Methods*, section S3). The maximal surge index during hurricane Katrina in 2005 is shown as a dotted line.

Surge index series is **not stationary**

Non-stationarity

- It is non-stationary...
- We fit the surge index record with a **non-stationary GEV distribution with parameters** varying with a predictor as:

$$k = k_0(1 + a_k T)$$

$$\sigma = e^{s_0(1 + a_s T)}$$

$$\mu = \mu_0(1 + a_\mu T)$$

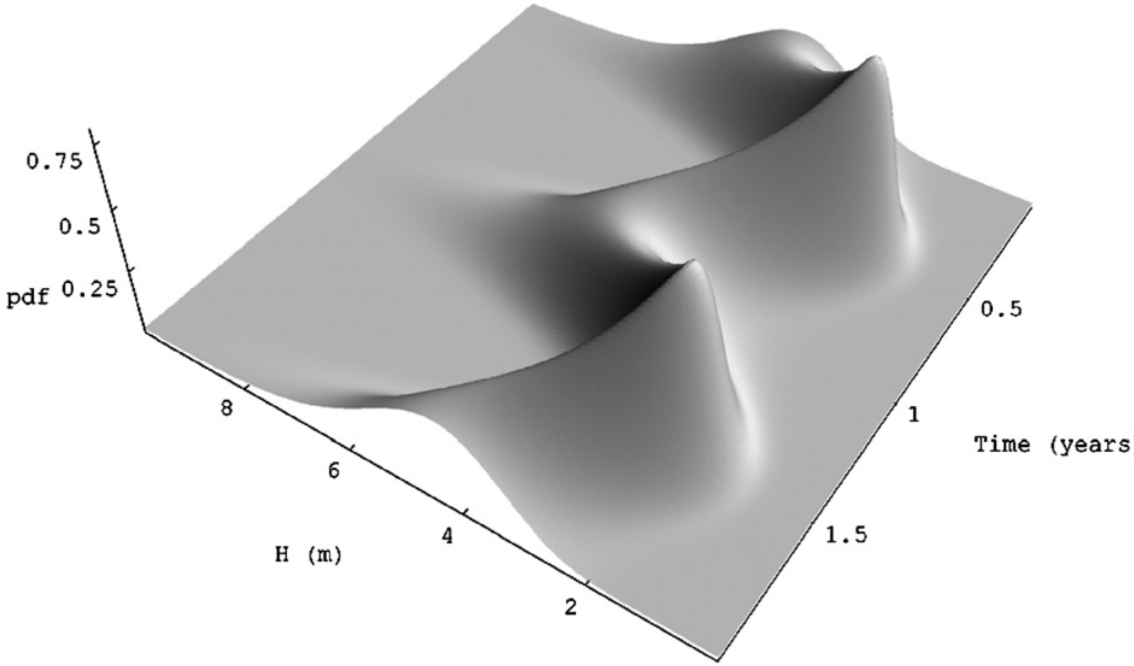


Illustration: Menéndez et al. 2009

Danish National Research Foundation

Two potential predictors: MDR & rMDR

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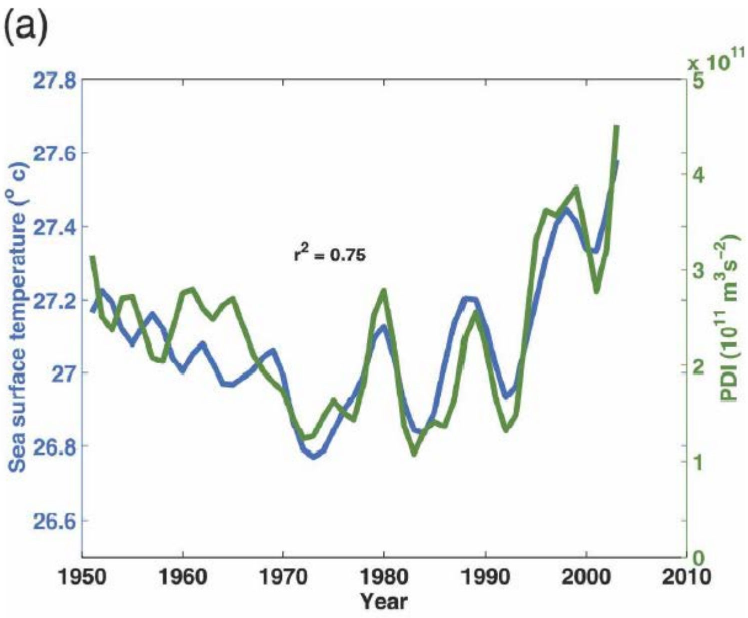
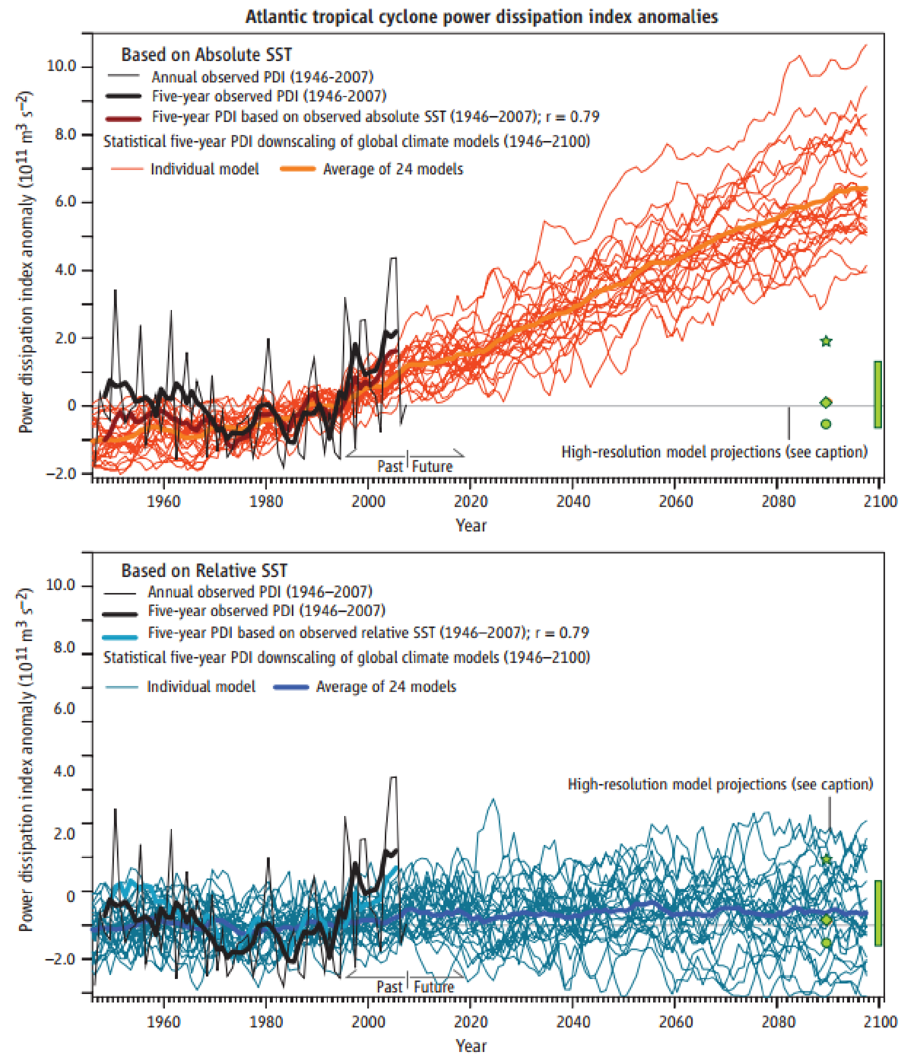


Emanuel 2005



Past and extrapolated changes in Atlantic hurricane activity. Observed PDI anomalies are regressed onto observed absolute and relative SST over the period from 1946 to 2007, and these regression models are used to build estimates of PDI from output of global climate models for historical and future conditions. Anomalies are shown relative to the 1981 to 2000 average (2.13 x 10^{11} m^3 s^{-2}). The green bar denotes the approximate range of PDI anomaly predicted by the statistical/dynamical calculations of (*12*). The other green symbols denote the approximate values suggested by high-resolution dynamical models: circle (*8*), star (*13*) and diamond (*15*). SST indices are computed

