Hurricane Disaster Infrastructure Resilience and Planning Workshop II

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Predicting Wind Hurricane Hazard under Changing Climate Conditions

Michele Barbato

Department of Civil and Environmental Engineering,
University of California Davis

UC DAVIS
CIVIL AND ENVIRONMENTAL ENGINEERING

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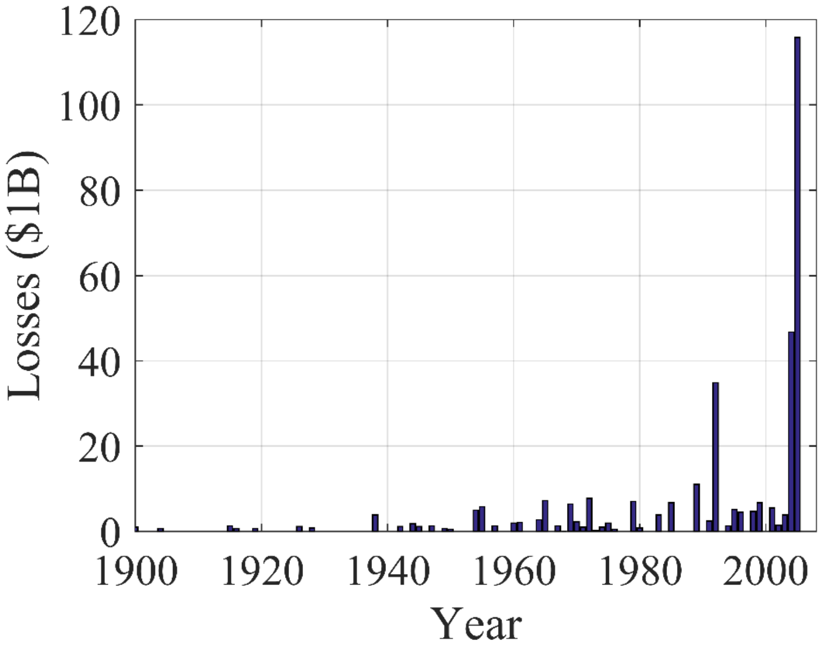
Outline

- Motivation and objective
- Changes in hurricane risk
- Wind speed under changing climate
- Validation of wind speed model
- Hurricane wind hazard predictions
- Case Studies
- Conclusions

Motivation and Objective

- Hurricanes cause significant economic and societal losses.
- Climate change is believed to intensify hurricane actions and induced losses.
- The effects of climate change need to be quantified.
- **<u>OBJECTIVE:</u>** rational method to predict changes in hurricane hazard and their effects on expected losses for structures and infrastructure systems.

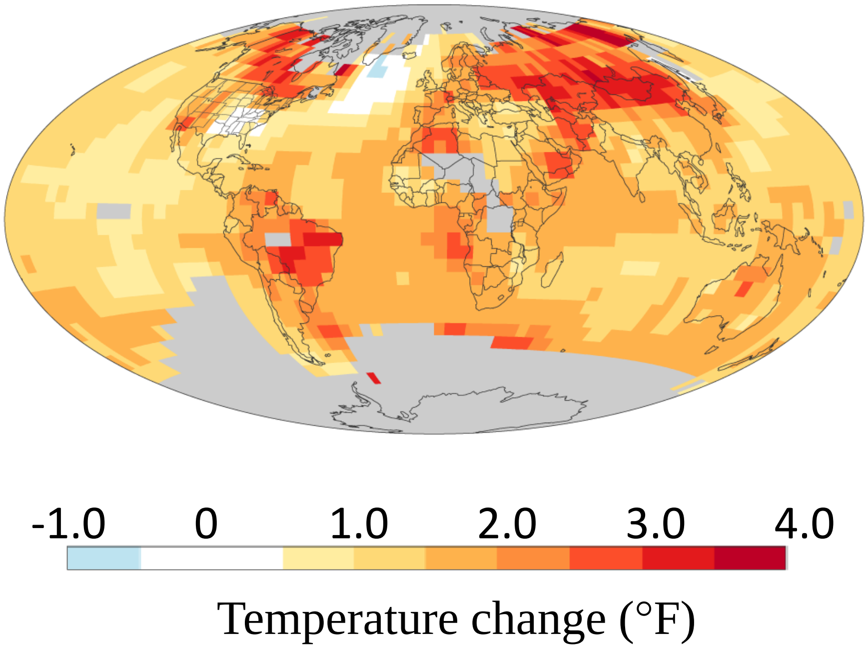


Trend of hurricane losses

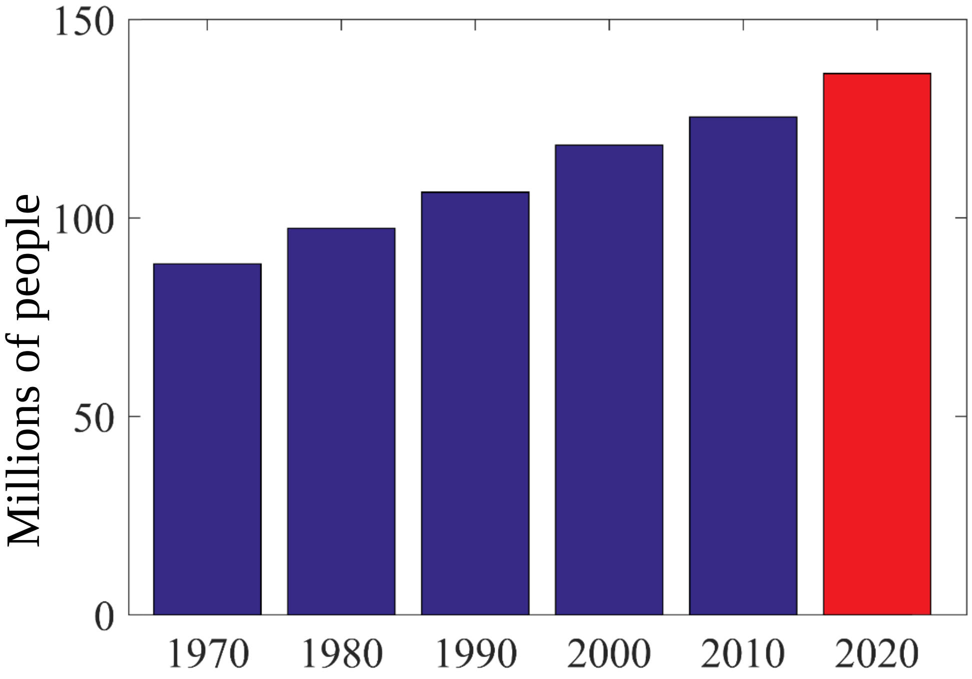
[data from Pielke et al. (2008)]

Changes in Hurricane Risk (1)

- Global sea surface temperature (SST) has increased significantly in the last 100 years.
- Hurricane intensities have increased in the same period.
- Risk and losses increase because both hazard and vulnerability increase.



