Temporal Coherence in Wind Simulation and Atmospheric Data

J.M. Rinker, H.P. Gavin (Duke University)
A. Clifton (NREL)

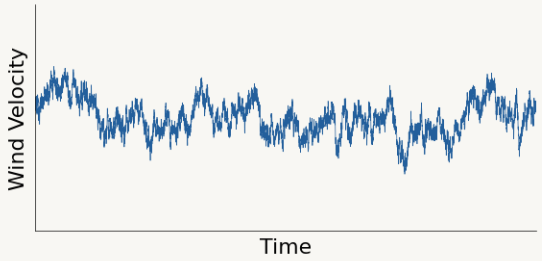
NAWEA 2015 Symposium
June 10, 2015

Duke UNIVERSITY

Wind is (incorrectly) assumed to be stationary

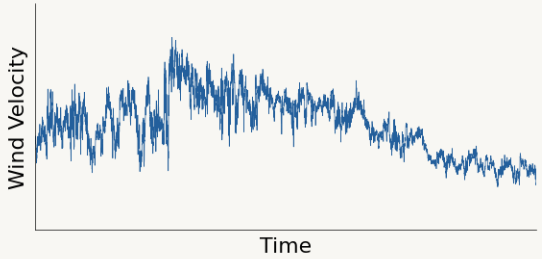
Simulation

Time-invariant statistics



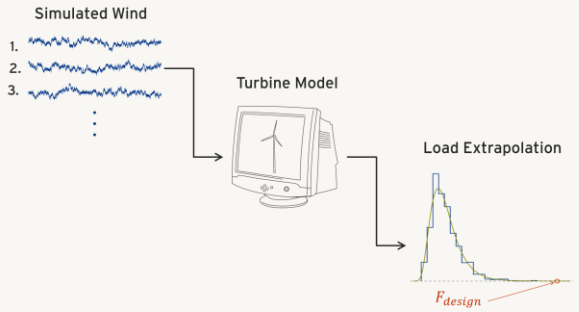
Reality

Time-varying statistics

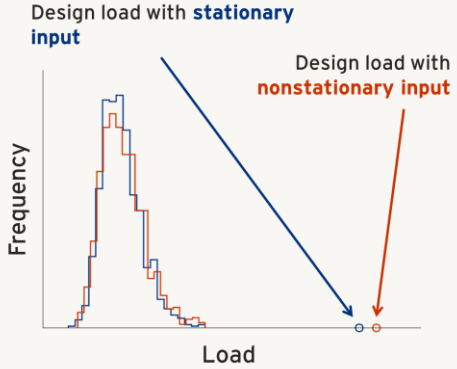


Nonstationary inflow increases wind turbine design loads

Wind Turbine Design Loads



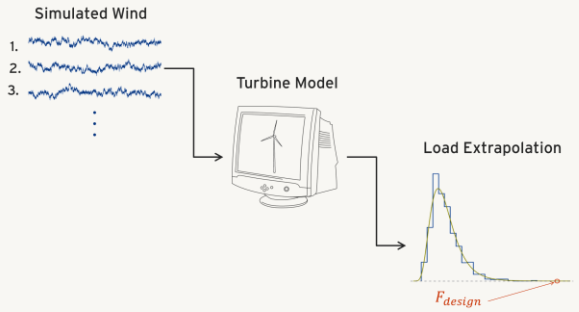
Effect of nonstationary inflow on dynamical system



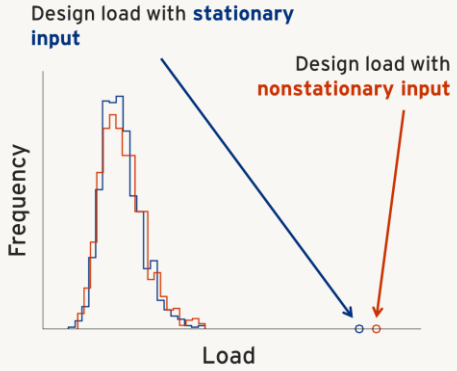
J.M. Rinker, H.P. Gavin, A. Clifton

Nonstationary inflow increases wind turbine design loads

Wind Turbine Design Loads

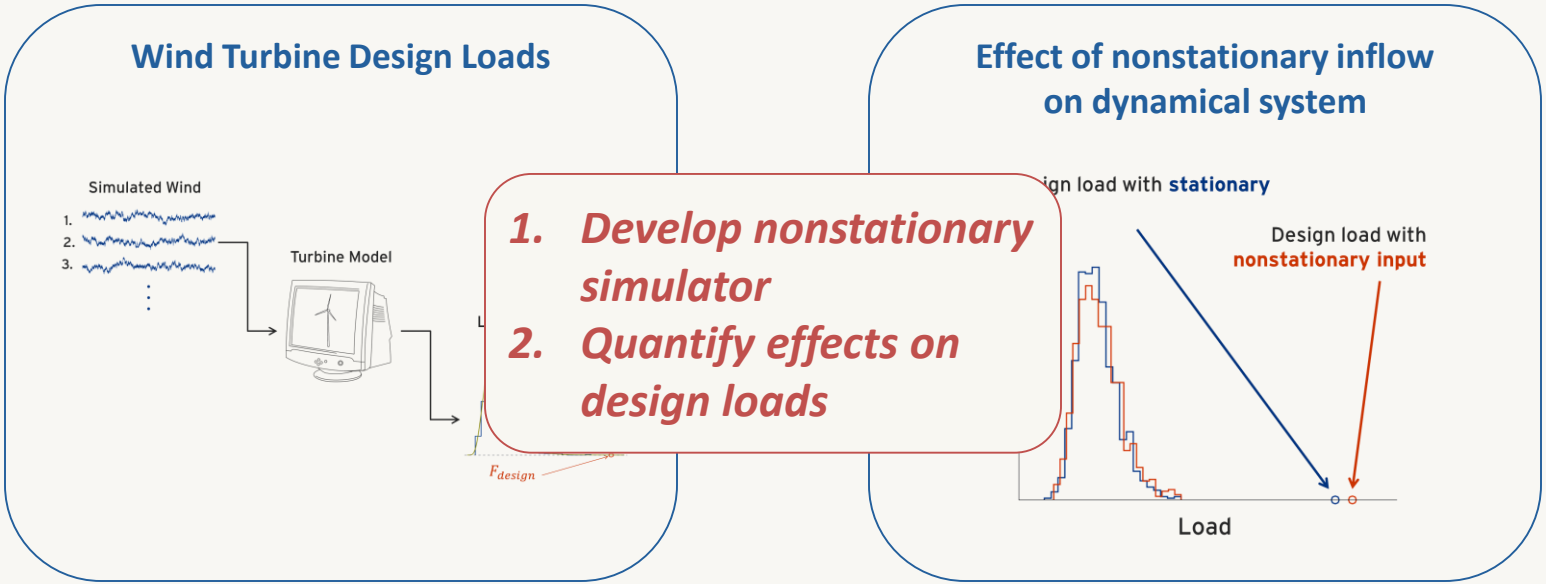


Effect of nonstationary inflow on dynamical system



Neglecting nonstationarity could lead to non-conservative turbine design loads.

Nonstationary inflow increases wind turbine design loads

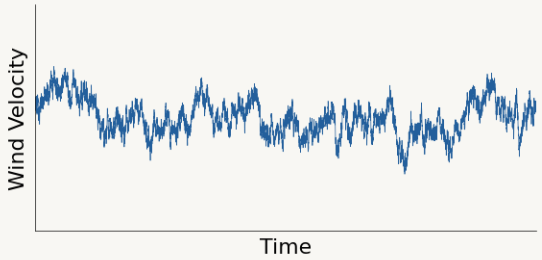


Neglecting nonstationarity could lead to non-conservative turbine design loads.