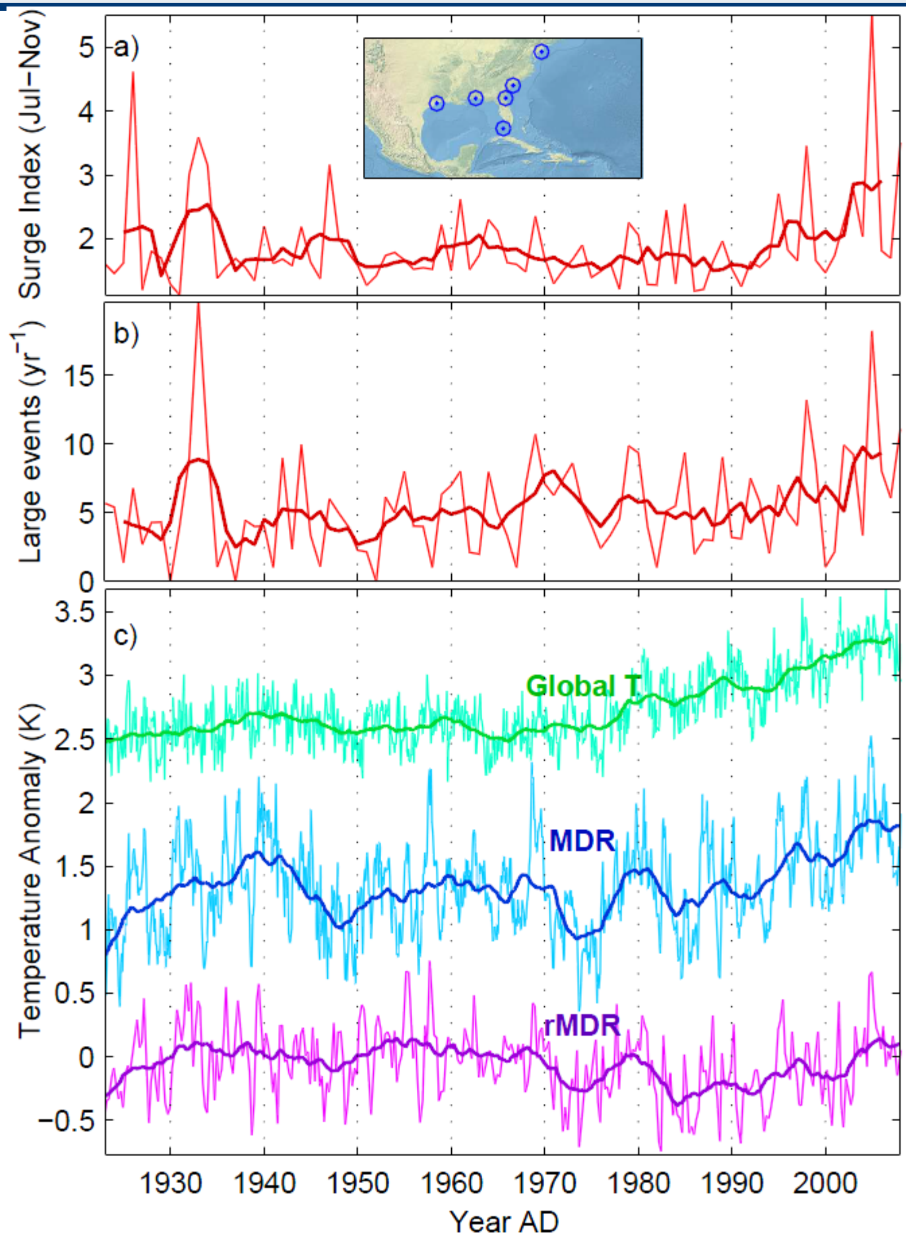
Vecchi et al. 2008 argues that MDR minus tropical mean SST also correlates.

3 potential predictors: MDR, rMDR & GlobalT

$$k = k_0(1 + a_k T)$$

$$\sigma = e^{s_0(1 + a_s T)}$$

$$\mu = \mu_0(1 + a_\mu T)$$



Model using Global T as predictor.

Table 1. Model parameters with confidence intervals for the non-stationary GEV distribution using global average temperature (23) as predictor.

	k_0	s_0	μ_0	a_k	a_s	a_μ
5%	0.51	0.44	2.36	0.04	0.26	0.05
16%	0.52	0.45	2.38	0.11	0.35	0.08
Best guess	0.54	0.48	2.41	0.22	0.49	0.13
84%	0.56	0.5	2.45	0.33	0.62	0.18
95%	0.57	0.51	2.47	0.39	0.71	0.21

