Bayesian Networks for storm surge estimation in Mississippi (US)

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Content

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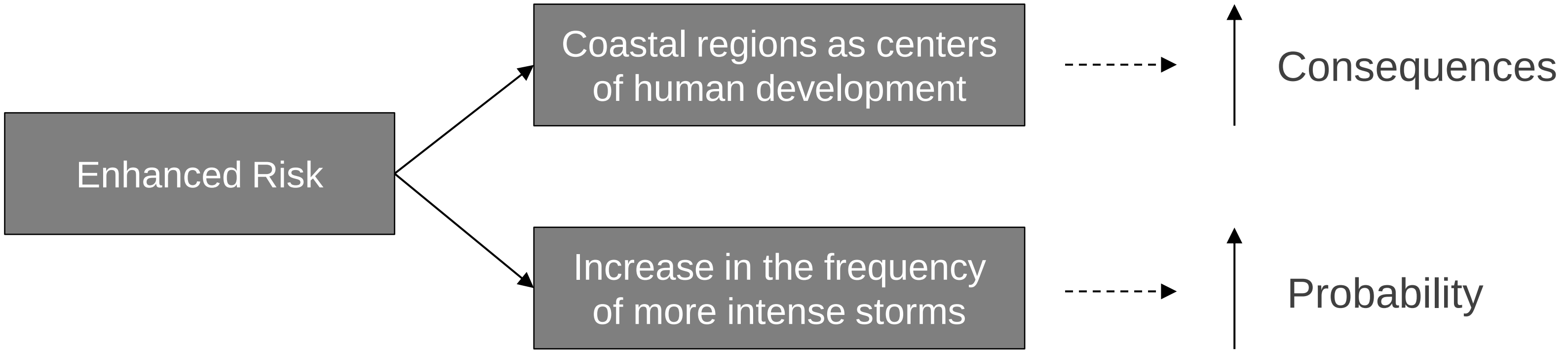
Literature review	*What is a hurricane and what is storm surge?*
Model development	*How a physical and a stochastic model is set up to estimate surge in Mississippi?*
Discussion	*What can be observed from the results and what are the limitations of the models proposed?*
Conclusion	*What can be concluded from the models developed?*

1. Introduction

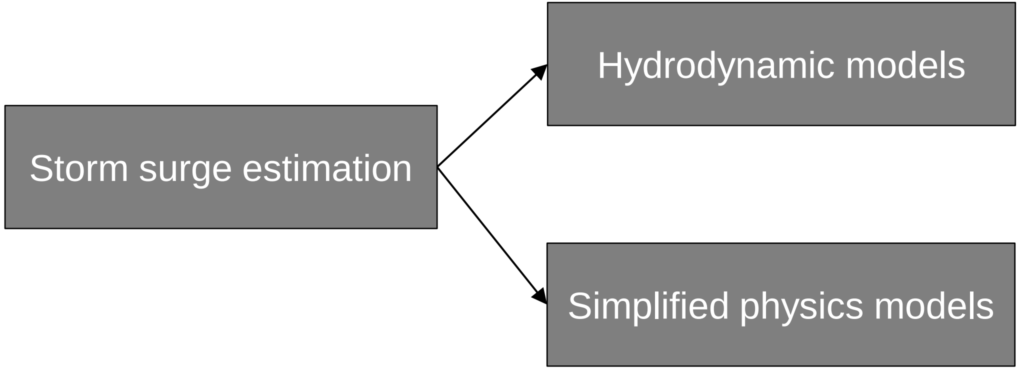
Motivation

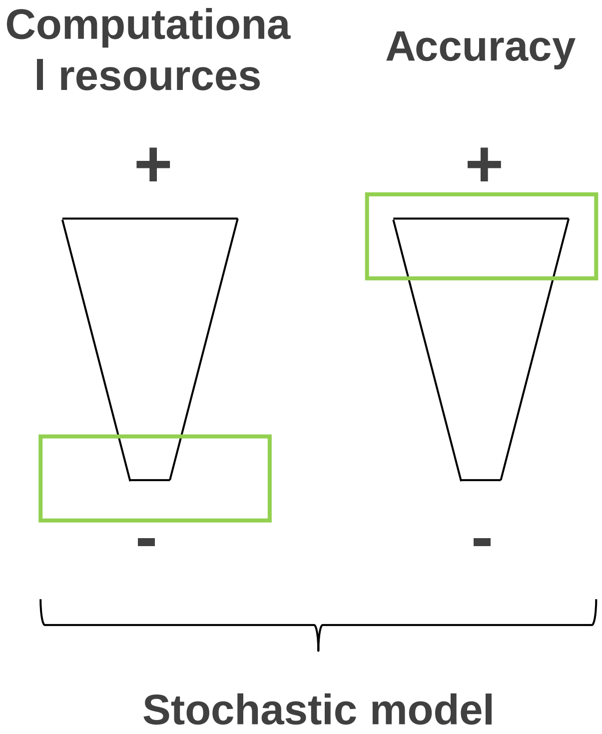
Flood Risk = Probability x Consequences



1. Introduction

Problem statement





1. Introduction

Research question and subquestions

Is it possible to estimate storm surge at reasonable accuracy and time in the coast of Mississippi by using a stochastic model?

1. How should the different input of the hydrodynamic model be calibrated to simulate surge at high fidelity?

2. How should the hurricane data scarcity be tackled in order to generate a sufficiently large data set for the training of the stochastic model?

3. What is the accuracy of the surge estimation and the time of computation of the stochastic model?

1. Introduction

Location of the project

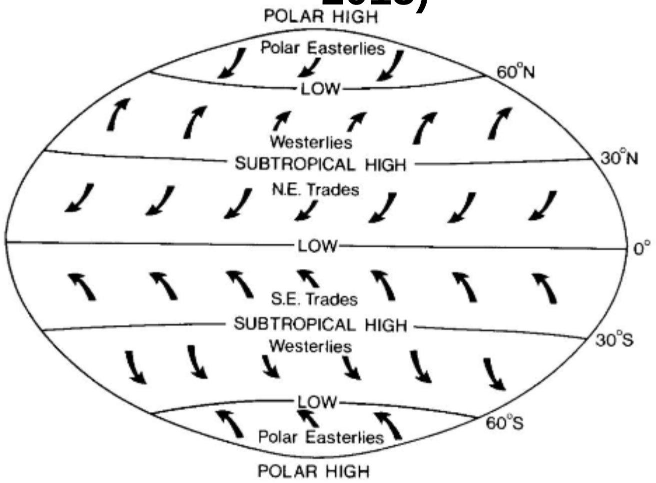
Mississippi coast, North of the Gulf of Mexico

2. Literature review

Description of the physical processes: Hurricanes

Rotating low pressure system with maximum sustained winds larger than 119 km/h originating in the Atlantic Ocean

Pressure belts and prevailing wind systems on Earth's surface (Bosboom, 2015)



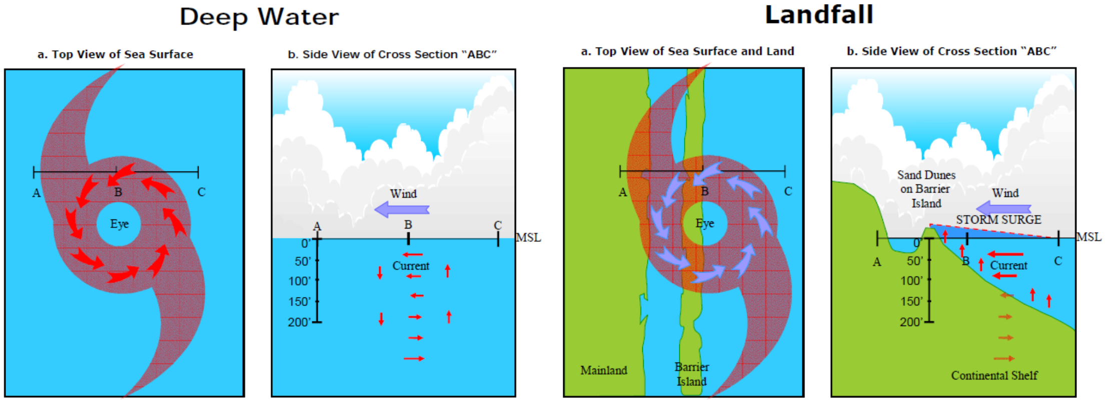
HURDAT2 database (1851-2018) based on Saffir-Simpson scale

Counterclockwise spin in the Northern Hemisphere due to the Coriolis force.