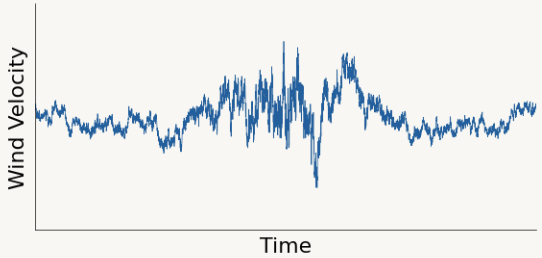
Proposed solution: simulator with temporal coherence

Developing a stochastic simulator that produces nonstationary fields

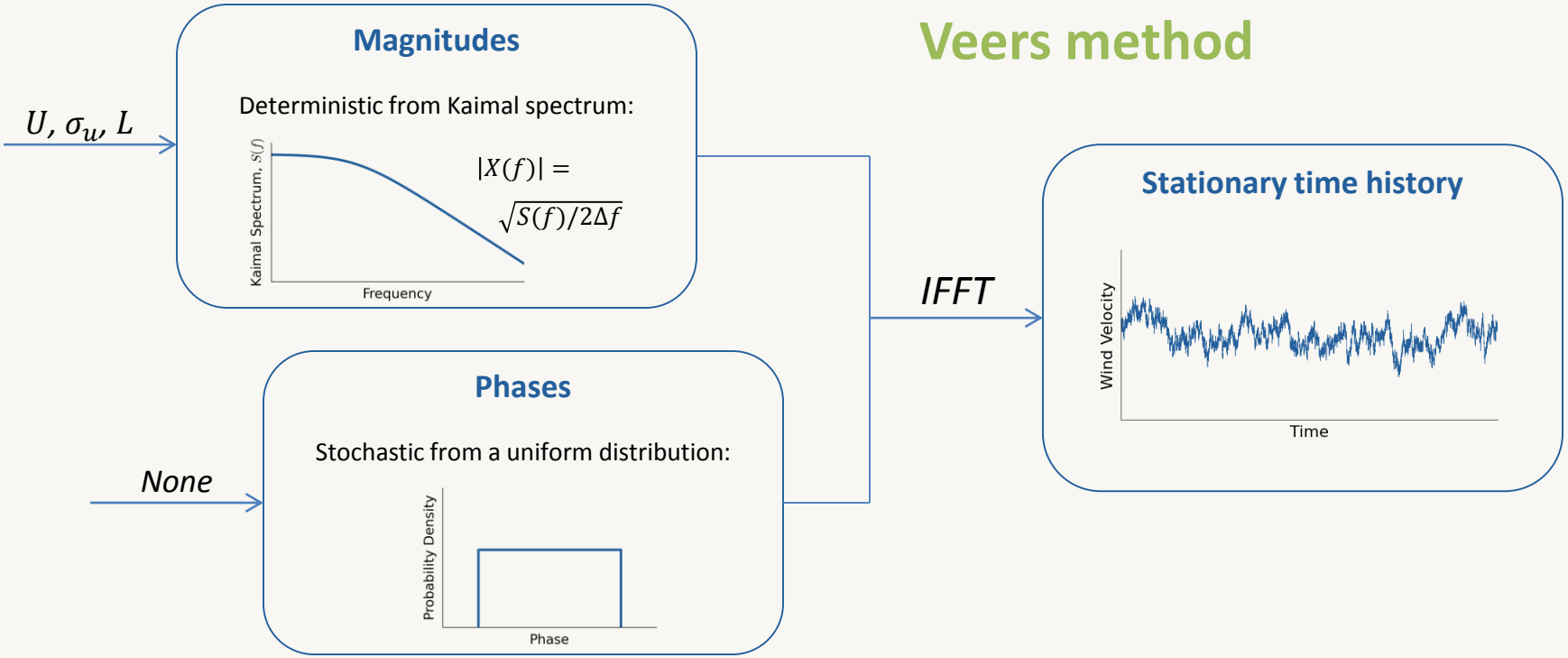
Instead of



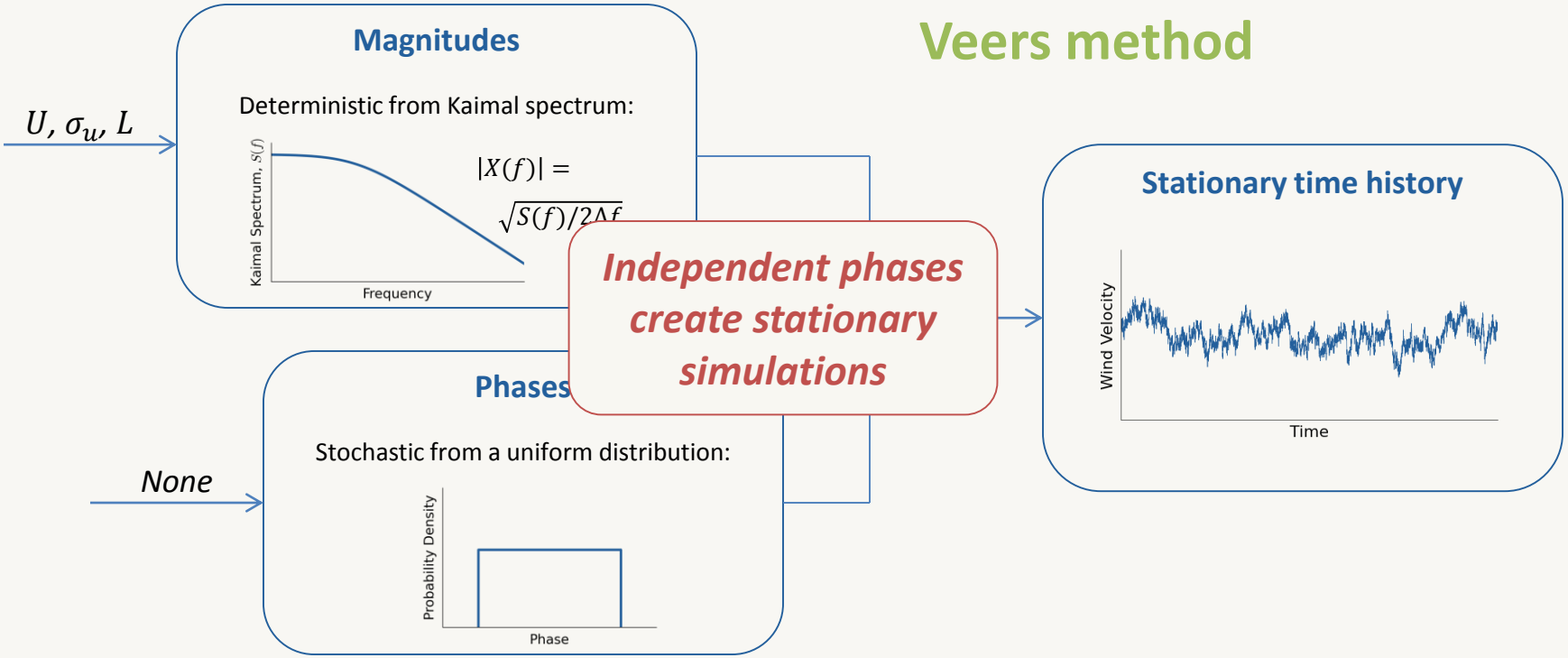
produces



Proposed simulator modifies standard simulation method

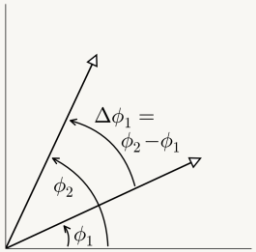


Proposed simulator modifies standard simulation method



Correlate phases using phase difference distributions

Phase difference distributions (PDDs)