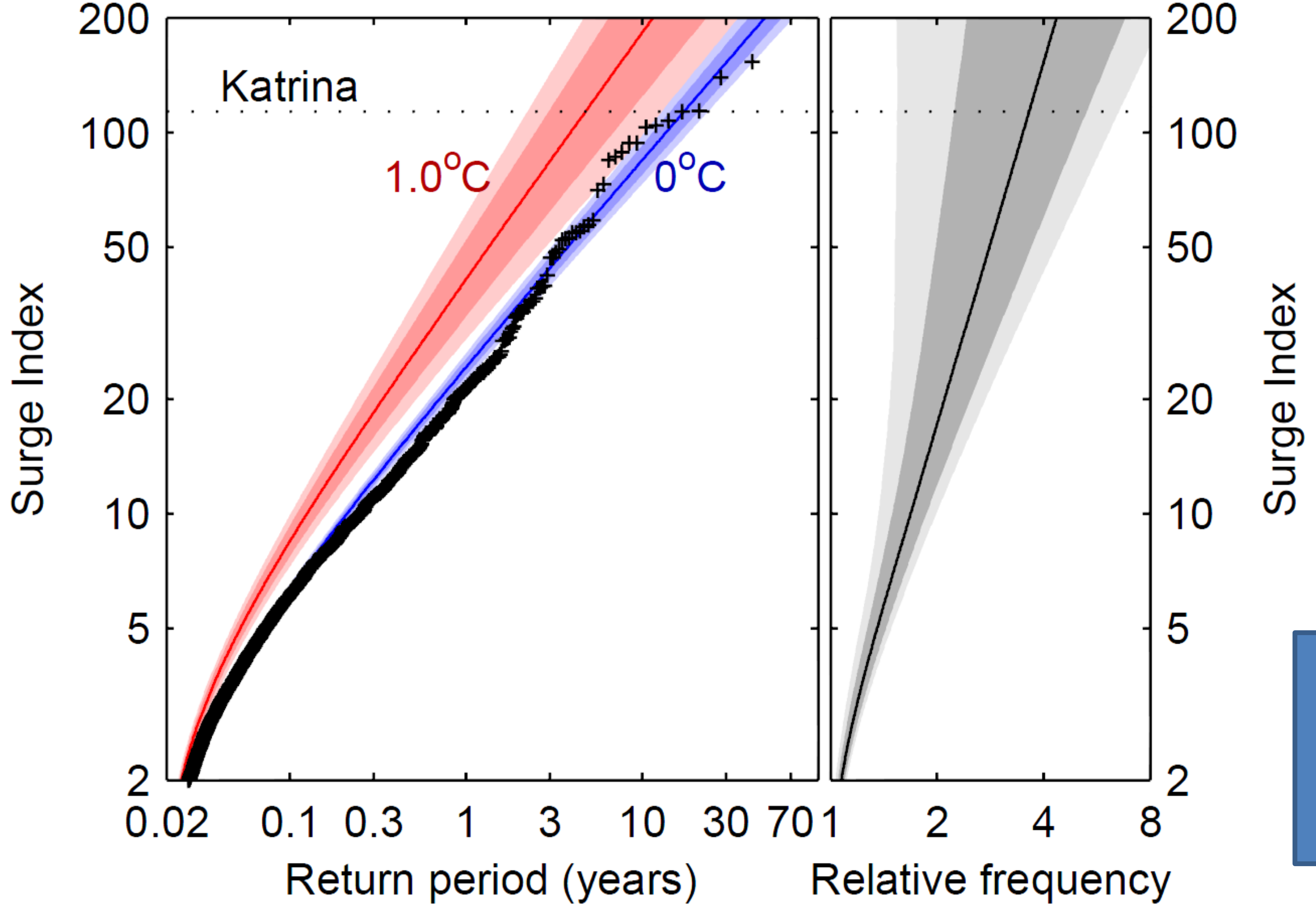
Non-stat params:
All Positive

$$k = k_0(1 + a_k T)$$

$$\sigma = e^{s_0(1 + a_s T)}$$

$$\mu = \mu_0(1 + a_\mu T)$$

1 degC global warming



More and Stronger

Which models fit best?

Table 2. : Performance of alternative models expressed as an odds ratio relative to the model using global average temperature as the predictor.