2. Literature review

Description of the physical processes: Storm surge

Abnormal rise ofwater level above the expected tide associated to low pressure atmospheric systems

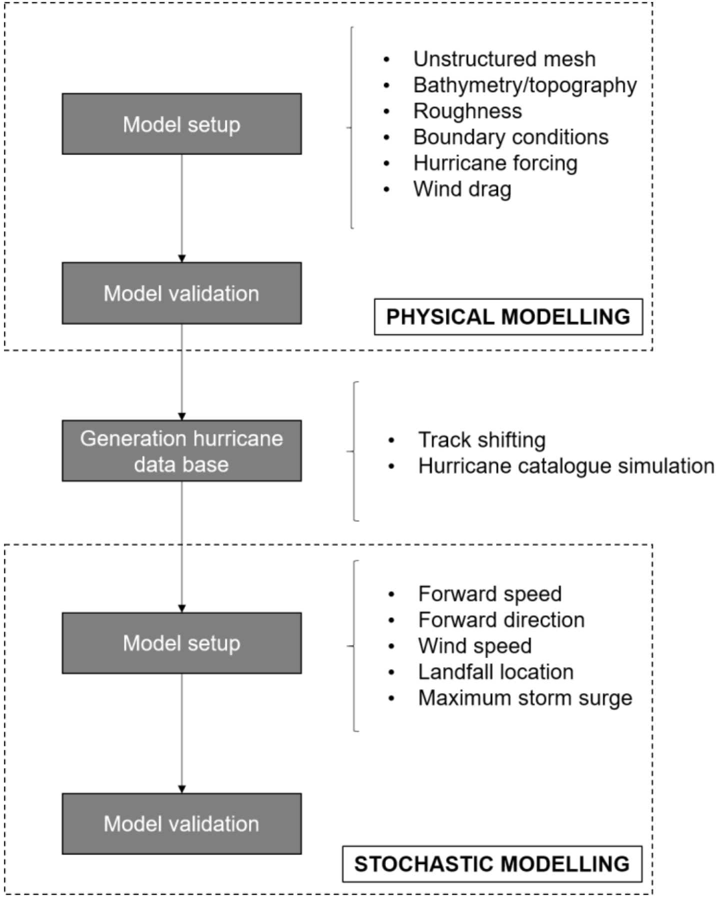


NOAA (2015)

Factors influencing storm surge

- Central pressure
- Storm intensity
- Forward speed of the hurricane
- Angle of approach to the coast
- Storm size
- Shape of the coastline
- Width and slope of the ocean bottom
- Local features (e.g. barrier islands)

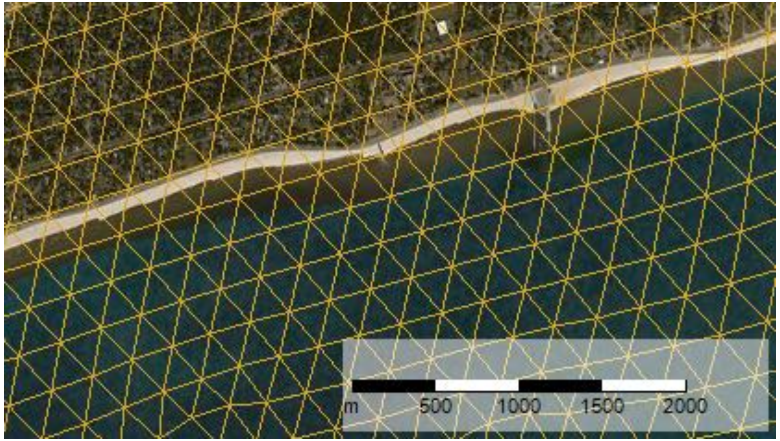
3. Methodology

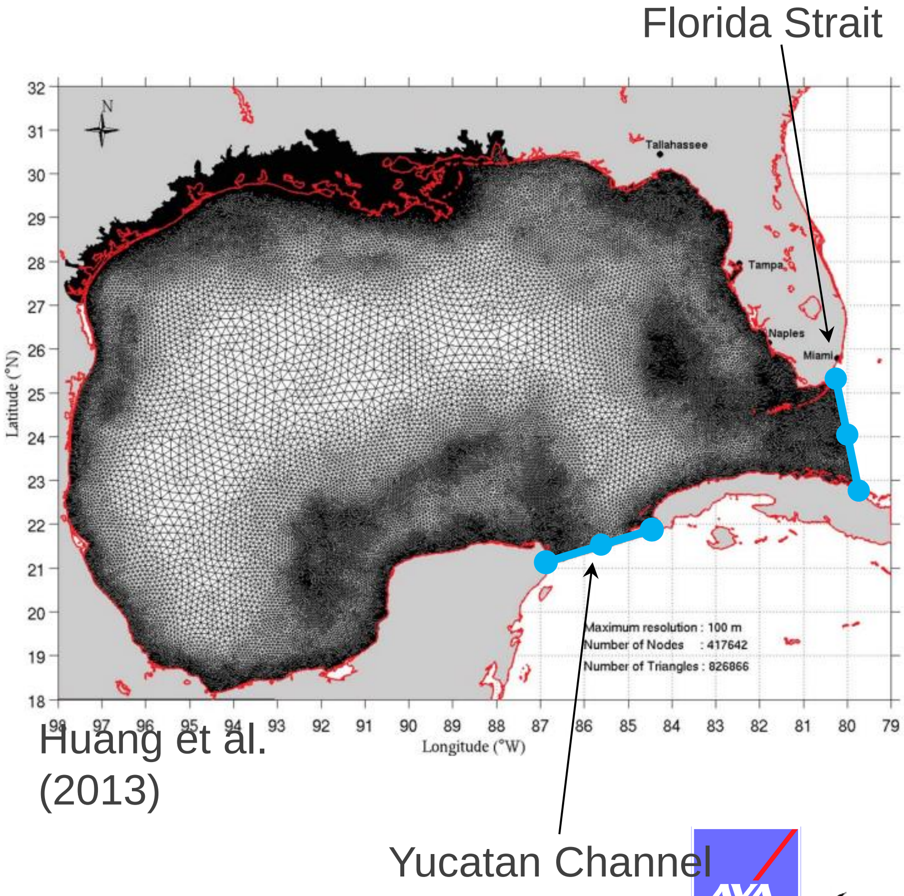


4. Physical model setup and validation

Unstructured mesh

- Unstructured mesh formed by 826,866 triangles
- It has been refined at the continental shelf of Mississippi (MS) from ~ 500 m to ~ 200 m



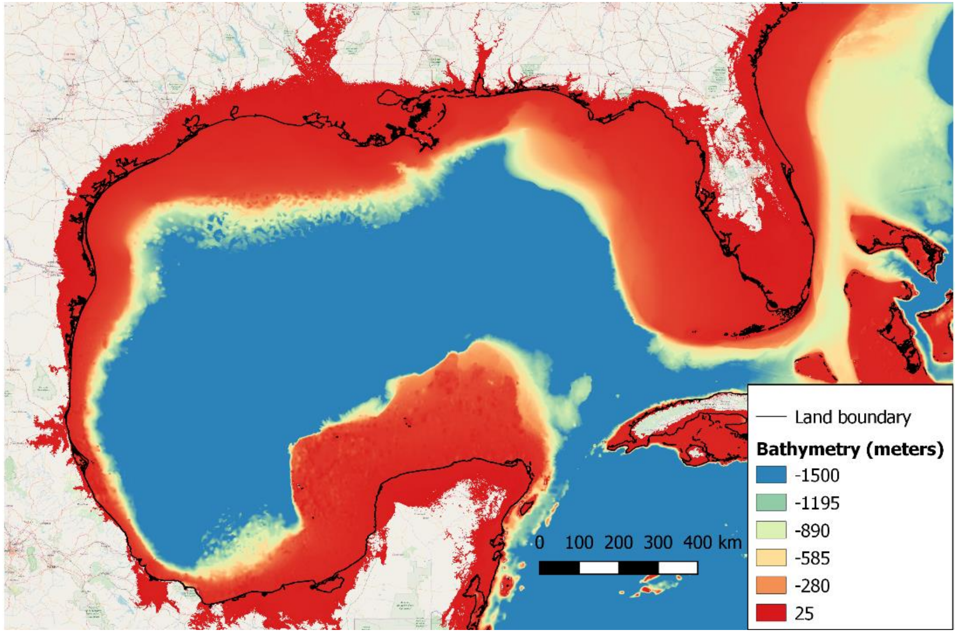


Huang et al. (2013)

4. Physical model setup and validation

Bathymetry/Topography

- Resolution: 15 arc-seconds (approx. cellzsize of 460 meters x 460 meters)
- Deep waters vs continental shelf