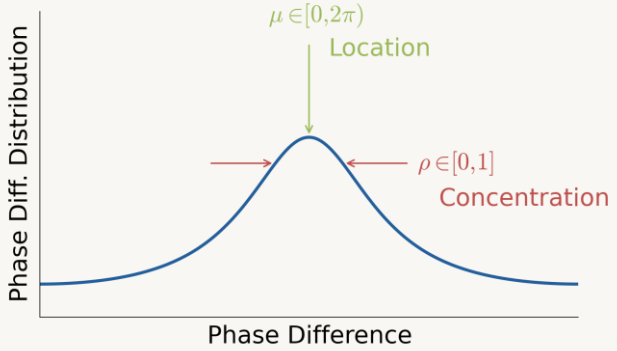


Phase difference $\Delta\phi_k$ is difference in phases at f_{k+1} and f_k

$$\phi_2 = \phi_1 + \Delta\phi_1$$

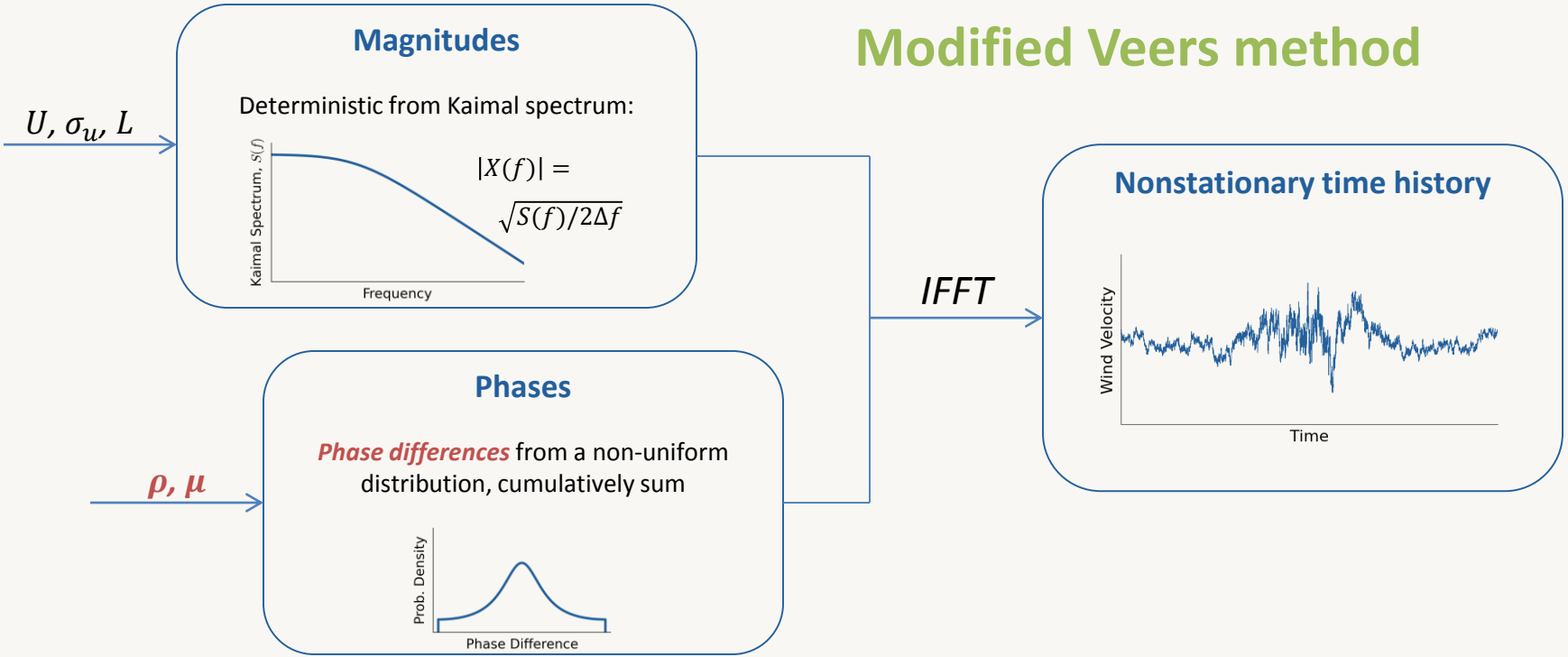
Non-uniform distribution on $\Delta\phi_1$ → Phases ϕ_1 and ϕ_2 are correlated