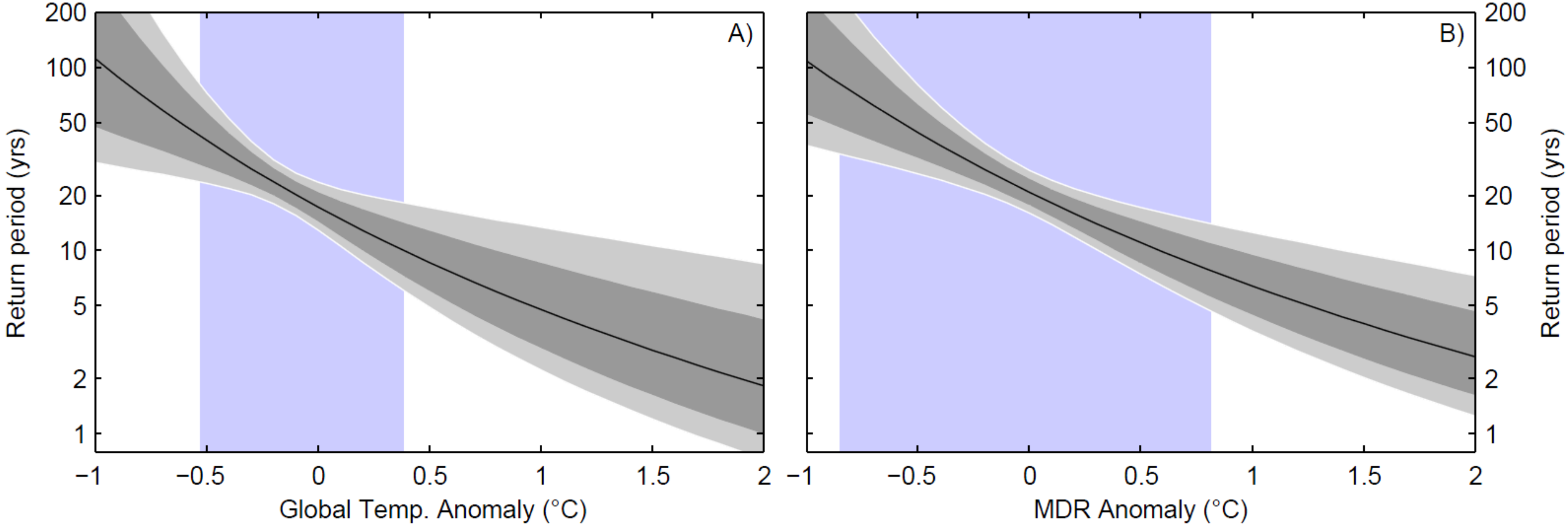
Predictor	Katrina Sensitivity	Odds
Gridded temperatures (23)	2.1x-6.6x	4:1
MDR SST (24)	1.8x-5.5x	3:1
Global T (23)	1.5x-6.6x	1:1
Linear increase	1.3x-4.7x	1:5
Radiative Forcing (25)		1:10
rMDR (24)	1.8x-10x	1:75
Pacific Decadal Oscillation (26)		1:400
Quasi-Biennial Oscillation (27)		1:600
Southern Oscillation Index (28)		1:700
North Atlantic Oscillation (29,30)		1:800
Sahel Rainfall Index (31)		1:1200

The average likelihood of each hypothesis is calculated from entire sample of models from the MCMC, while ensuring that the likelihood is calculated over the same time interval in the numerator and denominator of the ratio. The Katrina Sensitivity is expressed as the relative frequency increase of Katrinas [5-95%] per °C. The linear trend sensitivity is given per century.

- MDR SST best simple model
- Global T also really good.
- rMDR worse than a linear trend.
- Trend is so large that it can explain more than the natural variations such as ENSO.