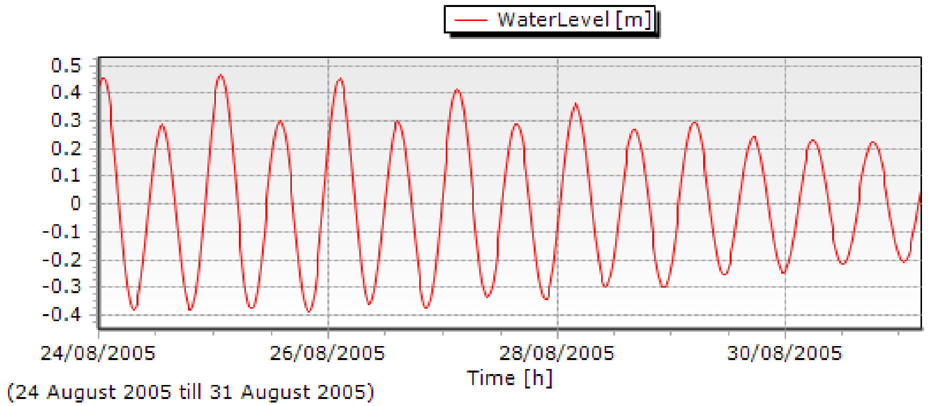


4. Physical model setup and validation

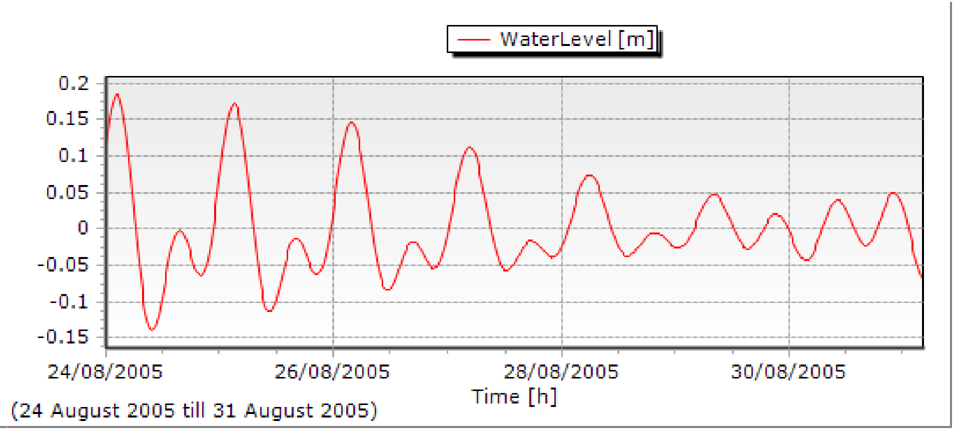
Boundary conditions

Tidal constituents: Q1, O1, K1, N2, M2, S2, K2. Extracted from Eastcoast2001 database (ADCIRC).

Florida Strait



Yucatan Channel



Noticeable influence of the diurnal constituents in the tide in the case of Yucatan channel due to resonance in the Caribbean Sea.

4. Physical model setup and validation

Hurricane forcing

TC best track (HURDAT2) → Adapted Holland model (Veltcheva, 2002) → Wind speed (W), Wind direction (φ), Pressure drop (ΔP)

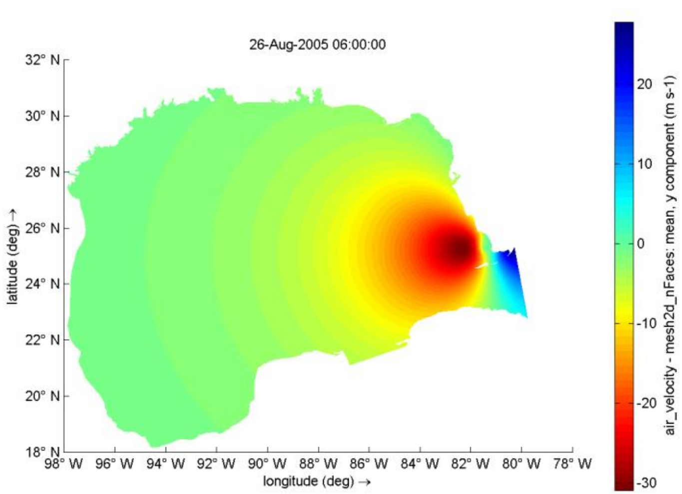
$$= f(W_{max}, p_c, R, \varphi, t)$$

4. Physical model setup and validation

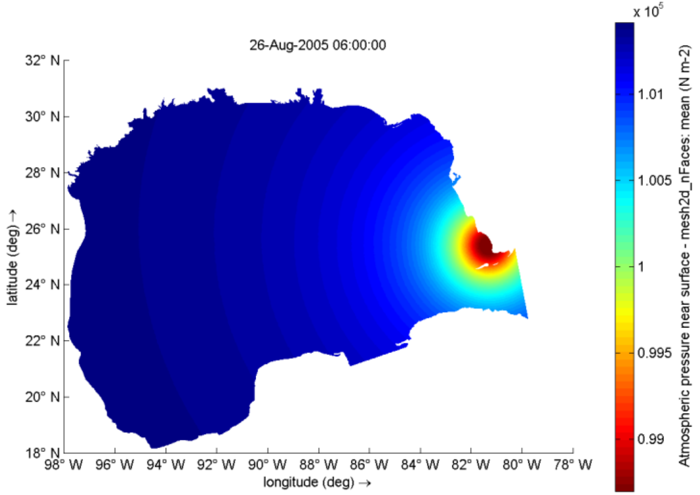
2D wind and pressure fields (Delft3D FM)

Wind velocities in y-direction and pressure fields (2D) at the moment of landfall (Katrina 2005), generated in Delft3D FM.

Wind velocities in y-direction



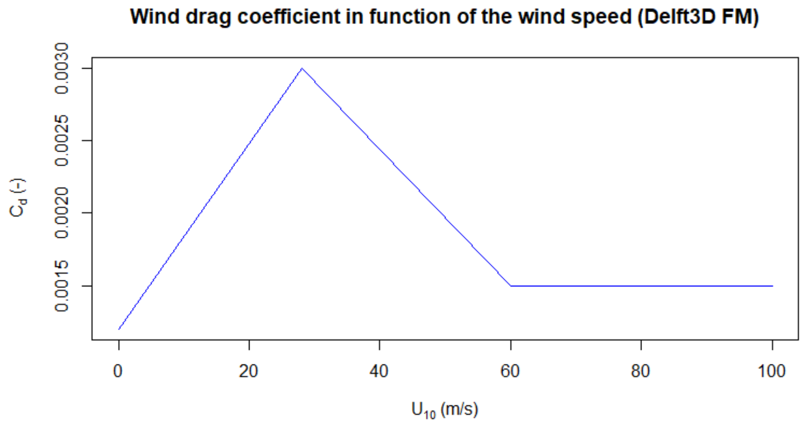
Air pressure

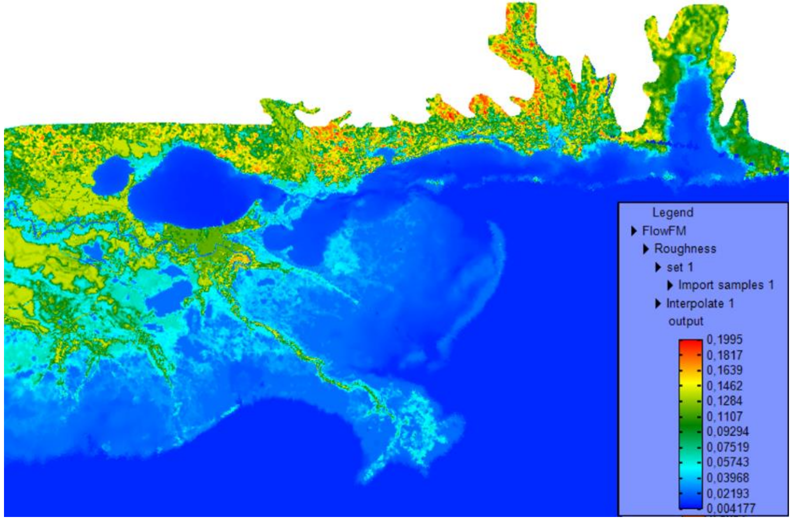


4. Physical model setup and validation

Wind drag and hydraulic roughness

- Approximate fit of the wind drag to the Makin model (2005)
- Assumed non-uniform Manning coefficient (Dietrich et al., 2011). n-Manning of 0.025 at open sea

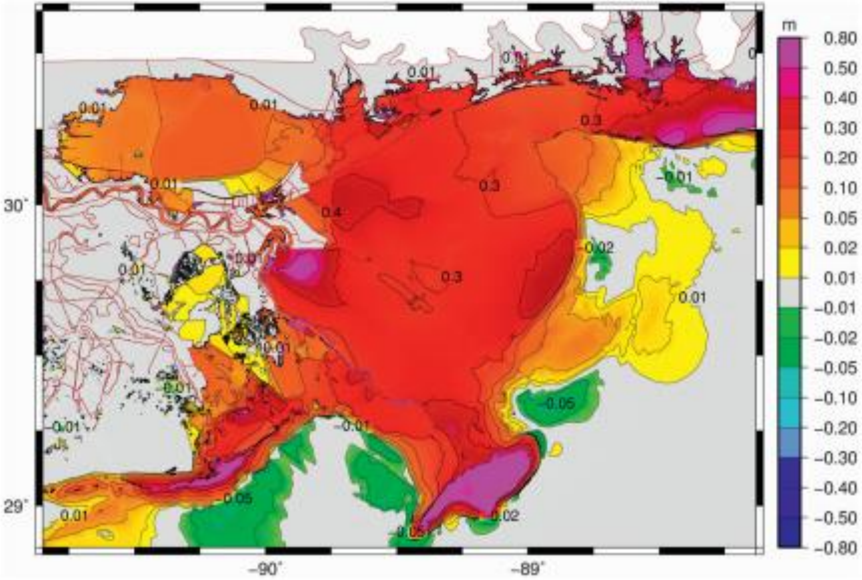




4. Physical model setup and validation

Wave setup

- Dissipation of energy due to barrier islands (Smith, 2008)
- $H_{setup,max} \approx (0.10 - 0.14) H_{max,0}$ (FEMA, 2005)
- $H_{setup,max}$ at Mississippi during Katrina (2005) was approx. 0.3 meter, according to the SWAN+ADCIRC model developed by Bunya et al. (2010)