Higher distribution concentration increases phase correlation

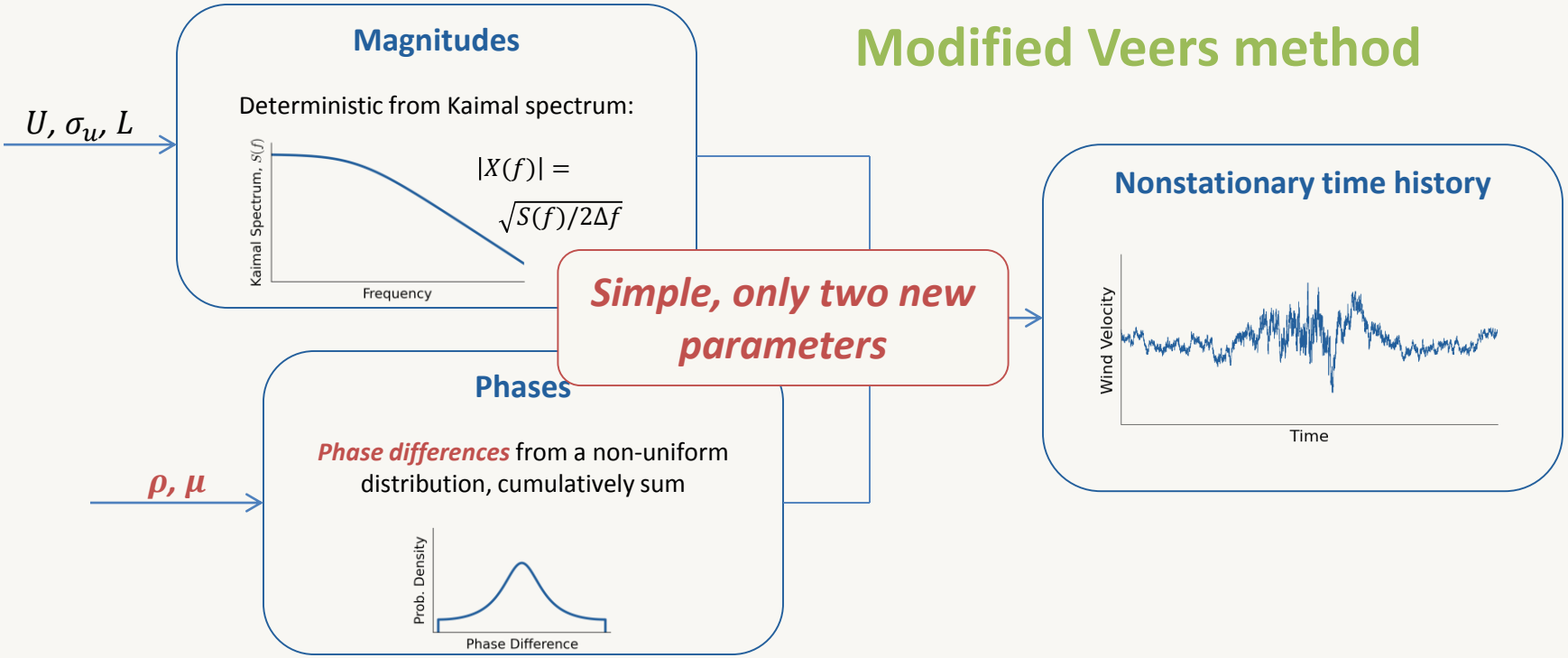


No phase correlation: $\rho = 0$

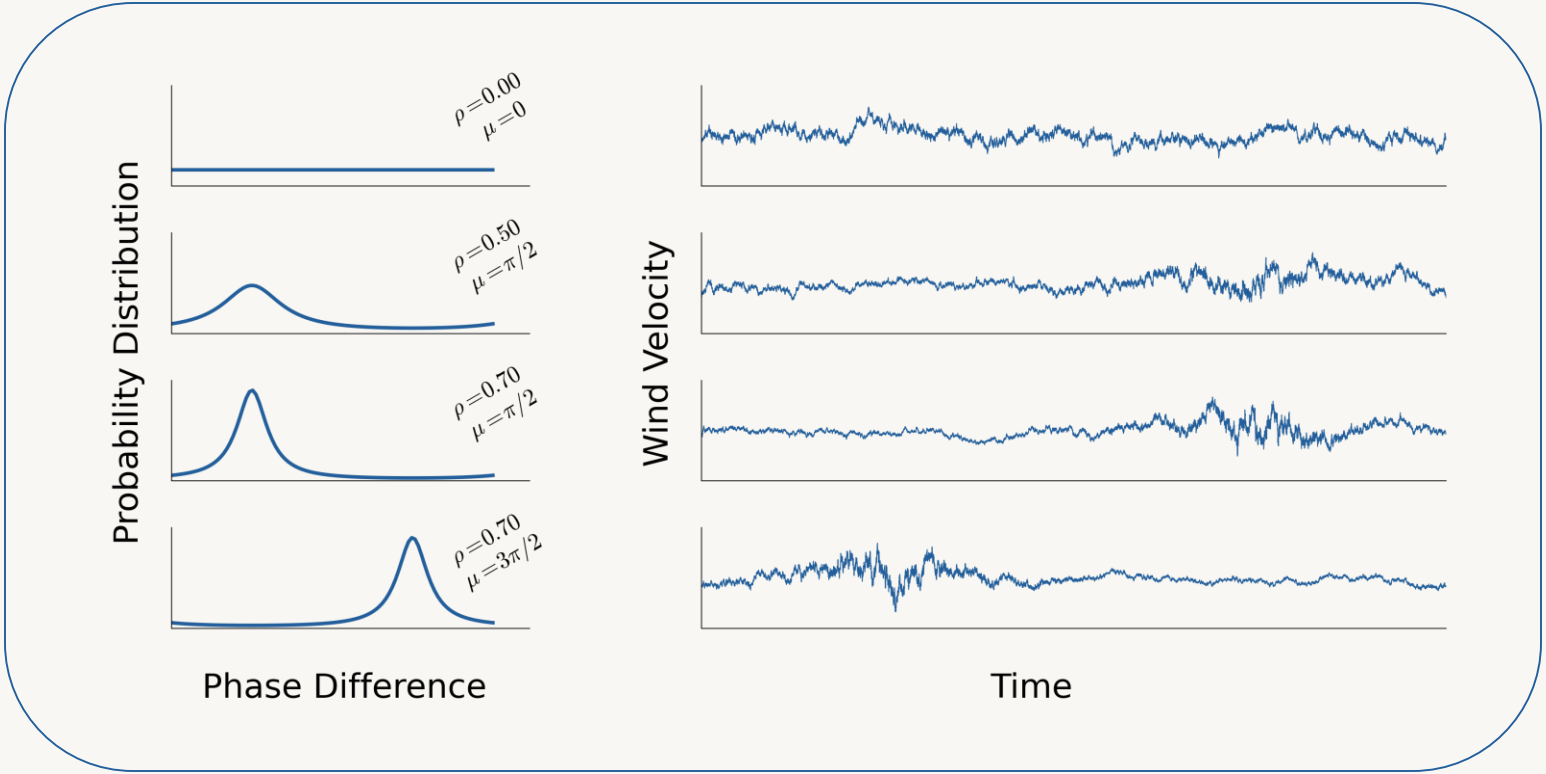
Nonstationary simulator samples phase differences



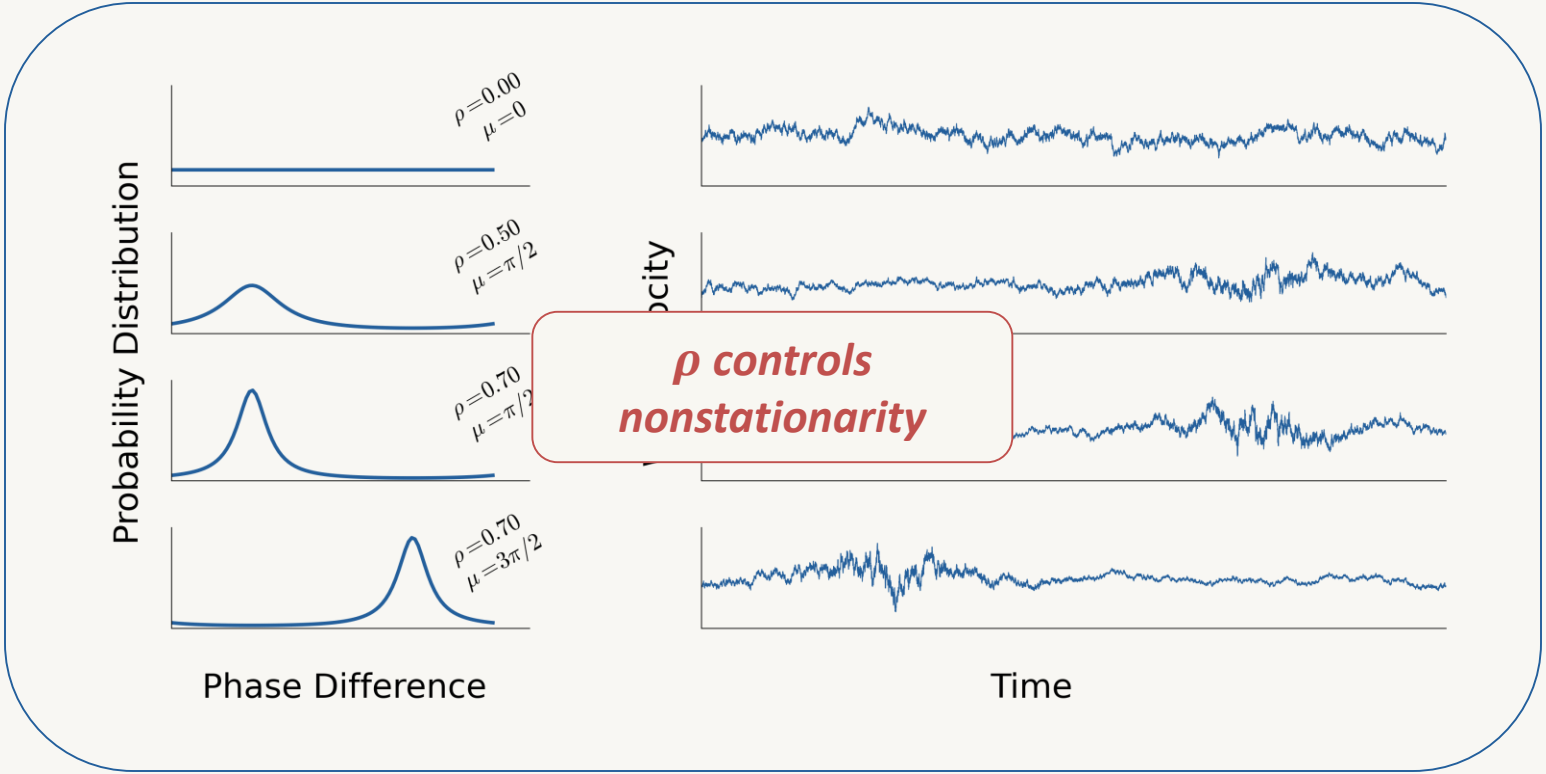
Nonstationary simulator samples phase differences



PDD parameters have direct effect on time domain behavior



PDD parameters have direct effect on time domain behavior



How to choose simulation parameters

Parameters	High-frequency time series available?	Calculation method
Standard wind parameters (U, σ_u, L)	Yes	From time series
	No	IEC 61400-1
Temporal coherence parameter (ρ)	Yes	From time series ($\frac{1}{N}\sum_{k=1}^{N} e^{i\Delta\phi_k} \approx \rho e^{i\mu}$)
	No	…

How to choose simulation parameters

Parameters	High-frequency time series available?	Calculation method
Standard wind parameters (U, σ_u, L)	Yes	From time series
	No	IEC 61400-1
Temporal coherence parameter (ρ)	Yes	From time series ($\frac{1}{N}\sum_{k=1}^{N} e^{i\Delta\phi_k} \approx \rho e^{i\mu}$)
	No	???