- Quite high sensitivity

Katrina events vs global temperatures

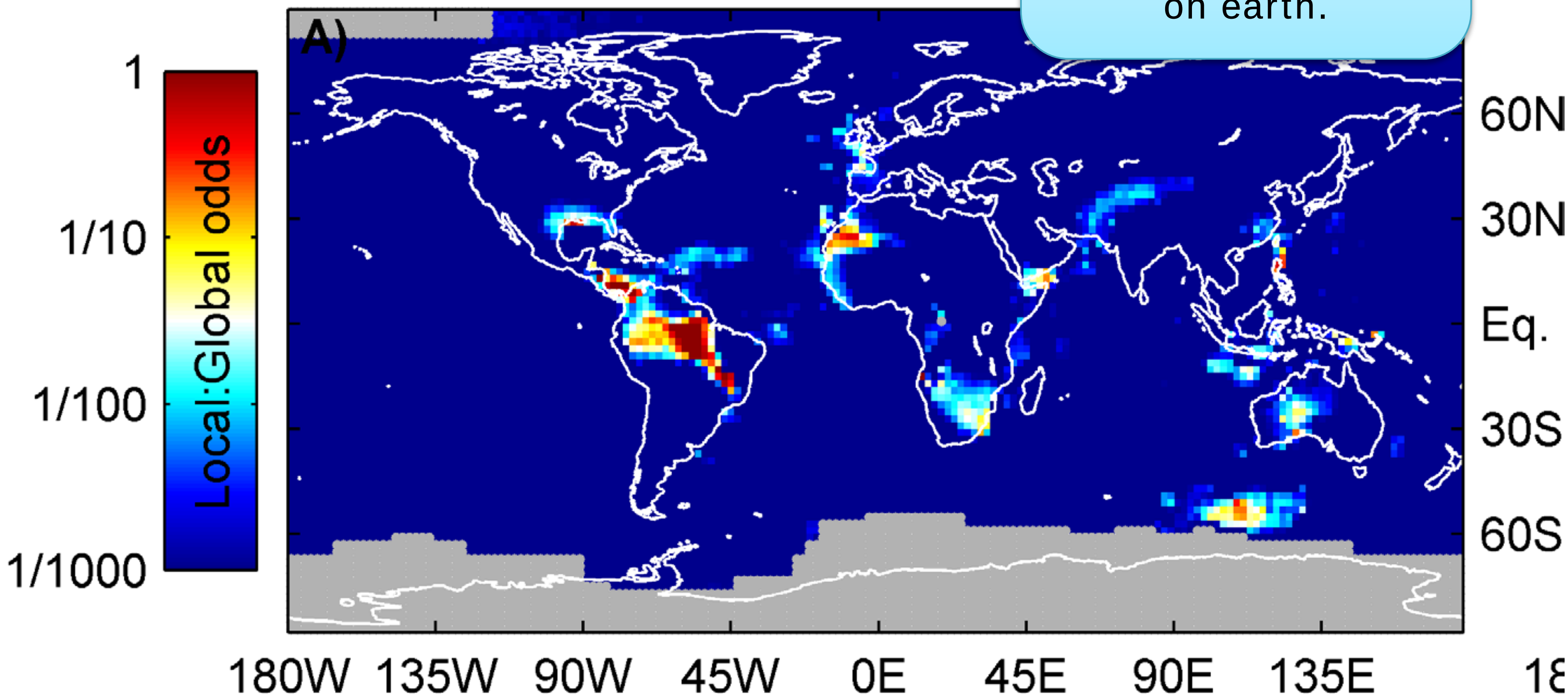


Baseline 1980:2000

Odds map

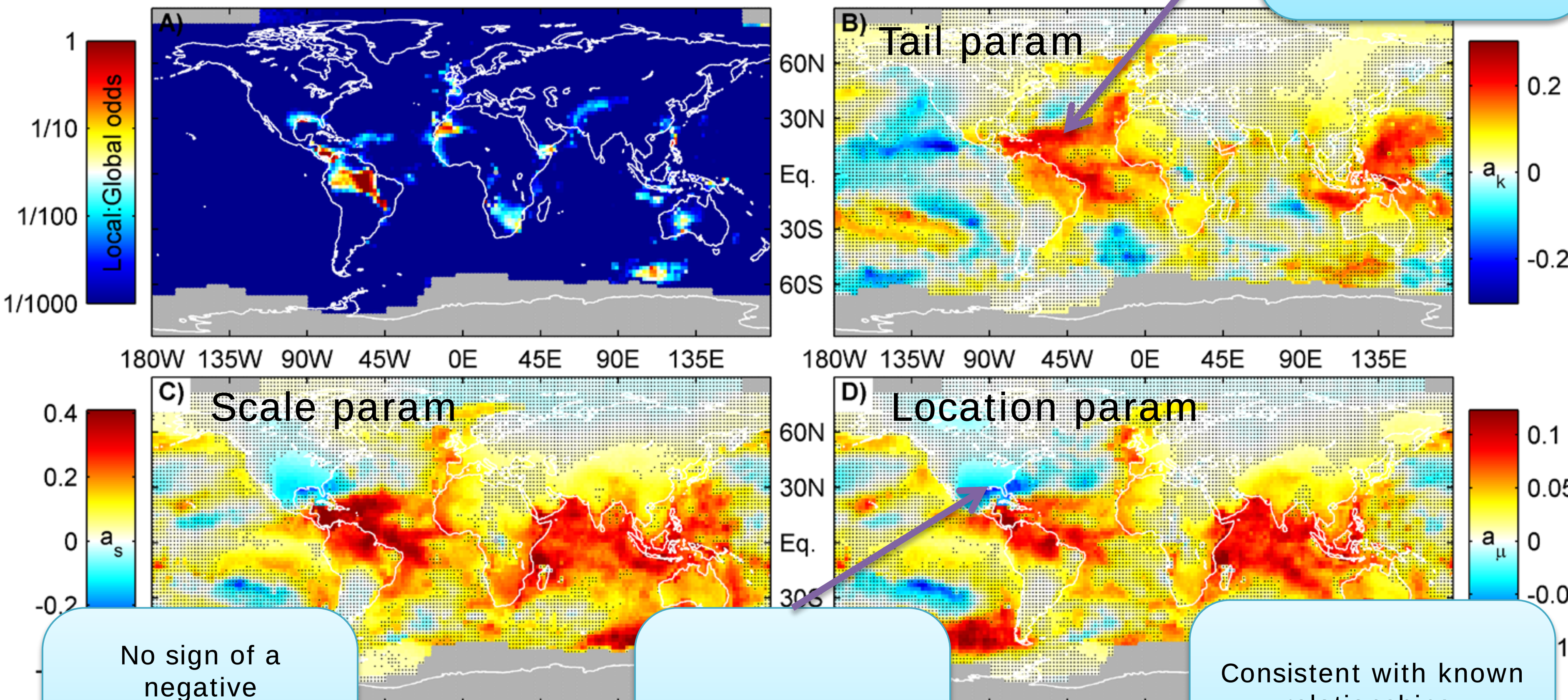
How good are surface temperatures as surge index distribution preditors?