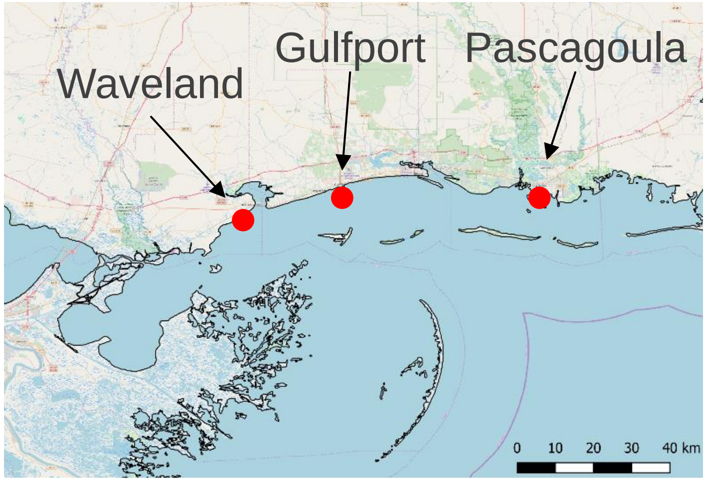


Bunya et al. (2010)

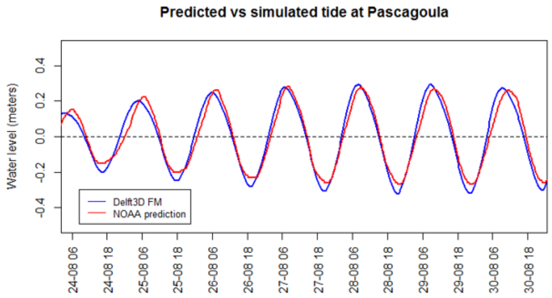
4. Physical model setup and validation

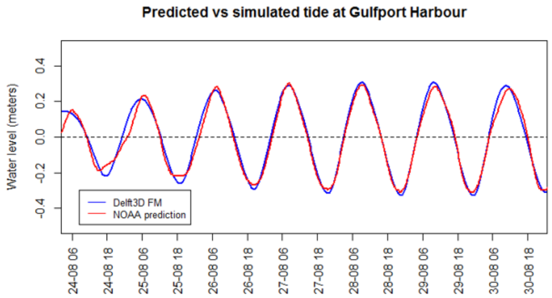
Validation of the tide

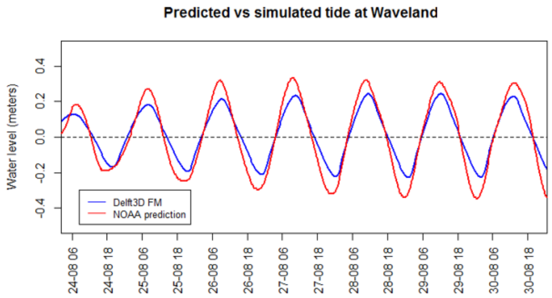
- Results recorded at 3 stations along MS
- Compared to predicted tides from NOAA



	Waveland	Gulfport Harbour	Pascagoula	Average
SI	0.389	0.190	0.303	0.294
Bias	-0.246	-0.342	-0.008	-0.199





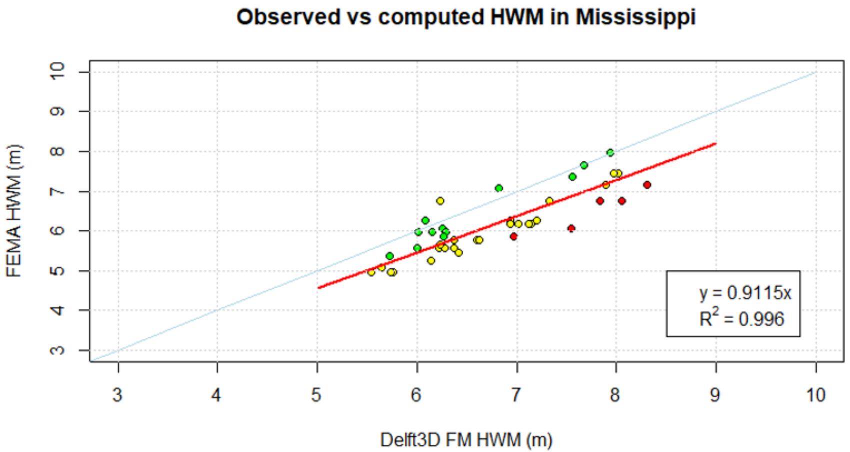


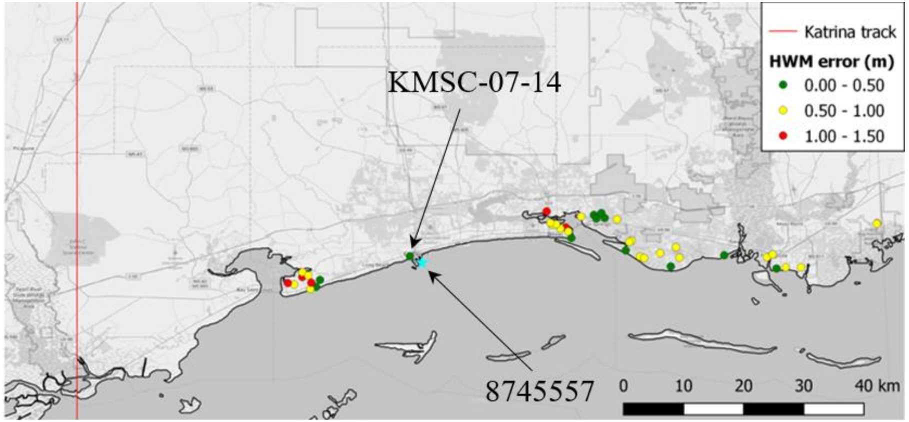
4. Physical model setup and validation

Validation of the storm tide in Mississippi

Storm tide = Storm surge + Tide + Wave setup

- Observations for validation: high watermarks recorded by FEMA
- $\bar{E} = 0.64\,meter$; $\bar{E}_{rel} = 9.5\%$; $m_{bestfit} = 0.9115$





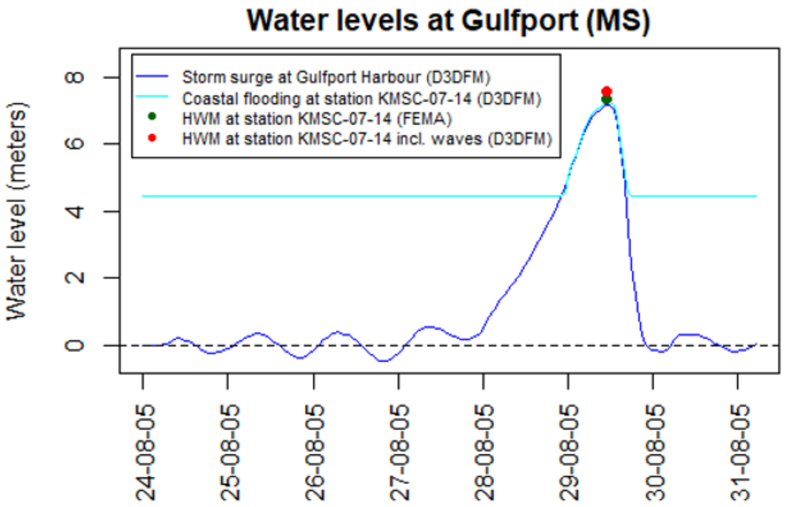
Green: Error within 0.5 m; Yellow: error within 0.5 and 1 m; Red: error within 1 and 1.5 m