How to choose simulation parameters

Parameters	High-frequency time series available?	Calculation method
Standard wind parameters (U, σ_u, L)	Yes	From time series
	No	IEC 61400-1
Temporal coherence parameter (ρ)	Yes	From time series ($\frac{1}{N}\sum_{k=1}^{N} e^{i\Delta\phi_k} \approx \rho e^{i\mu}$)
	No	???

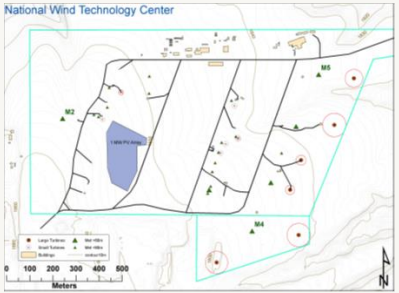
Use dataset to determine what values of ρ are realistic, correlations with other parameters

High-frequency sonic anemometer data from NWTC

Site - National Wind Technology Center

Joe Smith, NREL

Highly turbulent,
non-neutral conditions



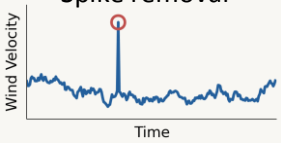
Sonic Anemometer on Tower M4

Lee-Jay Fingersh, NREL

- About 3 years of data
- 20 Hz sampling
- Measurement heights:
  15 m, 30 m, 50 m,
  76 m, 100 m, 131 m

Quality control

Cleaning:
Spike removal



Screening:

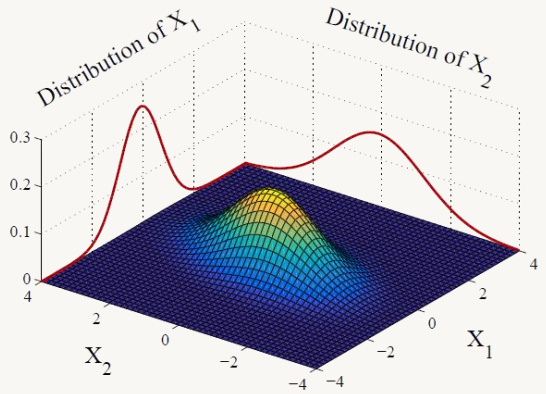
1. Mean wind speed
2. Wind direction
3. Precipitation

Characterize ρ using joint probability distribution

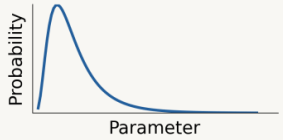
Joint distribution (U, σ_u, L, ρ)

Probability density function
for multiple random variables

Probability is area under curve



1. Marginals



- Distribution single random variable
- Frequency of occurrence of values
- Model or empirical

2. Correlations

- Linear relationship between different random variables
- Organized in matrix
- Direct calculation

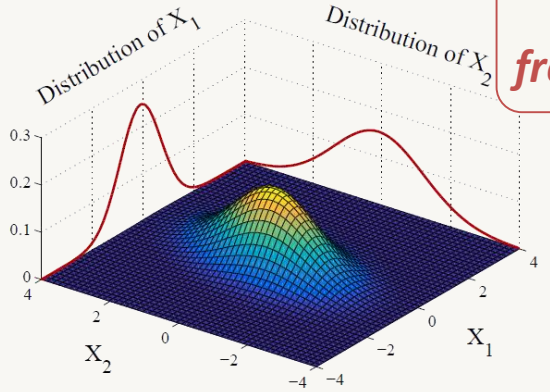
	X_1	X_2
X_1	1	0.7
X_2	0.7	1

Characterize ρ using joint probability distribution

Joint distribution (U, σ_u, L, ρ)

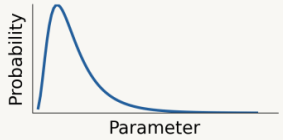
Probability density function
for multiple random variables

Probability is area under curve



Can draw samples from joint distribution

1. Marginals



- Distribution single random variable
- Frequency of occurrence of values
- Model or empirical

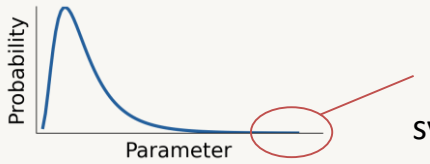
2. Correlations

- Linear relationship between different random variables
- Organized in matrix
- Direct calculation

	X_1	X_2
X_1	1	0.7
X_2	0.7	1

Important that marginal models match data at high values

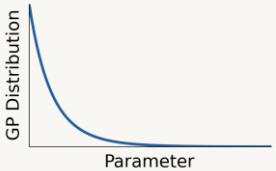
Tail data



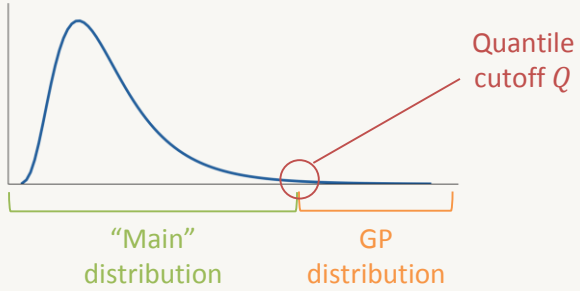
Larger U, σ_u, ρ produce larger system responses

Generalized Pareto (GP) distribution

Probability of values above a specified threshold



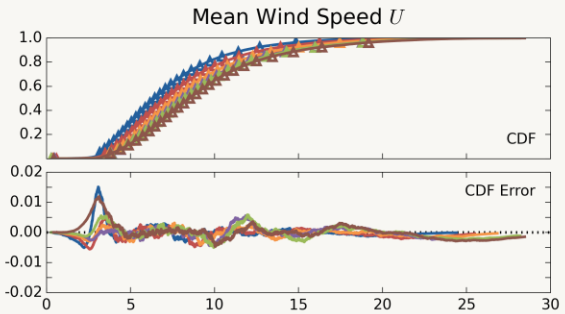
"Composite" distribution

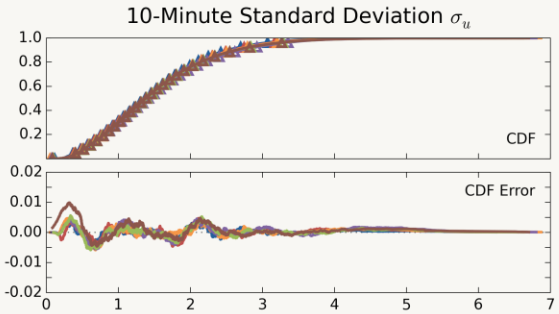


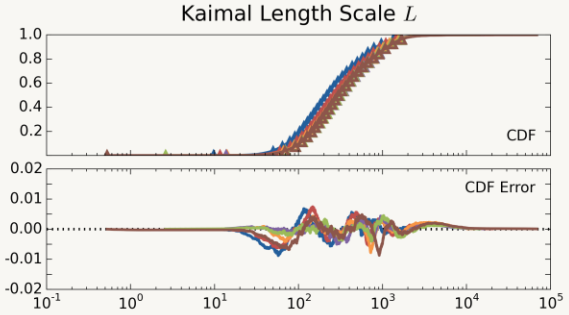
Optimize parameters to minimize sum of CDF error