Global temperature trend between 1900-2014
[adapted from NOAA climate.gov]

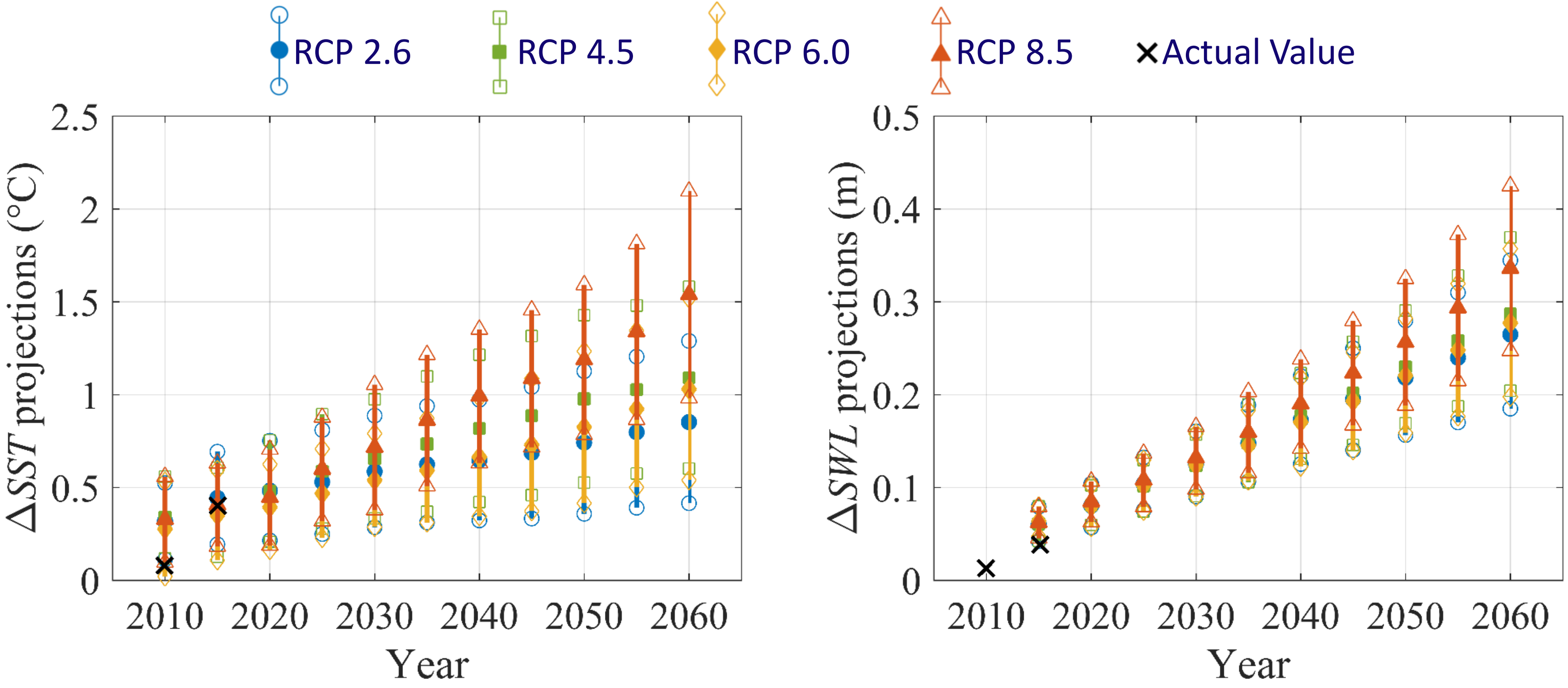


Population living along the US coast
[data from NOAA National Coastal Population Report (2013)]

Changes in Hurricane Risk (2)

- Scenarios for future climate from Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5).
- Changes in SST and sea water level (SWL) affect hurricane hazard.
- Need to predict probabilistically the hurricane intensification and its effects on structures.

RCP: Representative Concentration Pathways



Projections for changes in global SST and SWL [data from IPCC AR5 (2013)]

Wind Speed under Changing Climate (1)

- Statistically-based projection models for intensity measures (IMs) developed using historical data.

ν_h : hurricane annual frequency

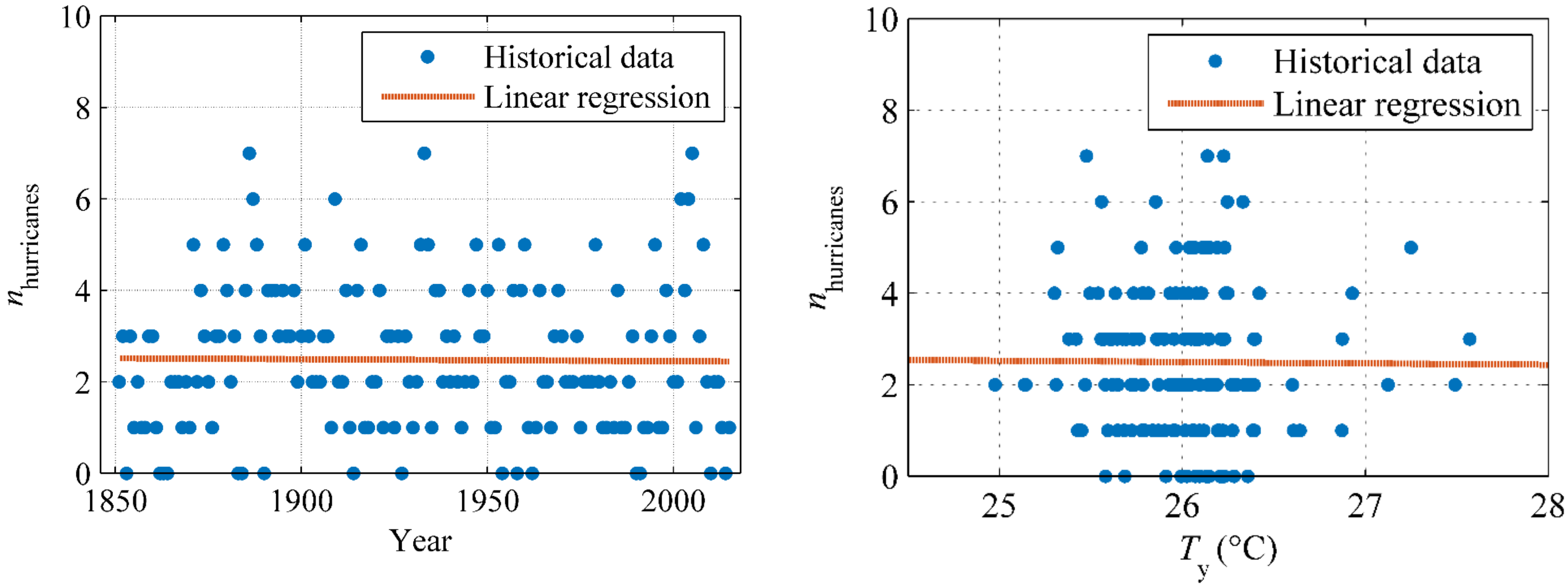
$V_{\max}$: peak hurricane wind speed

$R_{\max}$: radius at peak wind speed from eye

Δp : central pressure deficit

"T_y" : annual average

"T" : at time of hurricane



Data from HURDAT2 and NOAA optimum interpolation (SST) V2

Wind Speed under Changing Climate (2)