Global temperatures are much better predictors than almost everywhere on earth.



Non-stationarity parameters...

Longer tails in warm years. More extreme events.

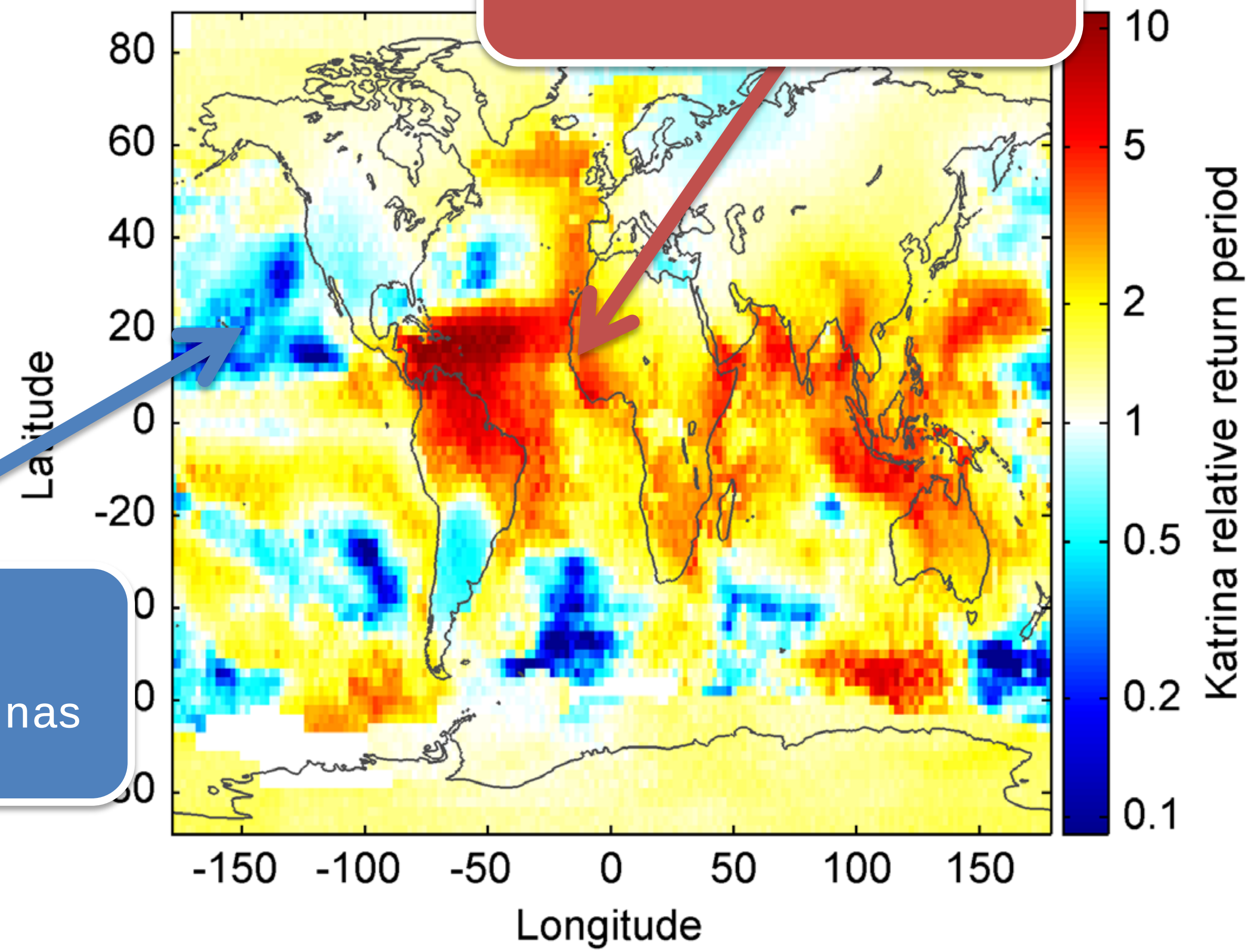


No sign of a negative 'correlation' with tropical SST except for Eastern Pacific (ak).