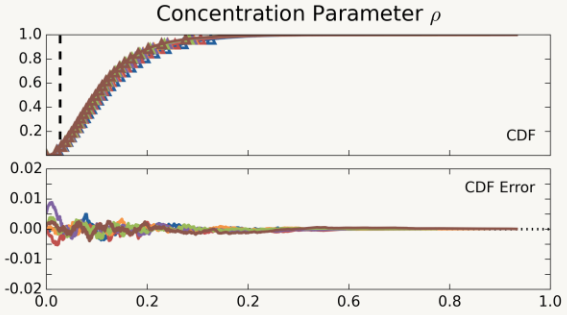
Multiple main distribution candidates

Information from wind parameter distributions/model fits









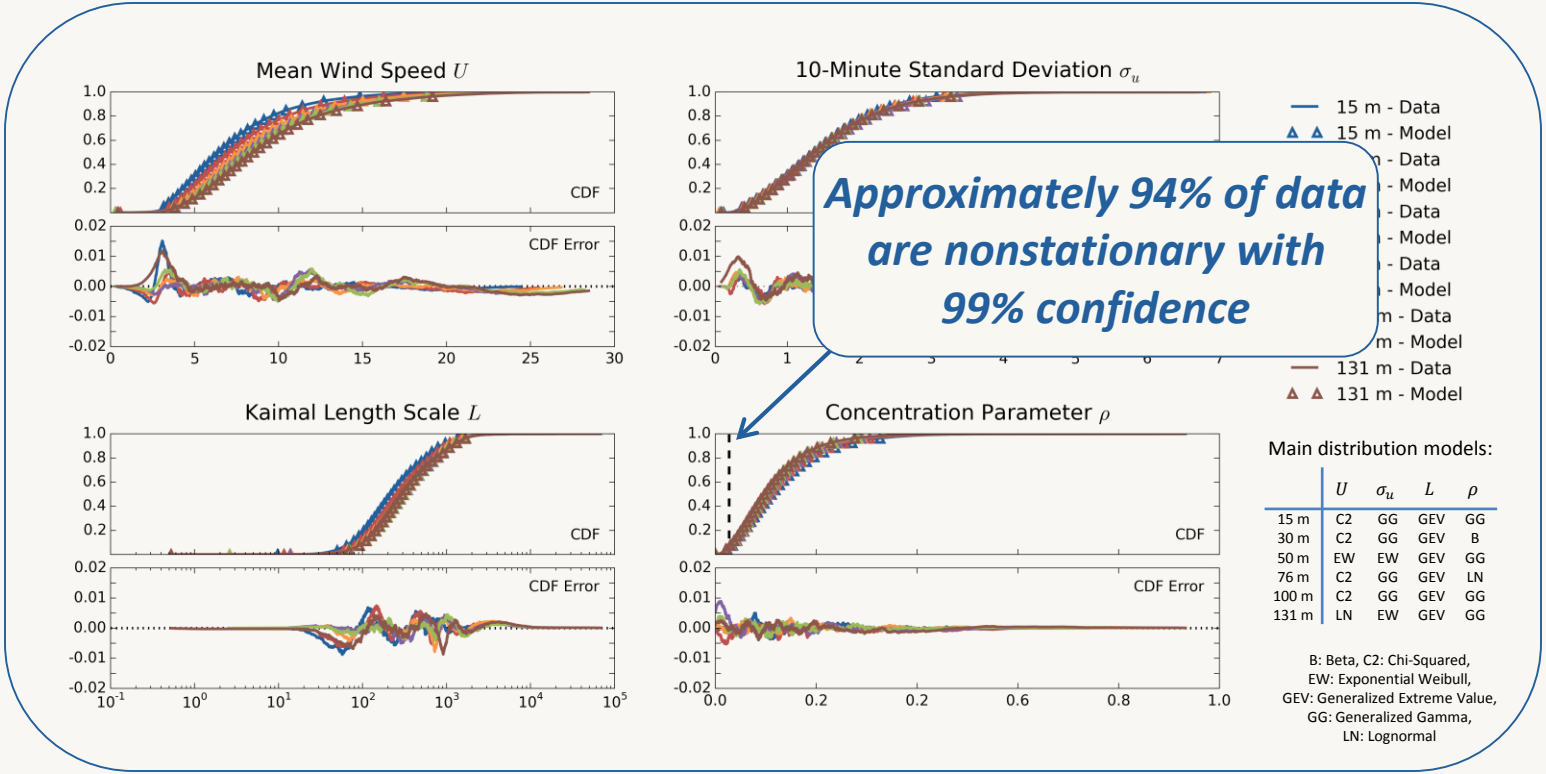
15 m - Data
15 m - Model
30 m - Data
30 m - Model
50 m - Data
50 m - Model
76 m - Data
76 m - Model
100 m - Data
100 m - Model
131 m - Data
131 m - Model

Main distribution models:

	U	σ_u	L	ρ
15 m	C2	GG	GEV	GG
30 m	C2	GG	GEV	B
50 m	EW	EW	GEV	GG
76 m	C2	GG	GEV	LN
100 m	C2	GG	GEV	GG
131 m	LN	EW	GEV	GG

B: Beta, C2: Chi-Squared,
EW: Exponential Weibull,
GEV: Generalized Extreme Value,
GG: Generalized Gamma,
LN: Lognormal