Simulation of temperature *T* at time of hurricane

- Sample ΔT_{y} from a normal distribution based on the IPCC projection scenarios
- Obtain T_{y} at the year of interest as: $T_{\mathrm{y}} = T_{2005} + \Delta T_{\mathrm{y}}$
- Sample the number of hurricanes in a year
- Sample T from linear regression and historical data $T : N(\mu_T, \sigma_T)$
- σ_T is selected based on historical data for the location that is generated for $V_{\max}$.

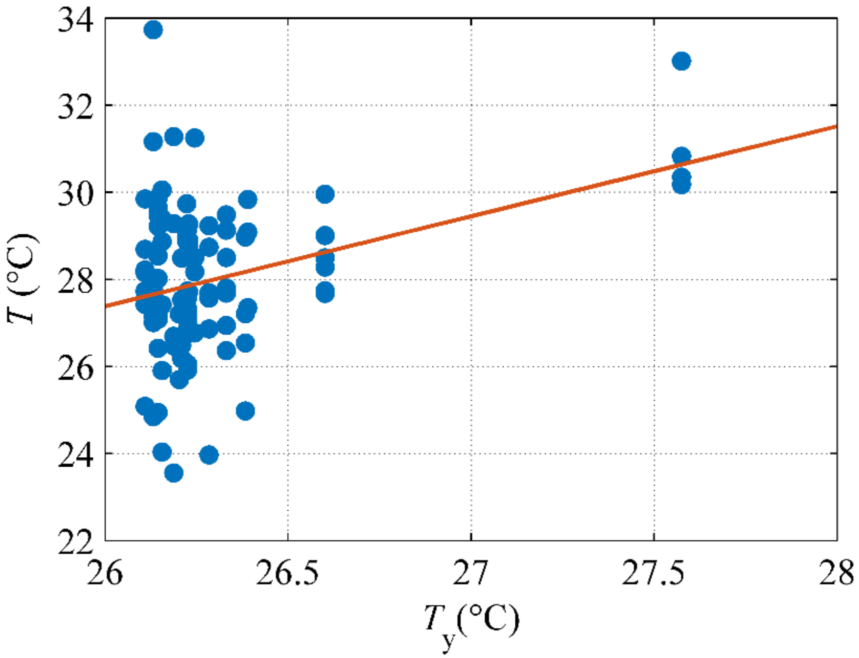
$$\mu_T = b_0 + b_1 \cdot T_{\mathrm{y}}$$

$$\sigma_T = 1.22\ °\mathrm{C}$$

$b_0 = -26.36\,(°\mathrm{C})$

$b_1 = 2.07$

$T_{\mathrm{y}} \geq 25\ °\mathrm{C}$

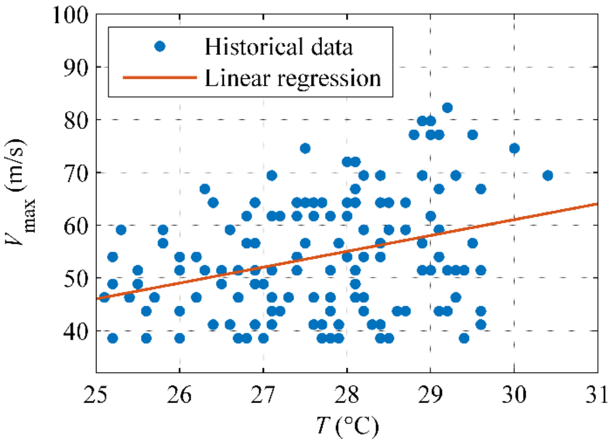


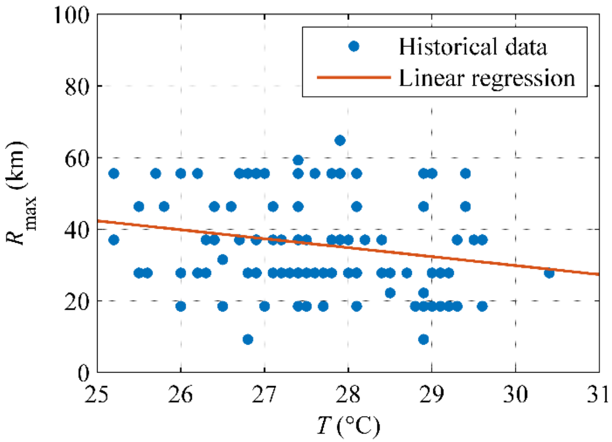
Wind Speed under Changing Climate (3)

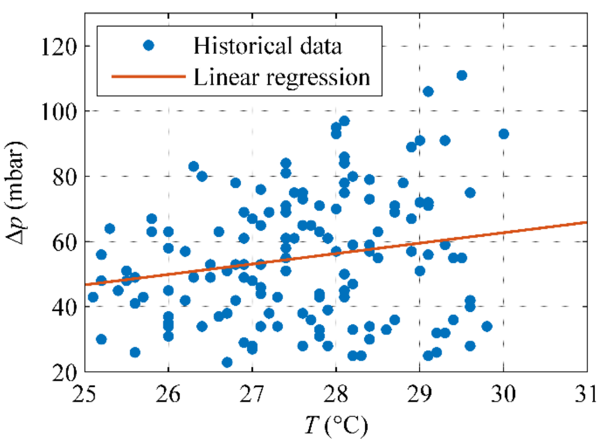
Simulation of $V_{\max}$, $R_{\max}$, and Δp

- $V_{\max}$, $R_{\max}$, and Δp for each hurricane are simulated from a Weibull, truncated normal, and lognormal distribution, respectively.
- Mean values are derived using linear regression of historical data:

$$y(T) = a_0 + a_1 \cdot T \qquad y(T) = \mu_{V_{\max}}, \mu_{R_{\max}}, \mu_{\Delta p}$$