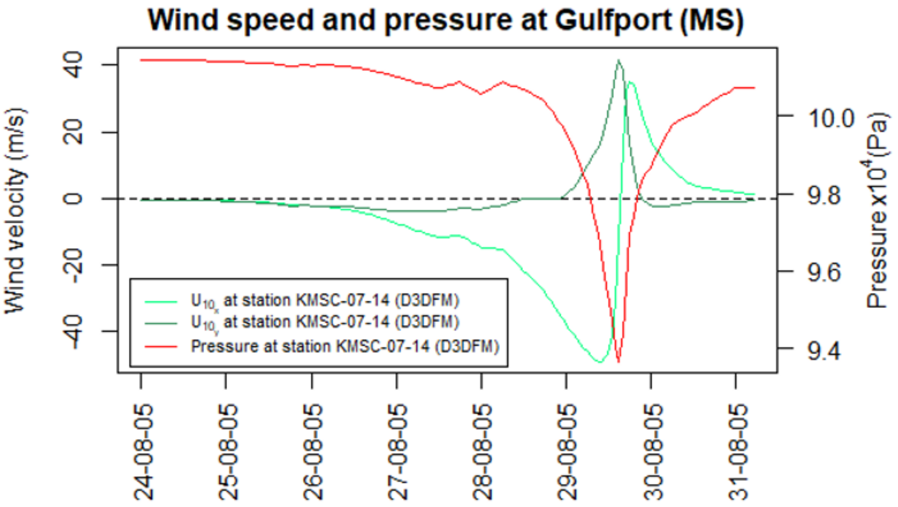
4. Physical model setup and validation

Validation of the storm tide at Gulfport (Mississippi)

Storm tide = Storm surge + Tide + Wave setup

- $E = 0.19\,meter;\ E_{rel} = 2.5\%$



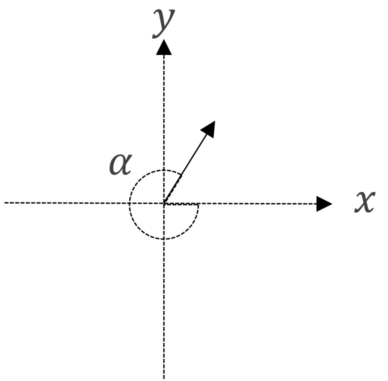


5. Generation of the hurricane data base

Hurricane catalogue filtered from HURDAT

Filtering HURDAT2

- Geographical location of the landfall: $[lat, lon] \in [-91.796, -86.405] \times [28.500, 31.000]$
- Hurricane intensity: Hurricane category should be from 1 to 5
- Number of track points: more than 15
- Forward direction (FD) of the hurricane at landfall between 201º and 349º



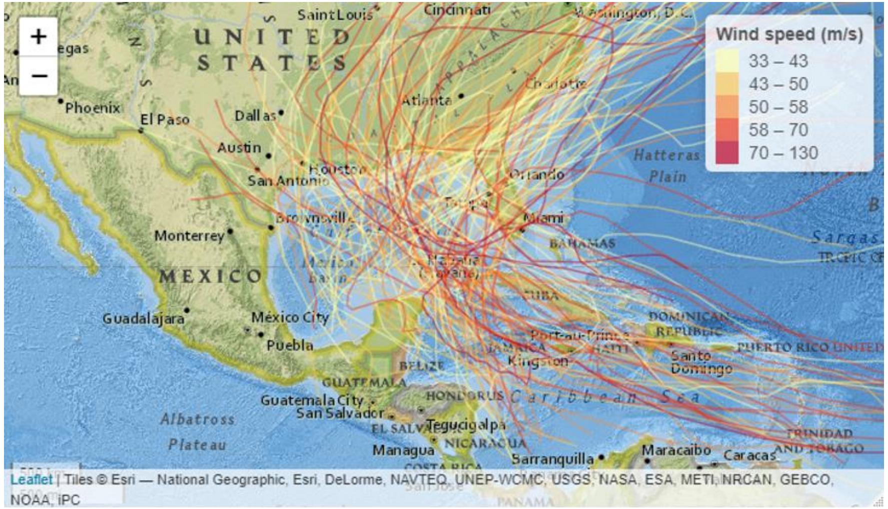
$\alpha = FD$

5. Generation of the hurricane data base

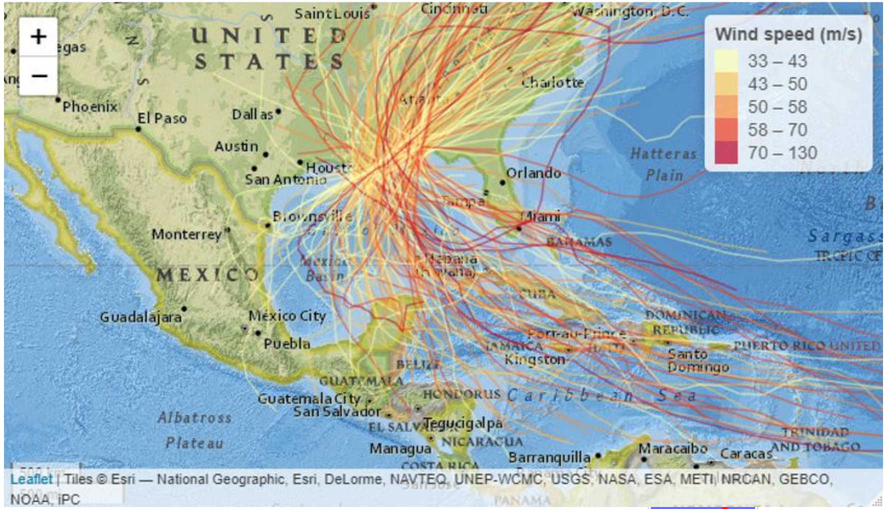
Hurricane catalogue filtered from HURDAT (shifted)

- Track shifting $\begin{cases} \Delta x = lon_{point} - lon_{hur,real} \\ \Delta y = lat_{point} - lat_{hur,real} \end{cases}$
- Simulation of 140 hurricanes with HPC (approx. 45’ per hurricane)