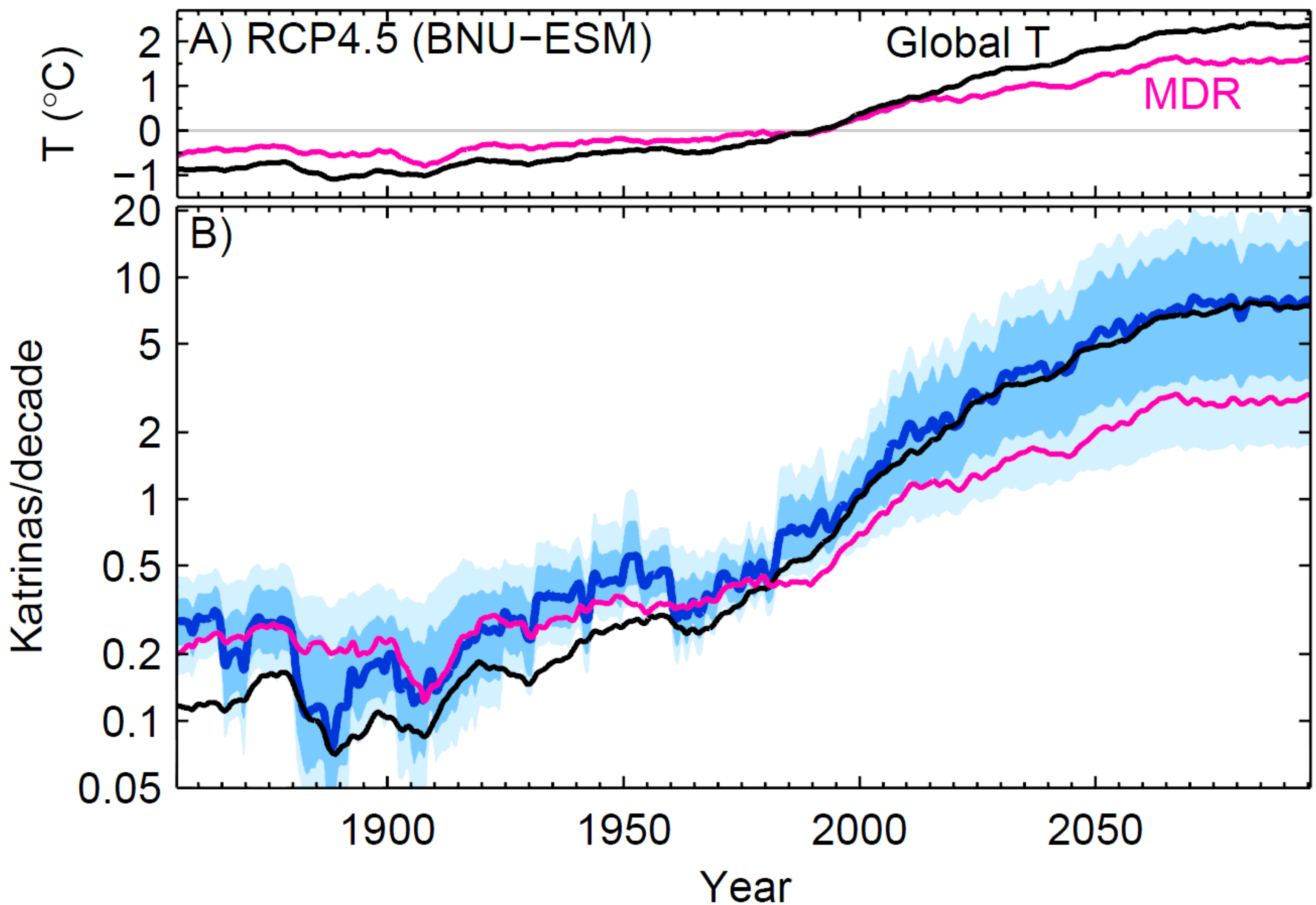
Land-falling Cyclones cool US.

Consistent with known relationships:
e.g. MDR, ENSO
Sahel region

Change in Katrina return period associa
2degC warming.



One model projection



Results:

- Constructed a **homogeneous** record of hurricane surge threat since 1923
- Katrinas are twice as frequent in globally warm years compared to cold.
- Found that temperatures are much better predictors than rMDR.
- GlobalT is a very good predictor. (surprisingly perhaps)
- ~0.4°C global warming → halving of Katrina return period.
  - This is less than the warming over the 20th century.
- Arguably: We are crossing the threshold where large hurricane surges are more likely 'caused' by global warming than not. (or indeed have crossed)

Projected Atlantic hurricane surge threat from rising temperatures

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Homogeneous record of Atlantic hurricane surge threat since 1923

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