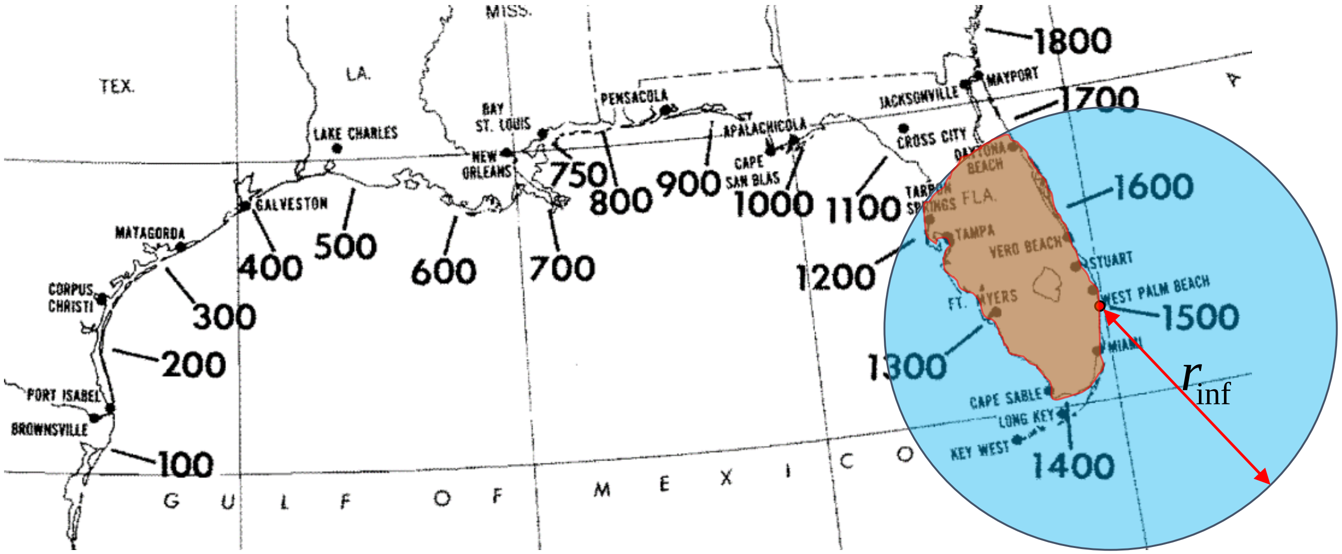


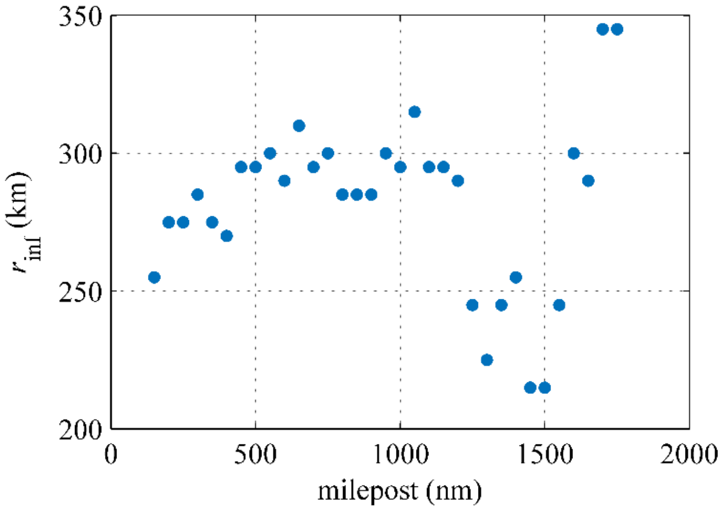
Parameter	$V_{\max}$ (m/s)	$R_{\max}$ (km)	Δp (mbar)
a_0	-29.12	104.80	-33.31
a_1	3.00	-2.50	3.20

St. Dev.	$V_{\max}$ (m/s)	$R_{\max}$ (km)	Δp (mbar)
$25° \le T < 26.5°$	6.12	10.69	10.17
$26.5° \le T < 28°$	9.50	16.22	16.53
$T \ge 28°$	12.83	23.88	14.40

Wind Speed under Changing Climate (4)

Simulation of hurricane distance from site





- r_{inf} = radius of influence selected so that the hurricane frequency between 1871-1963 in the region within the radius coincides with ν_{NIST}
- A generalized extreme value (GEV) distribution is fit to historical data to define the distribution of r.

Wind Speed under Changing Climate (5)

Simulation of wind speed at site

- Willoughby's model used to simulate hurricane wind speed at the site location
- Distributions for A, X_1, and n are provided in Willoughby et al. (2005)

$$
\begin{aligned}
V_{1-\min}^{\text{rot}}(r) &= V_i && (0 \le r \le R_1) \\
V_{1-\min}^{\text{rot}}(r) &= V_i \cdot (1-w) + V_o \cdot w && (R_1 \le r \le R_2) \\
V_{1-\min}^{\text{rot}}(r) &= V_o && (R_2 \le r)
\end{aligned}
$$

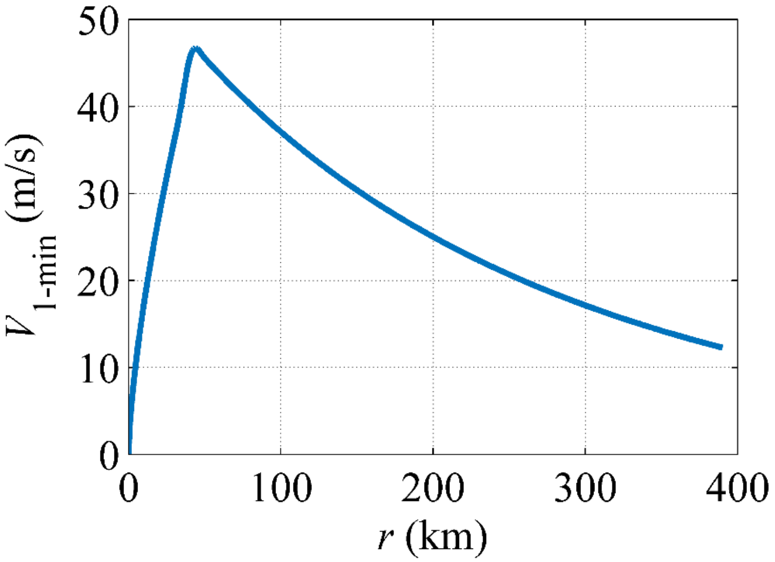
$$V_i = V_{\max} \cdot \left(\frac{r}{R_{\max}} \right)^n$$

$$V_o = V_{\max} \cdot \left[(1-A) \cdot \exp\left(\frac{R_{\max} - r}{X_1} \right) + A \cdot \exp\left(\frac{R_{\max} - r}{X_2} \right) \right]$$

$$R_1 = R_{\max} - (R_2 - R_1)\xi$$

$$
\begin{cases}
w(\xi) = \dfrac{n \cdot \left((1-A) \cdot X_1 + A \cdot X_2 \right)}{\left(n \cdot \left((1-A) \cdot X_1 + A \cdot X_2 \right) \right) + R_{\max}} \\
w(\xi) = 126\xi^5 - 420\xi^6 + 540\xi^7 - 315\xi^8 + 70\xi^9
\end{cases}
$$