Original tracks

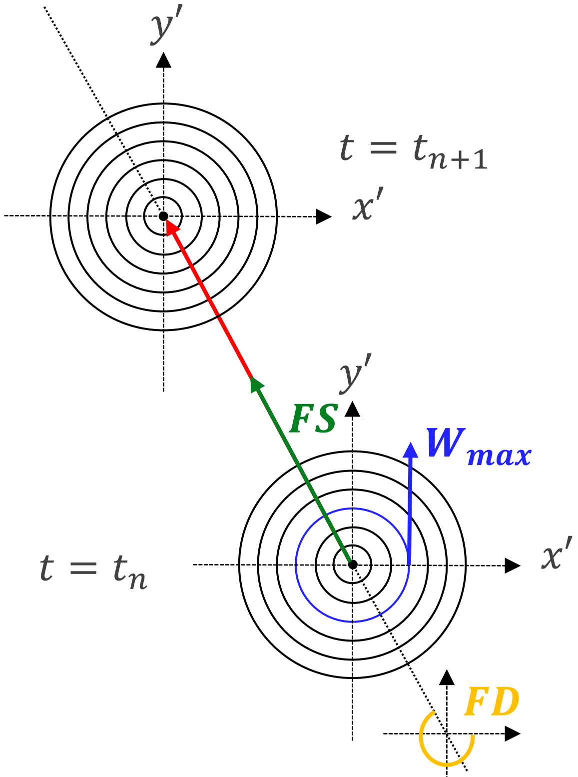


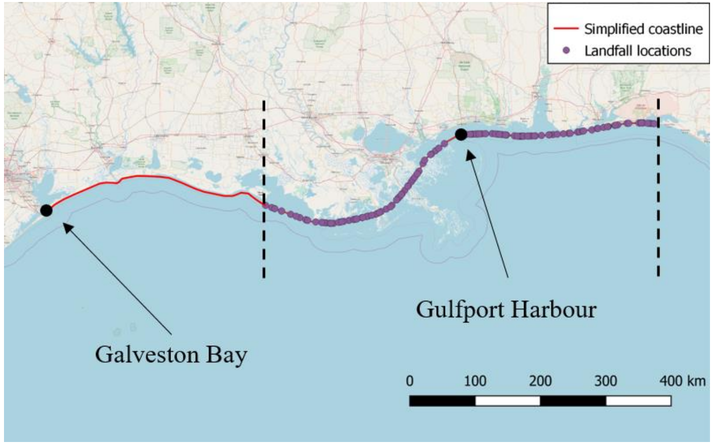
Shifted tracks



5. Generation of the hurricane data base

Hurricane variables



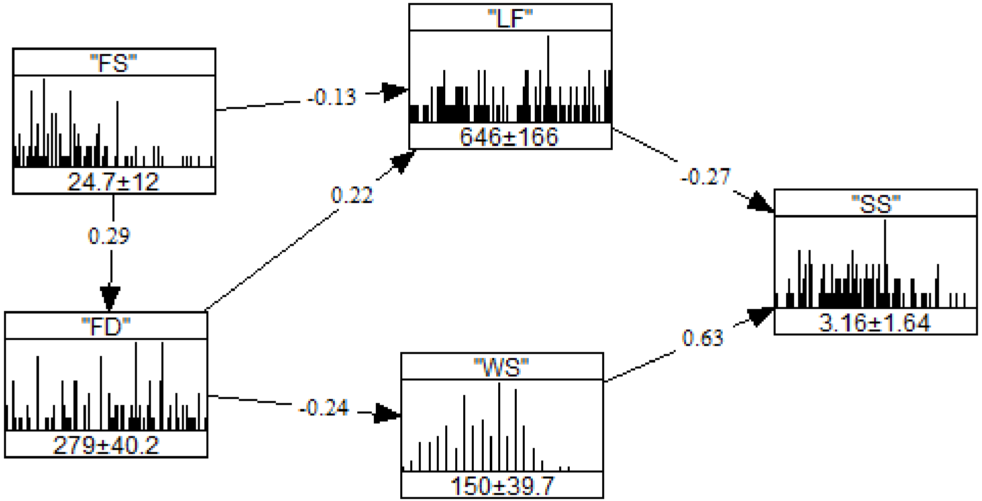


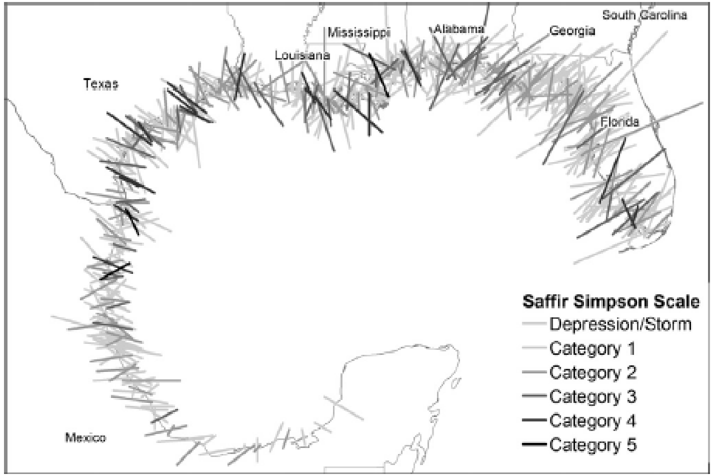
	Units	Range	Mean	Standard deviation
Wind Speed (WS)	[km/h]	64.76-277.56	147.11	39.57
Forward Direction (FD)	[degrees]	201.80-348.69	280.17	40.32
Forward Speed (FS)	[km/h]	7.87-61.42	24.86	12.08
Landfall Distance (LF)	[km]	347.46-915.46	635.86	164.64
Maximum Surge (SS)	[m]	0.03-7.52	3.11	1.62

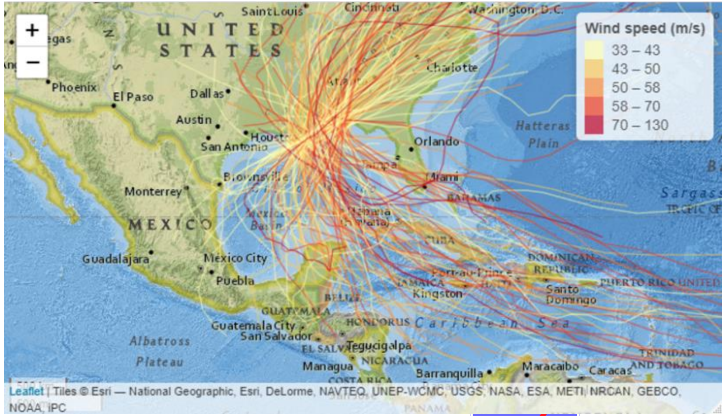
6. Stochastic model setup and validation

Bayesian Network structure

- Structure based on Sebastian et al. (2017)
- Structure respects $|\rho| > 0.1$ in all the arcs
- Gaussian copula assumption
- 85% of the sample (119 hurricanes) for BN training
- 15% (21 hurricanes) for BN validation





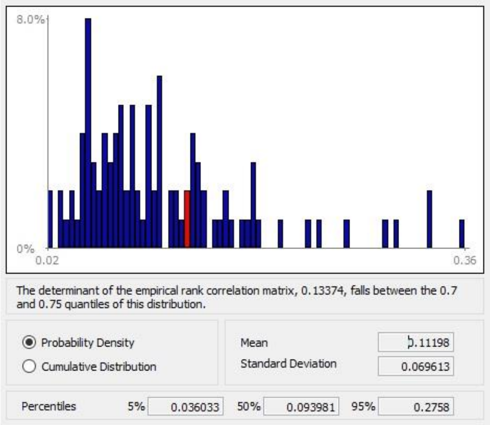


6. Stochastic model setup and validation

Validation of the Gaussian copula assumption and the BN structure

Validation Gaussian copula assumption

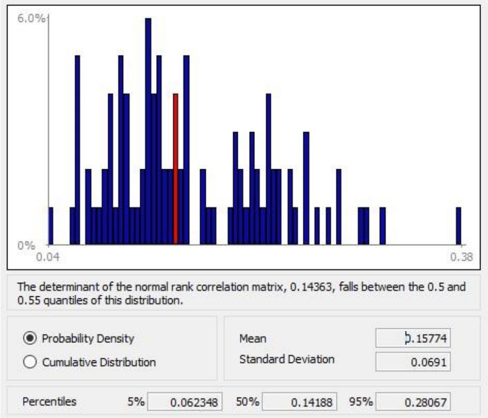
Compare the dependence structure of the original data to the dependence structure of the 'normal' data



$\mathrm{DER} \in 90\%\ central\ interval\ DNR\ distribution$

Validation BN structure

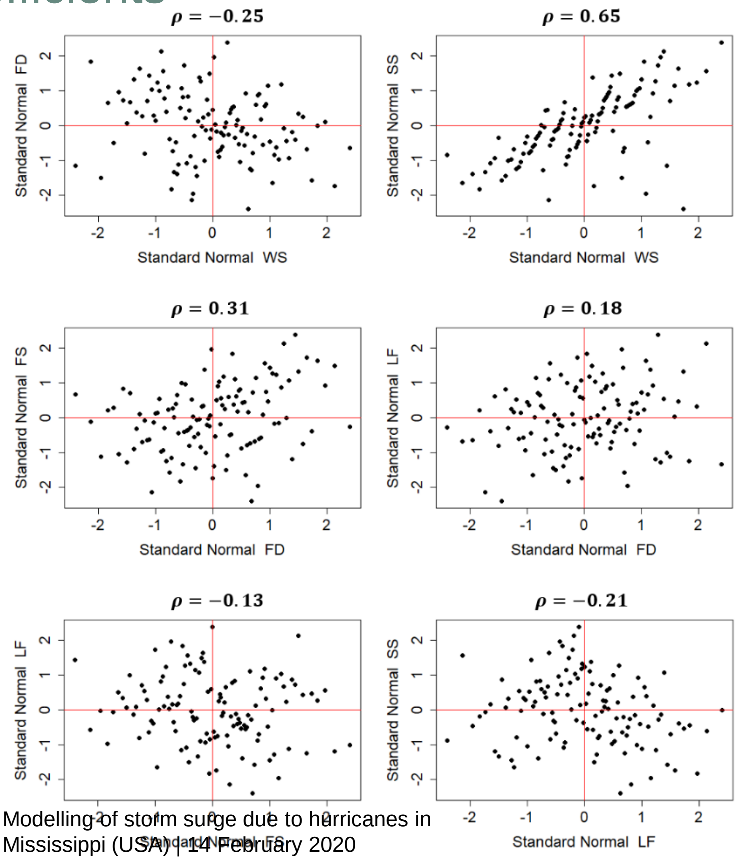
Check if the assumed conditional independencies assigned by the structure of the BN hold sufficiently well for the data



$\mathrm{DNR} \in 90\%\ central\ interval\ DBR\ distribution$

6. Stochastic model setup and validation

Validation of the Gaussian copula assumption and analysis of the correlation coefficients



Semicorrelations and Cramer-von-Misses statistic

		ρ	ρ_{SW}	ρ_{NE}	ρ_{SE}	ρ_{NW}	CM_{Gauss}	$CM_{Clayton}$	CM_{Gumbel}
WS	FD	**-0.25**	0.18	-0.21	**-0.29**	**-0.10**	**3.64**	10.93	10.93
WS	SS	**0.65**	**0.55**	**0.68**	-0.62	-0.12	4.14	7.88	**3.50**
FD	FS	**0.31**	**0.17**	**0.54**	0.25	0.20	4.26	7.99	**2.87**
FD	LF	**0.18**	**-0.06**	**0.00**	-0.56	0.41	2.31	3.13	**2.08**
FS	LF	**-0.13**	-0.34	0.18	**-0.28**	**0.24**	**3.93**	4.95	4.95
LF	SS	**-0.21**	0.14	0.00	**-0.09**	**0.33**	**5.39**	11.35	11.35