Information from wind parameter distributions/model fits

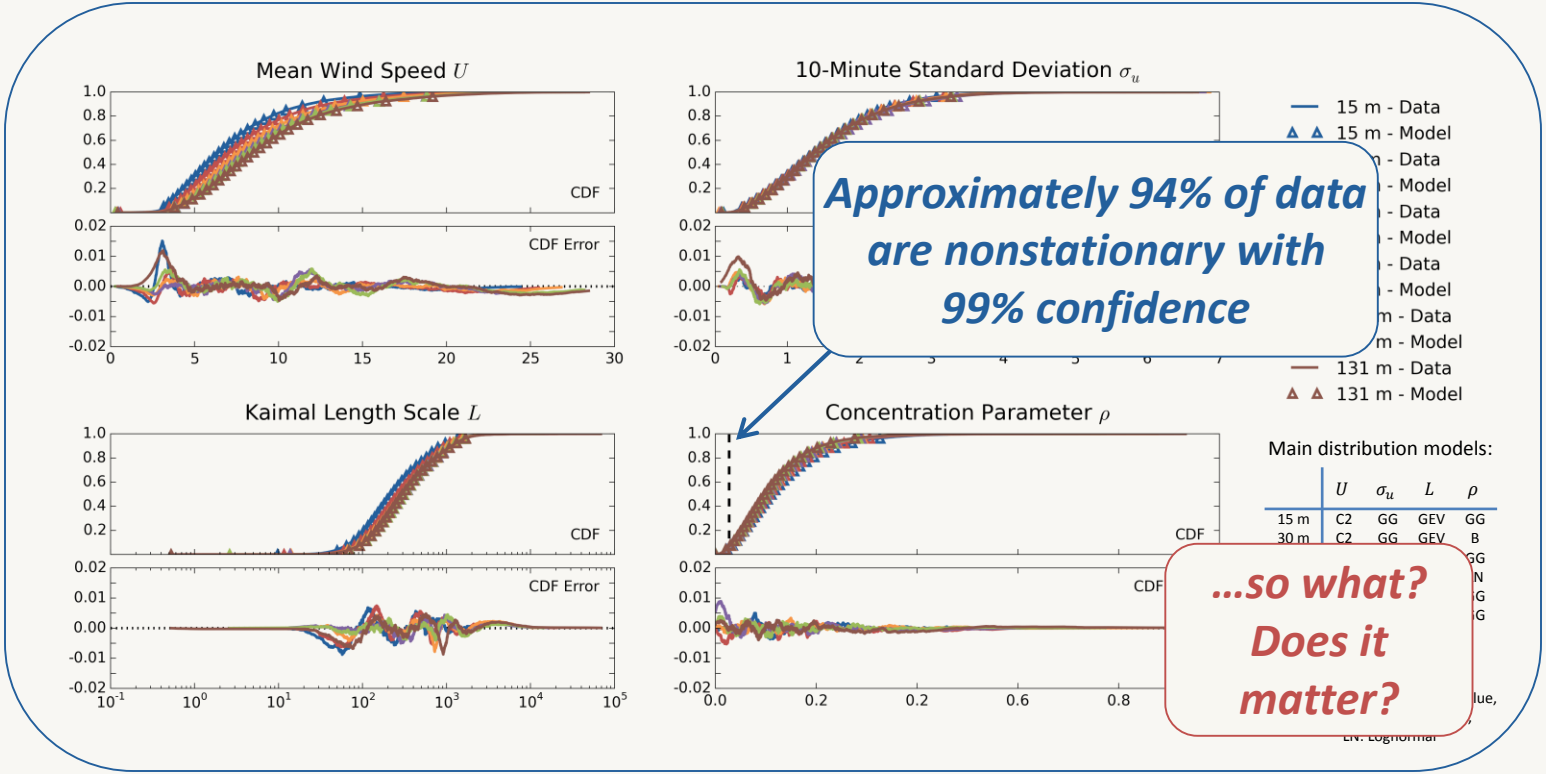


Main distribution models:

	U	σ_u	L	ρ
15 m	C2	GG	GEV	GG
30 m	C2	GG	GEV	B
50 m	EW	EW	GEV	GG
76 m	C2	GG	GEV	LN
100 m	C2	GG	GEV	GG
131 m	LN	EW	GEV	GG

B: Beta, C2: Chi-Squared,
EW: Exponential Weibull,
GEV: Generalized Extreme Value,
GG: Generalized Gamma,
LN: Lognormal

Information from wind parameter distributions/model fits

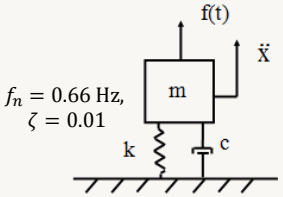


Use SDOF to calculate increase in extrapolated ultimate load

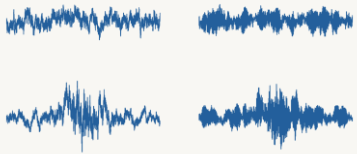
Extrapolating SDOF maximum response

3 cases:

1. IEC 61400-1 (WT II, TC B)
2. Distribution, $\rho = 0$
3. Distribution, $\rho \neq 0$



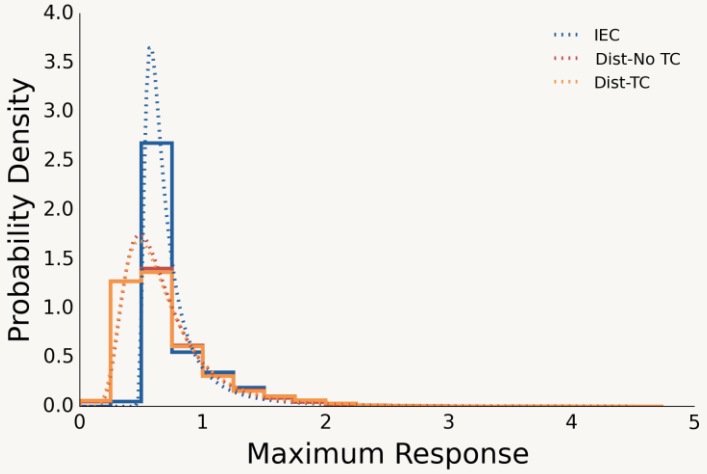
1. Sample wind parameters
2. Simulate turbulent wind
3. Calculate SDOF response
4. Extract maximum response
5. Extrapolate 50-year load



Wind Response

5,000 samples/ case

Maximum response distributions



$p_{ext} = 3.8 \times 10^{-7}$: $F_{IEC} \approx 449$

$\boldsymbol{F_{NoTC} \approx 21}$

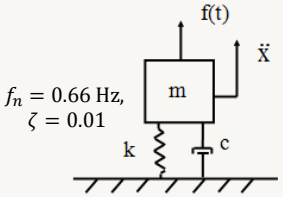
$\boldsymbol{F_{TC} \approx 27}$

Use SDOF to calculate increase in extrapolated ultimate load

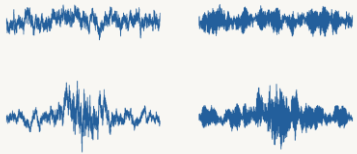
Extrapolating SDOF maximum response

3 cases:

1. IEC 61400-1 (WT II, TC B)
2. Distribution, $\rho = 0$
3. Distribution, $\rho \neq 0$



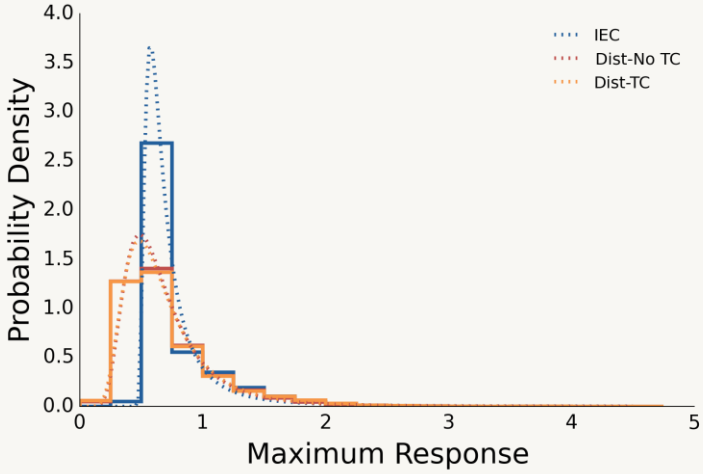
1. Sample wind parameters
2. Simulate turbulent wind
3. Calculate SDOF response
4. Extract maximum response
5. Extrapolate 50-year load



Wind Response

5,000 samples/ case

Maximum response distributions



$p_{ext} = 3.8 \times 10^{-7}$:

$F_{IEC} \approx 449$

$F_{NoTC} \approx 21$

$F_{TC} \approx 27$

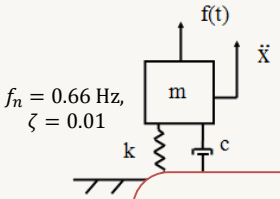
28.3% increase

Use SDOF to calculate increase in extrapolated ultimate load

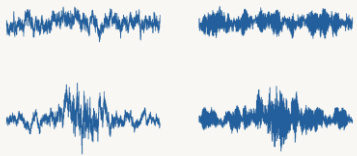
Extrapolating SDOF maximum response

3 cases:

1. IEC 61400-1 (WT II, TC B)
2. Distribution, $\rho = 0$
3. Distribution, $\rho \neq 0$



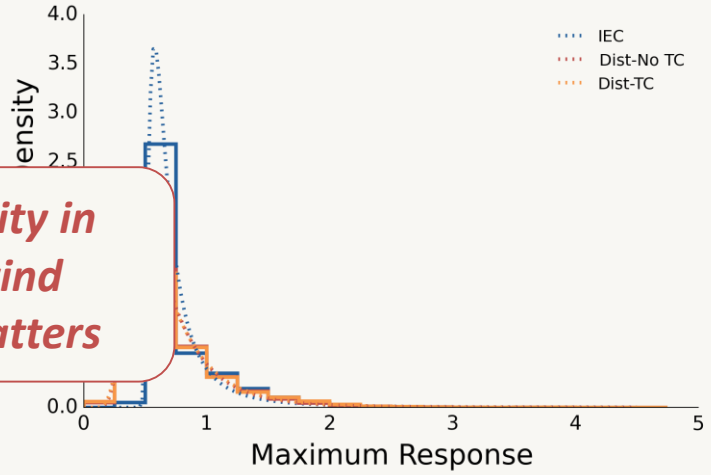
1. Sample wind parameters
2. Simulate turbulent wind
3. Calculate SDOF response
4. Extract maximum response
5. Extrapolate 50-year load