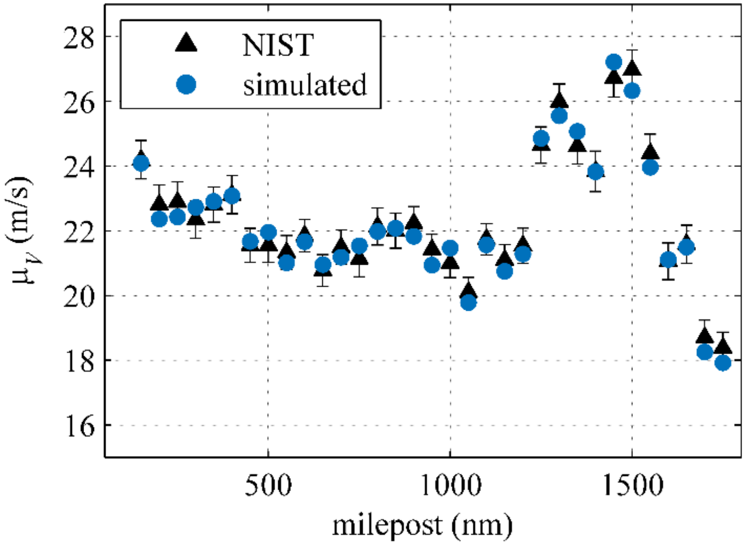
$X_2 = 25$ km $\qquad$ $R_2 - R_1 = 10$ km

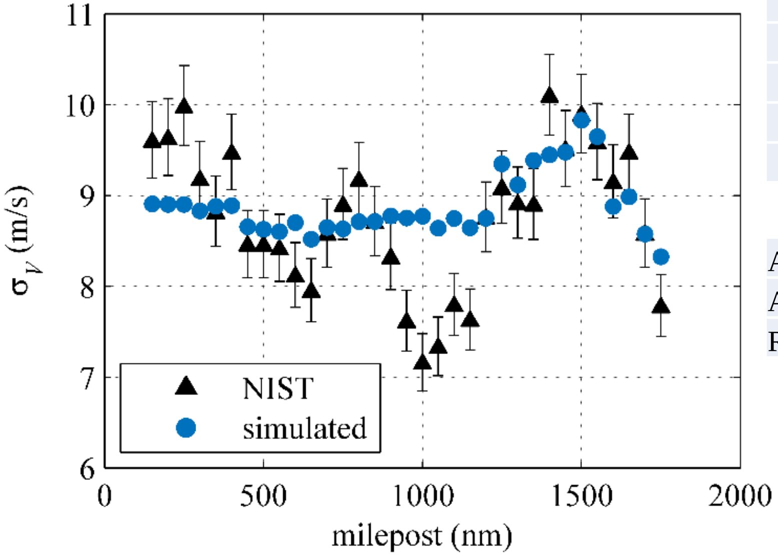


Willoughby et al. (2005)

Validation of Wind Speed Model (1)

Comparison with NIST data





Milepost	μ_V (m/s)		
	NIST	Simulated	Error
200	22.82	22.36	-0.46
300	22.35	22.73	0.38
400	23.11	23.08	-0.03
500	21.55	21.96	0.41
600	21.85	21.67	-0.18
700	21.49	21.18	-0.31
800	22.13	21.98	-0.15
900	22.23	21.83	-0.40
1000	21.00	21.47	0.47
1100	21.74	21.57	-0.17
1200	21.54	21.28	-0.26
1300	25.99	25.56	-0.43
1400	23.84	23.83	-0.01
1500	26.97	26.33	-0.64
1600	21.06	21.12	0.06
1700	18.71	18.26	-0.45

Milepost	σ_V (m/s)		
	NIST	Simulated	Error
200	9.62	8.90	-0.72
300	9.17	8.83	-0.34
400	9.46	8.89	-0.57
500	8.44	8.63	0.19
600	8.11	8.70	0.59
700	8.56	8.65	0.09
800	9.16	8.71	-0.45
900	8.31	8.78	0.47
1000	7.15	8.77	1.62
1100	7.78	8.75	0.97
1200	8.74	8.75	0.01
1300	8.90	9.12	0.22
1400	10.08	9.45	-0.63
1500	9.88	9.83	-0.05
1600	9.13	8.88	-0.25
1700	8.57	8.58	0.01

Average error (m/s)	-0.14
Average error (%)	-0.60
RMSE error (m/s)	0.32

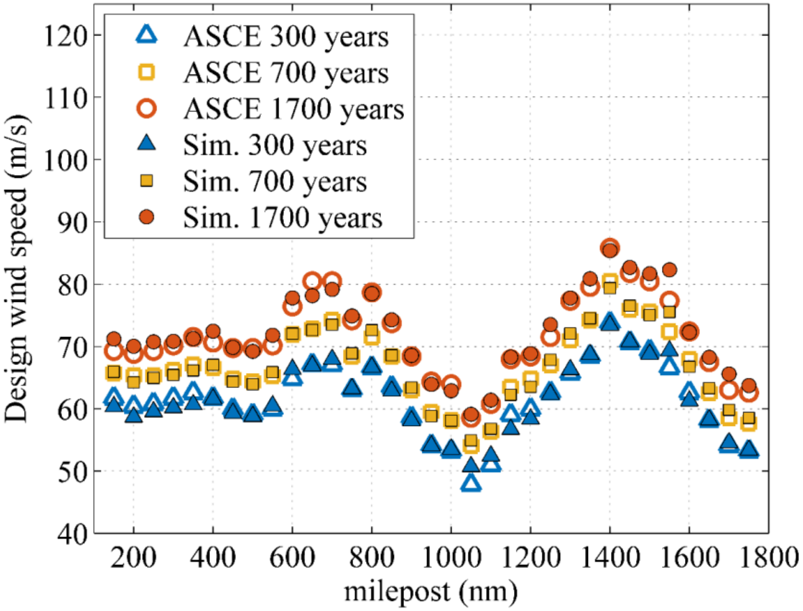
Average error (m/s)	0.07
Average error (%)	0.88
RMSE error (m/s)	0.60