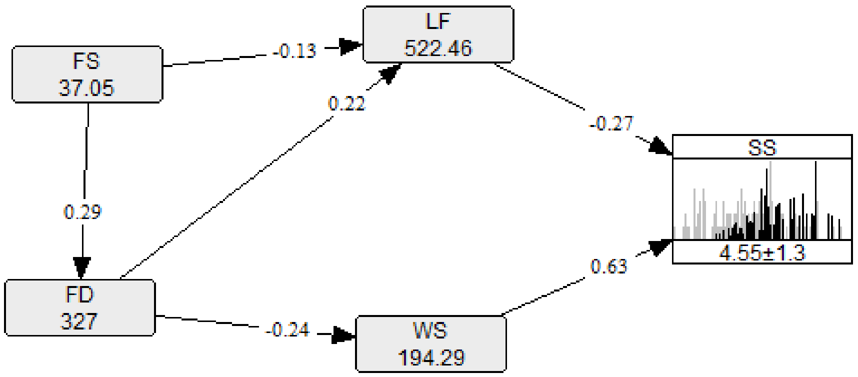
Correlation coefficients: Sebastian et al. (2017) vs Prida (2020)

		ρ (Sebastian, 2017)	ρ (Prida, 2020)
WS	FD	-0.11	-0.25
WS	SS	0.34	0.65
FD	FS	0.37	0.31
FD	LF	0.67	0.18
FS	LF	0.25	-0.13
LF	SS	-0.07	-0.21

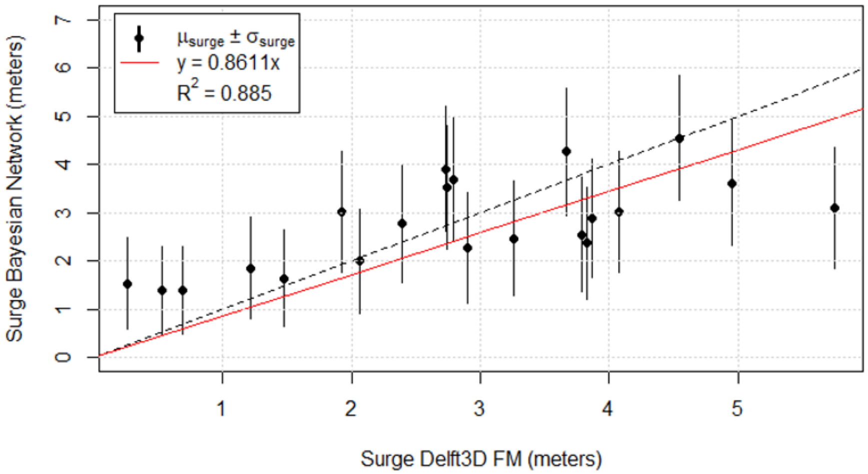
6. Stochastic model setup and validation

Validation of the BN

- Inference of hurricane variables in the BN except maximum surge for 21 events
- Slope for the best fitted line from the origin is 0.8611
- Average standard deviation is 1.16 meters



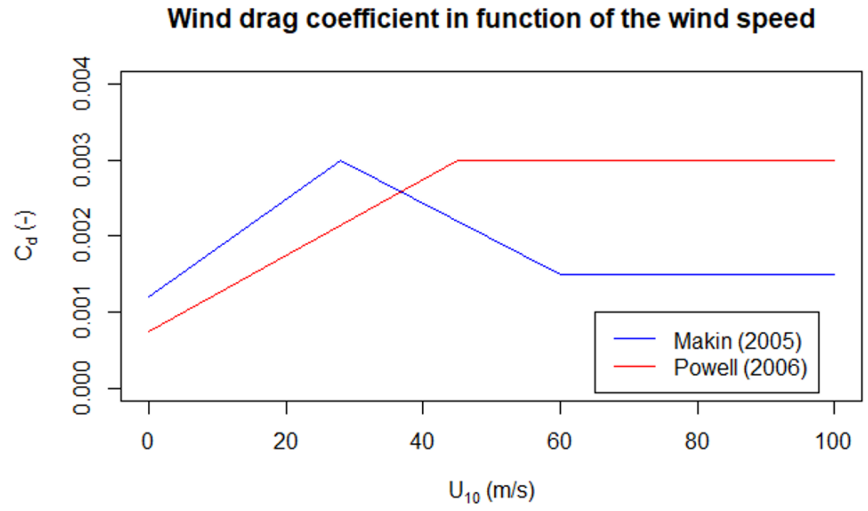
Storm surge in Delft3D FM vs BN (meters)

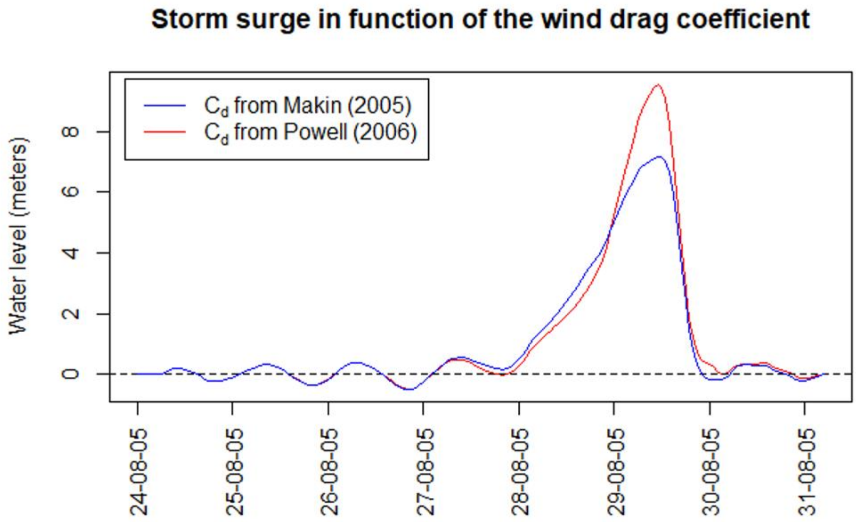


7. Discussion

Physical modeling: Sensitivity of the physical model to the wind drag

- Difference of 1.4 meters in surge when using wind drag model of Powell (2006) and Makin (2005)
- Different interpretation of the effect of the spray layer generated by breaking waves

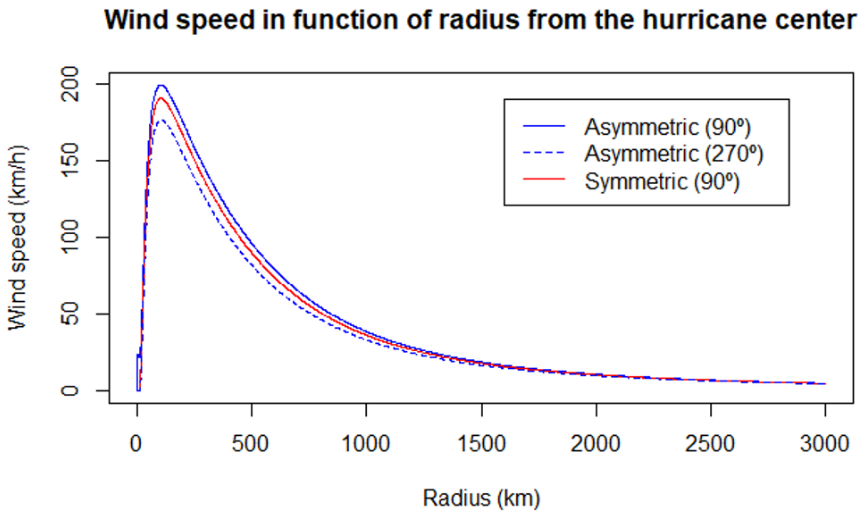


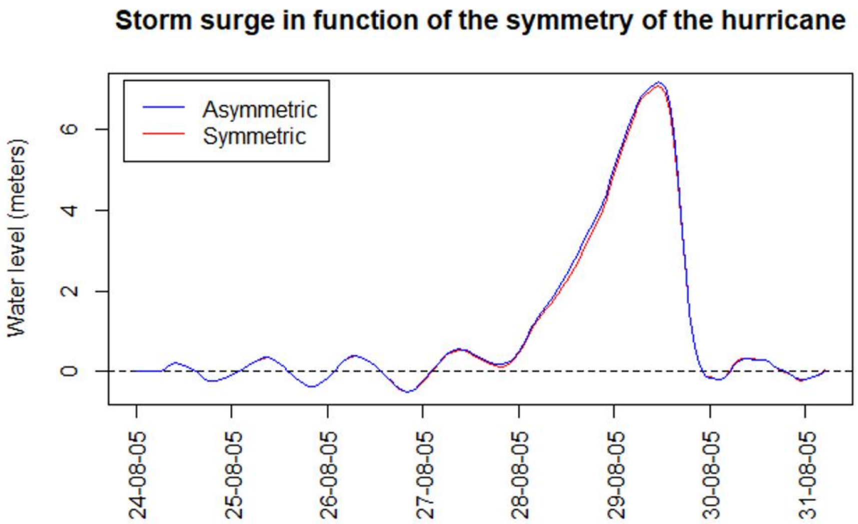


7. Discussion

Physical modeling: Sensitivity of the physical model to the hurricane structure

- Difference of 9 km/h (5%) between symmetric and asymmetric hurricane model at the region of maximum winds
- This is translated into a difference in storm surge of 10 centimeters at Gulfport Harbour (1%)