5,000 samples/ case

Nonstationarity in "normal" wind conditions matters

Maximum response distributions



$p_{ext} = 3.8 \times 10^{-7}$:

$F_{IEC} \approx 449$

$F_{NoTC} \approx 21$

$F_{TC} \approx 27$

28.3% increase

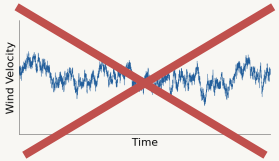
Summary

Simulator

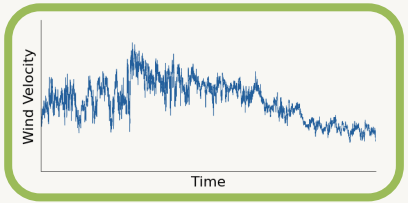
Data Analysis

Summary

Simulator



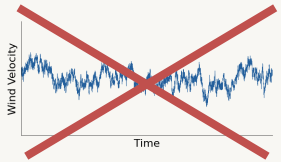
Nonstationary, stochastic



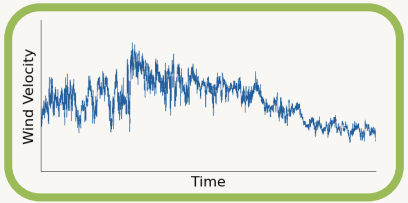
Data Analysis

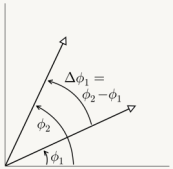
Summary

Simulator

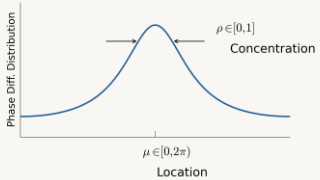


Nonstationary, stochastic





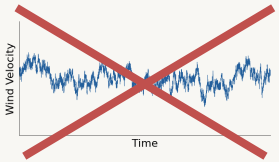
Temporal coherence via PDDs



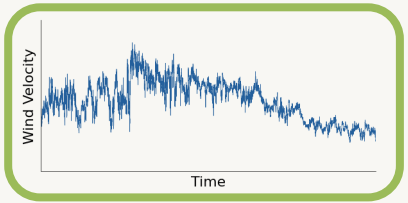
Data Analysis

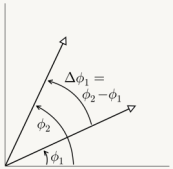
Summary

Simulator

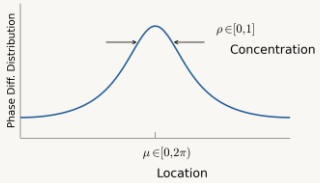


Nonstationary, stochastic

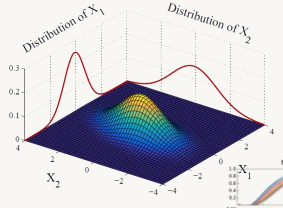




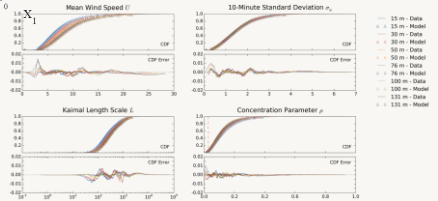
Temporal coherence via PDDs



Data Analysis



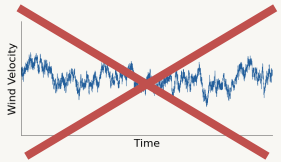
Fit joint dist. to NWTC data



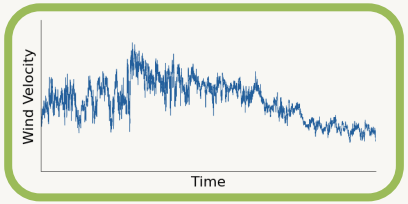
J.M. Rinker, H.P. Gavin, A. Clifton

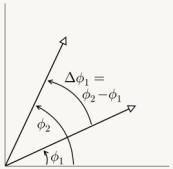
Summary

Simulator

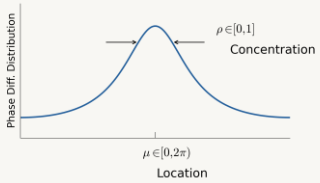


Nonstationary, stochastic

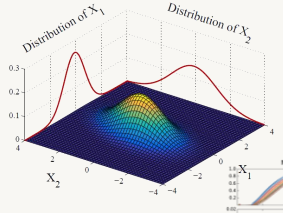




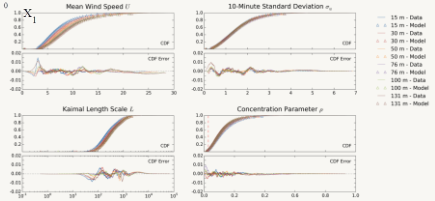
Temporal coherence via PDDs

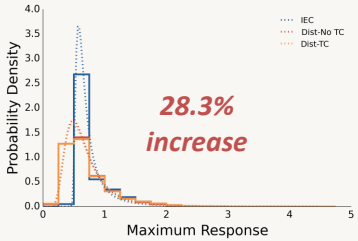


Data Analysis



Fit joint dist. to NWTC data





28.3% increase

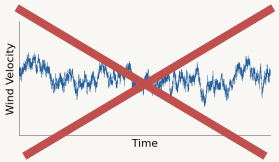
SDOF loads extrapolation

Acknowledgements

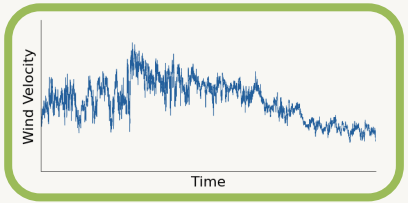
This material is based upon work supported by the **National Science Foundation Graduate Research Fellowship Program** under Grant No. 1106401; by the **U.S. Department of Energy (DOE)**, Office of Science (OS), Office of Workforce Development for Teachers and Scientists, **OS Graduate Student Research** (SCGSR) program; by the U.S. DOE under Contract No. DE-AC36-08GO28308 with NREL; by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.

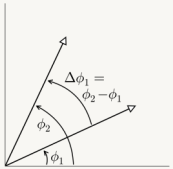
Thank you! Questions?

Simulator

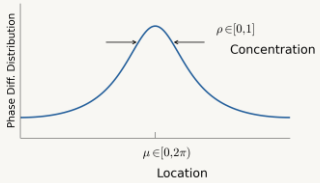


Nonstationary, stochastic

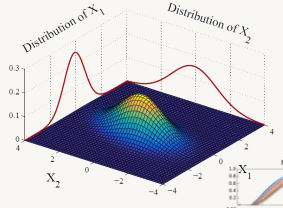




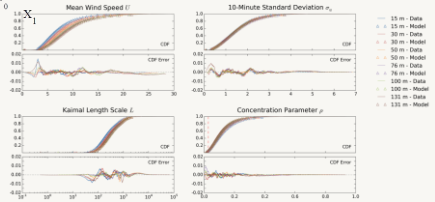
Temporal coherence via PDDs

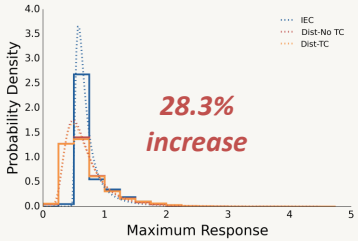


Data Analysis



Fit joint dist. to NWTC data





28.3% increase

SDOF loads extrapolation

Empirical histograms don't match IEC distributions