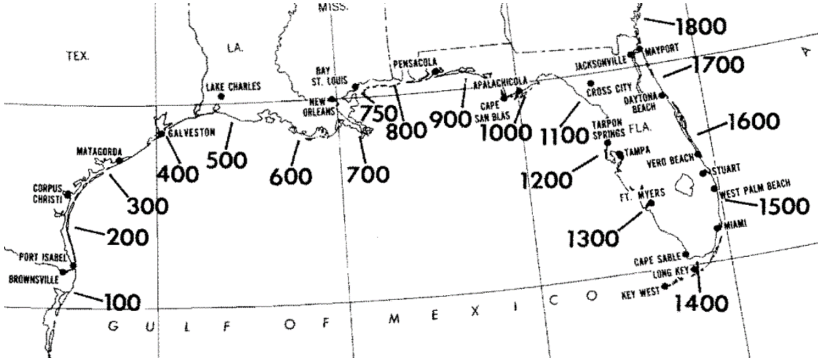
Time period: 1871-1963

Average annual temperature: 25.94 °C

Validation of Wind Speed Model (2)

Comparison with ASCE 7-16 design wind speeds





Milepost	ASCE 7-16 (m/s)			Simulated (m/s)			Error (%)		
	300 y	700 y	1700 y	300 y	700 y	1700 y	300 y	700 y	1700 y
200	60.35	65.27	68.84	58.69	64.25	70.05	-2.8	-1.6	1.8
300	61.69	66.16	70.19	60.18	65.41	70.82	-2.4	-1.1	0.9
400	61.69	66.61	70.63	61.59	67.05	72.46	-0.2	0.7	2.6
500	59.01	64.37	69.74	58.77	63.95	69.22	-0.4	-0.7	-0.7
600	64.82	71.97	76.44	66.34	72.05	77.81	2.3	0.1	1.8
700	67.06	74.21	80.47	67.95	73.48	79.17	1.3	-1.0	-1.6
800	66.61	71.53	78.68	66.66	72.61	78.50	0.1	1.5	-0.2
900	58.56	63.03	68.40	58.09	63.37	68.57	-0.8	0.5	0.2
1000	53.20	58.12	63.93	53.53	58.07	62.89	0.6	-0.1	-1.6
1100	50.96	56.33	60.80	52.44	56.79	61.38	2.9	0.8	1.0
1200	59.90	64.82	68.40	58.38	63.52	68.85	-2.5	-2.0	0.7
1300	65.71	71.08	77.34	66.31	72.10	77.78	0.9	1.4	0.6
1400	73.76	80.47	85.83	73.39	79.36	85.39	-0.5	-1.4	-0.5
1500	69.29	75.55	80.47	68.78	75.05	81.69	-0.7	-0.7	1.5
1600	62.59	67.95	72.42	61.27	66.73	72.30	-2.1	-1.8	-0.2
1700	54.09	58.56	63.03	54.56	59.82	65.57	0.9	2.2	4.0

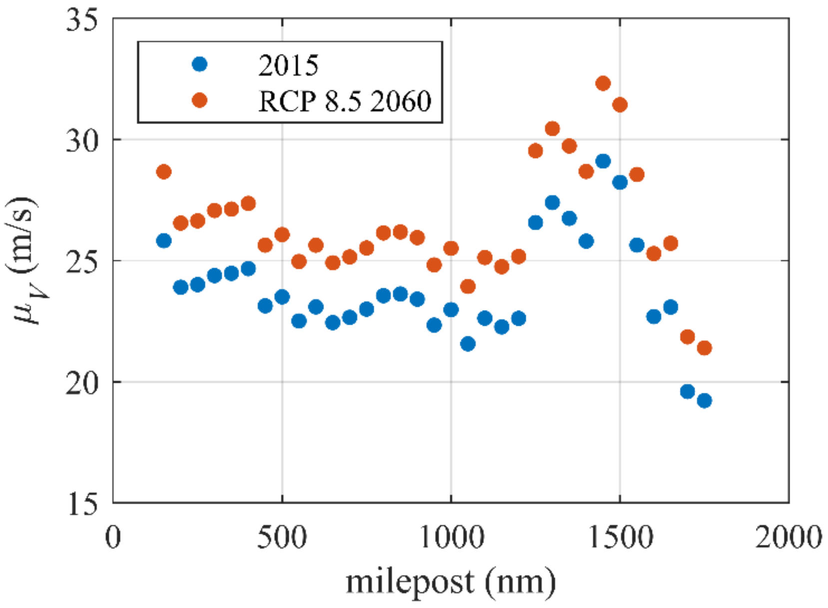
Return periods	300 years	700 years	1700 years
Average error (m/s)	-0.15	-0.15	0.43
Average error (%)	-0.2	-0.2	0.6
RMSE error (m/s)	0.98	0.71	1.19

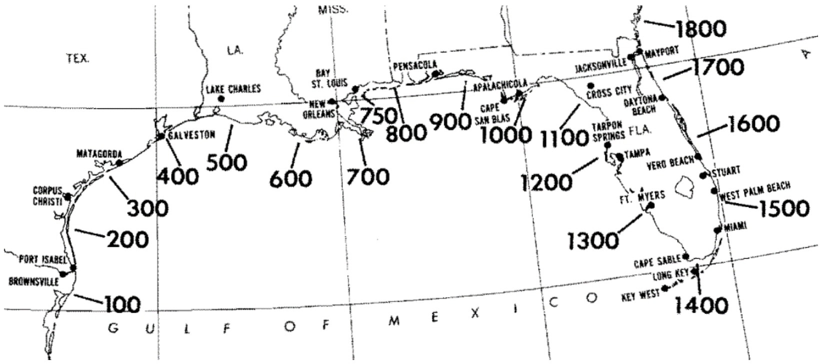
Time period: 1886-2010

Average annual temperature: 25.84 °C

Hurricane Wind Speed Predictions (1)