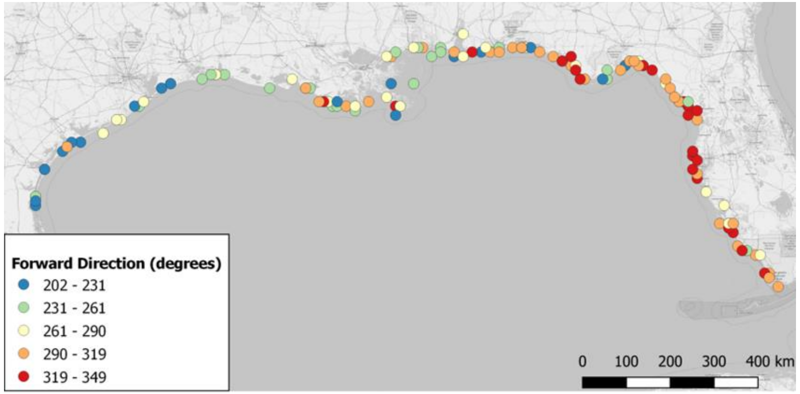


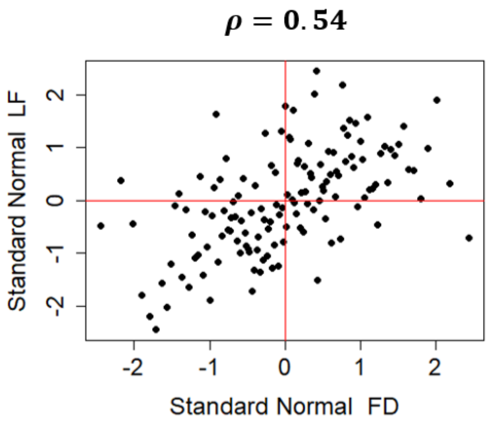


The degrees refer to the wind sections making an angle of *n* degrees from the North

7. Discussion

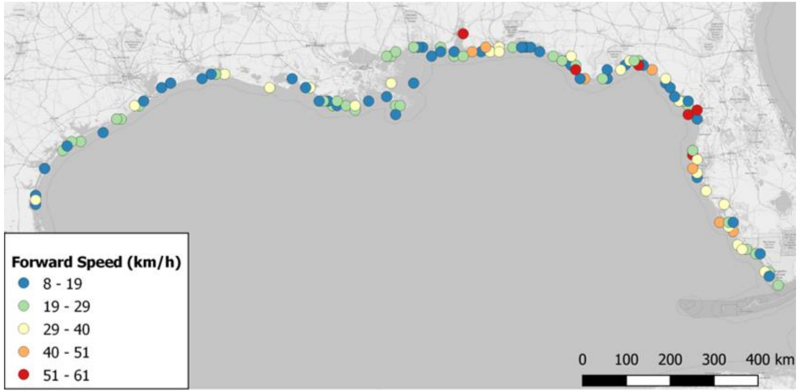
Stochastic modeling: limitation to track shifting approach

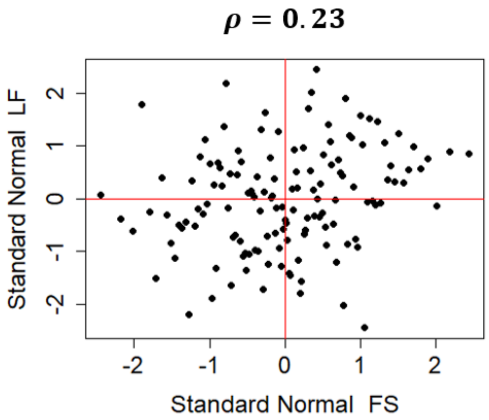




Sebastian et al. (2017)

$\rho = 0.71$



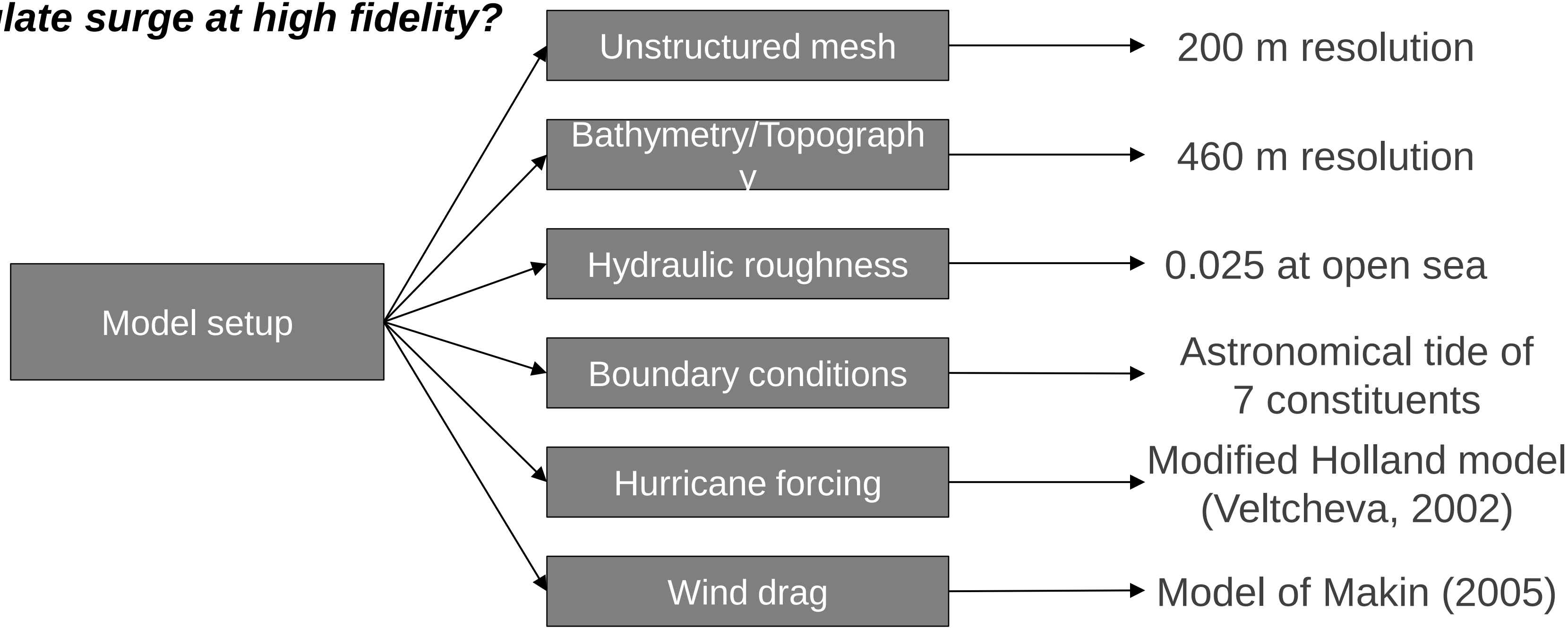


$\rho = 0.25$

8. Conclusion

Answering the research subquestions

1. How should the different input of the hydrodynamic model be calibrated to simulate surge at high fidelity?



Slope of best fitted line from the origin is 0.912 (relative error of 9.5%) for the observed vs simulated surge. Relative error at Gulfport is 2.5%.

8. Conclusion

Answering the research subquestions

2. How should the hurricane data scarcity be tackled in order to generate a sufficiently large data set for the training of the stochastic model?

- Consideration of a bounding box of 600 km around Gulfport Harbour
- Application of filters in hurricane intensity and forward direction to select representative hurricanes that made landfall in the North of the Gulf of Mexico
- With the conditions mentioned in the previous slide, the cluster does a simulation in approx. 45’
- Track shifting can solve effectively the scarcity in the size of the sample

3. What is the accuracy of the surge estimation and the time of computation of the stochastic model?

- Gaussian copula assumption is feasible given the results of the semicorrelations and the Cramer-von-Mises statistic for the different pairs of variables, what makes the application of BN feasible
- The slope of the best fit line from the origin for the observed vs estimated surge by the BN is 0.861, and the average of the standard deviations is 1.16 meters
- The BN can estimate the surge in the order of seconds

8. Conclusion

Recommendations

- **Finer resolution of the unstructured mesh and topography when simulating overland flood**: The use of Digital Terrain Models (DTM) is encouraged when simulating overland flood in order to capture the details of the terrain (such as linear infrastructure which can influence the water flow)
- **Size of the hurricane data set:** Extension of the database for surge prediction in order to generate a more robust BN
- **Consideration of other physical variables in the BN**: For instance, the gradient in the bathymetry which can have large influence in the surge
- **Alternative methods for the calculation of joint probabilities in a BN**: The use of other copulas to represent the joint distributions among variables is currently not feasible, due to high computational costs. Further research is encouraged to investigate alternative techniques to solve the copula expressions
- **Applicability of Dynamic BN to hurricane-induced surge problems:** In order to include the among variables for different time steps

Thank you

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