Projected changes in average wind speeds



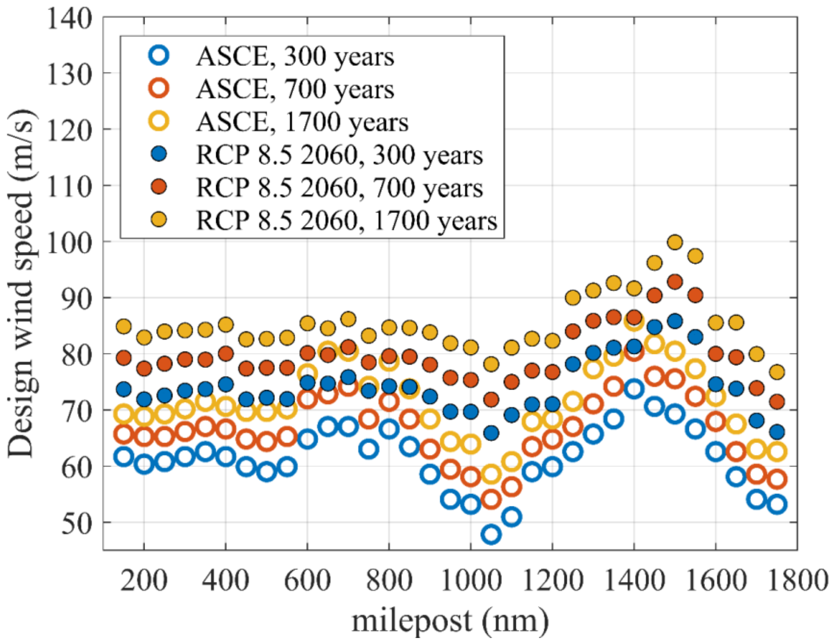


Milepost	Average wind speed (m/s)				
	2015	RCP 2.6 2060	RCP 4.5 2060	RCP 6.0 2060	RCP 8.5 2060
200	23.90	24.76	25.48	25.32	26.55
300	24.38	25.25	26.02	25.84	27.07
400	24.67	25.56	26.29	26.13	27.36
500	23.50	24.34	25.06	24.89	26.07
600	23.09	23.93	24.63	24.47	25.63
700	22.66	23.47	24.18	24.01	25.15
800	23.55	24.40	25.12	24.97	26.14
900	23.41	24.25	24.96	24.80	25.95
1000	22.97	23.82	24.51	24.36	25.51
1100	22.62	23.43	24.14	23.99	25.13
1200	22.61	23.46	24.16	24.03	25.17
1300	27.40	28.42	29.25	29.05	30.45
1400	25.80	26.75	27.53	27.37	28.68
1500	28.23	29.29	30.16	29.97	31.43
1600	22.69	23.55	24.27	24.10	25.29
1700	19.59	20.35	20.97	20.80	21.85

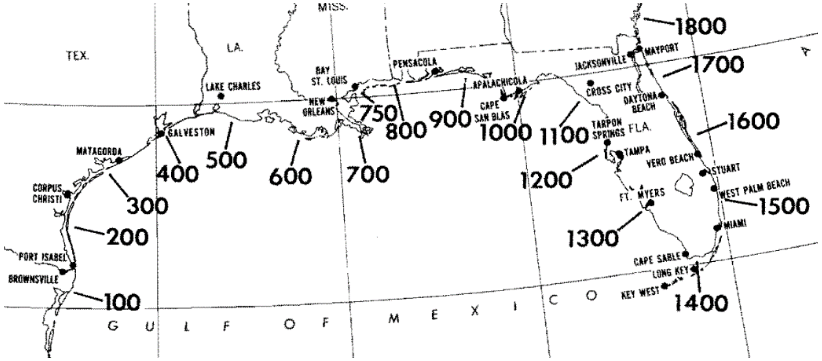
Average increase (%) from 2015	3.65%	6.73%	6.04%	11.09%

Hurricane Wind Speed Predictions (2)

Projected changes in design wind speeds

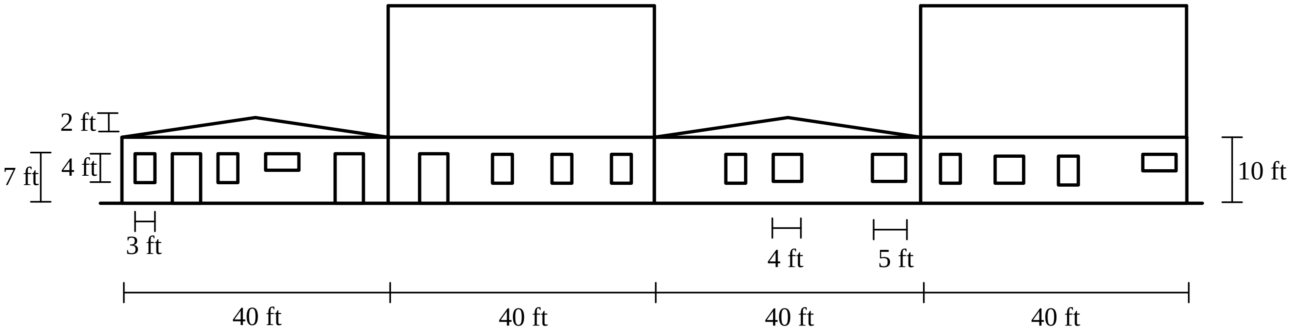


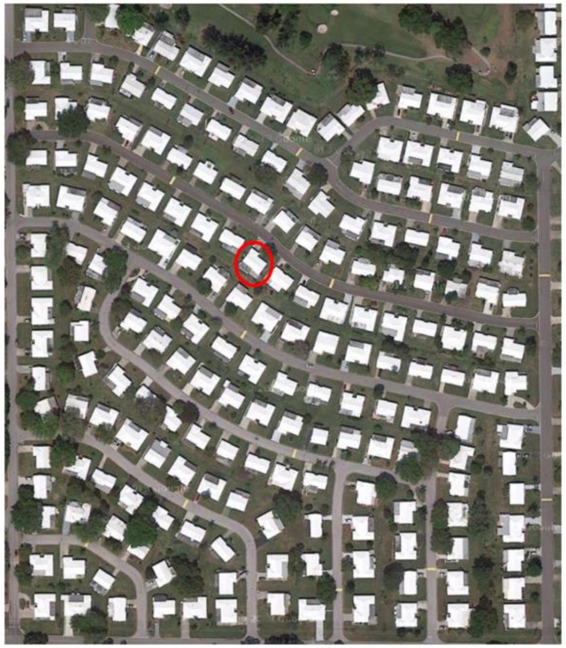
Milepost	ASCE 7-16 (m/s)			RCP 8.5 2060 (m/s)			Increase		
	300	700	1700	300	700	1700	300	700	1700
200	60.35	65.27	68.84	71.94	77.45	82.95	19%	19%	20%
300	61.69	66.16	70.19	73.2	78.52	84.02	19%	19%	20%
400	61.69	66.61	70.63	74.62	80.3	85.87	21%	20%	21%
500	59.01	64.37	69.74	72.19	77.39	82.7	22%	20%	19%
600	64.82	71.97	76.44	74.98	80.34	85.23	15%	11%	12%
700	67.06	74.21	80.47	75.69	80.95	86.18	13%	9%	7%
800	66.61	71.53	78.68	75.57	80.83	85.81	11%	11%	8%
900	58.56	63.03	68.40	72.29	77.91	83.27	24%	24%	23%
1000	53.20	58.12	63.93	69.81	75.85	82	31%	30%	27%
1100	50.96	56.33	60.80	68.78	74.81	81.21	36%	33%	33%
1200	59.90	64.82	68.40	71.25	76.44	81.85	19%	18%	20%
1300	65.71	71.08	77.34	80.22	86.07	91.59	22%	21%	18%
1400	73.76	80.47	85.83	82.35	87.79	92.93	10%	7%	7%
1500	69.29	75.55	80.47	85.63	92.6	99.69	24%	23%	24%
1600	62.59	67.95	72.42	74.5	80.26	85.8	19%	18%	18%
1700	54.09	58.56	63.03	68.2	74.13	79.91	26%	26%	27%

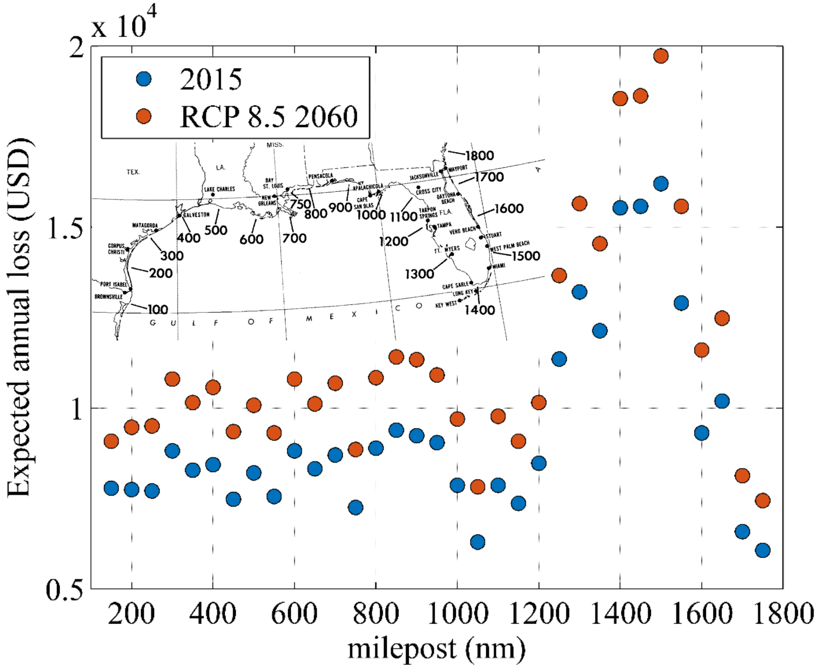


Return periods	300 years	700 years	1700 years
Average increase RCP 2.6 2060 (%)	14.6	14.5	14.8
Average increase RCP 4.5 2060 (%)	17.5	17.1	17.1
Average increase RCP 6.0 2060 (%)	17.0	16.6	16.7
Average increase RCP 8.5 2060 (%)	21.2	20.2	19.7

Case Study: Residential Housing





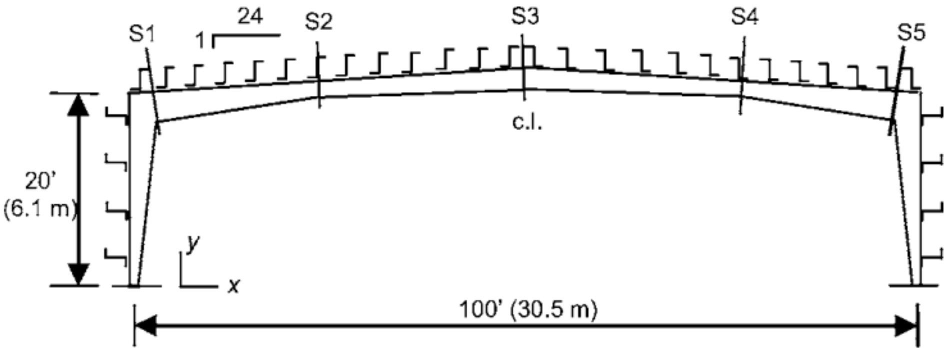


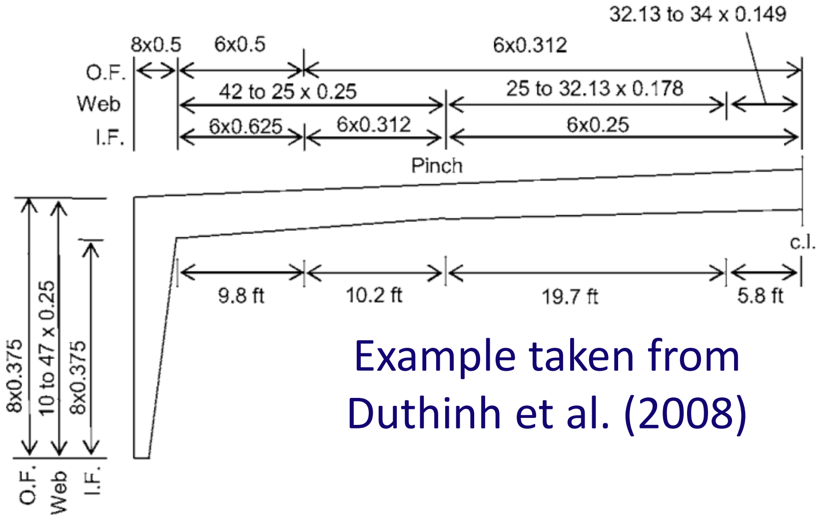
IPCC Scenario (2060)	Change in expected annual loss
RCP 2.6	+8.90 % ($160)
RCP 4.5	+15.92 % ($290)
RCP 6.0	+14.33 % ($260)
RCP 8.5	+22.05 % ($400)

Unnikrishnan and Barbato (2016)

Case Study: Low-Rise Steel Building

Location: Miami, FL (near milepost 1450)





Example taken from Duthinh et al. (2008)

Building Orientation	2006		RCP 8.5 2060	
	P_f (1/yr)	$I_{r,50}$	P_f (1/yr)	$I_{r,50}$
0°, 22.5°	1.50x10^{-5}	3.17	1.15x10^{-3}	1.59
45°, 67.5°	1.00x10^{-5}	3.29	7.20x10^{-4}	1.81
90°	5.00x10^{-6}	3.48	3.43x10^{-4}	2.12
112.5°, 135°,157.5°, 180°	1.00x10^{-5}	3.29	7.20x10^{-4}	1.81
202.5°, 225°	1.50x10^{-5}	3.17	1.15x10^{-3}	1.59
247.5°, 270°, 292.5°	2.00x10^{-5}	3.09	1.56x10^{-3}	1.43
315°, 337.5°	1.50x10^{-5}	3.17	1.15x10^{-3}	1.59

ASCE 7 - ductile failure		
Risk category	P_f (1/yr)	$I_{r,50}$
I	1.25x10^{-4}	2.5
II	3.00x10^{-5}	3.0
III	1.25x10^{-5}	3.25
IV	5.0x10^{-6}	3.5

Conclusions

- A methodology is developed to predict hurricane wind speed distributions under changing climate conditions.

- This methodology is validated against NIST data and ASCE design wind speeds.

- A significant increment in average wind speeds, standard deviation of wind speeds, and design wind speeds is observed along the entire US Gulf Coast region.

- In the worst-case climate change scenario, hurricane wind-induced losses on residential buildings are expected to increase by approximately 22% in the next 50 years.

- Under the worst-case scenario, low-rise steel buildings designed according to current ASCE 7 standards will be unsafe by 2060.

Acknowledgments

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Thank you!

Questions?