LSU | College of the Coast & Environment
Coupled Ocean Modeling @ LSU
LSU CENTER FOR COMPUTATION & TECHNOLOGY
COASTAL STUDIES INSTITUTE

Coupled Computer Modeling to Accurately Predict Coastal Flooding

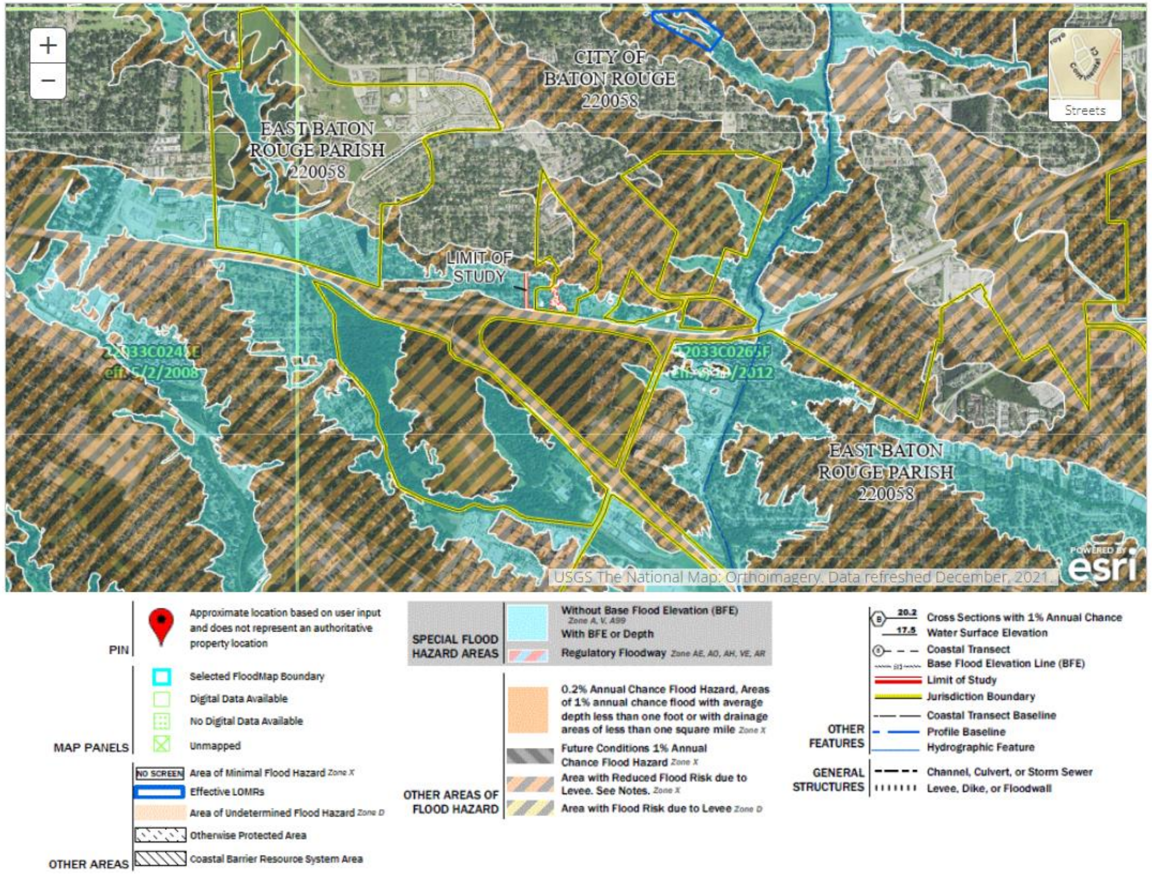
Crisis: 危 机

Danger & Opportunity

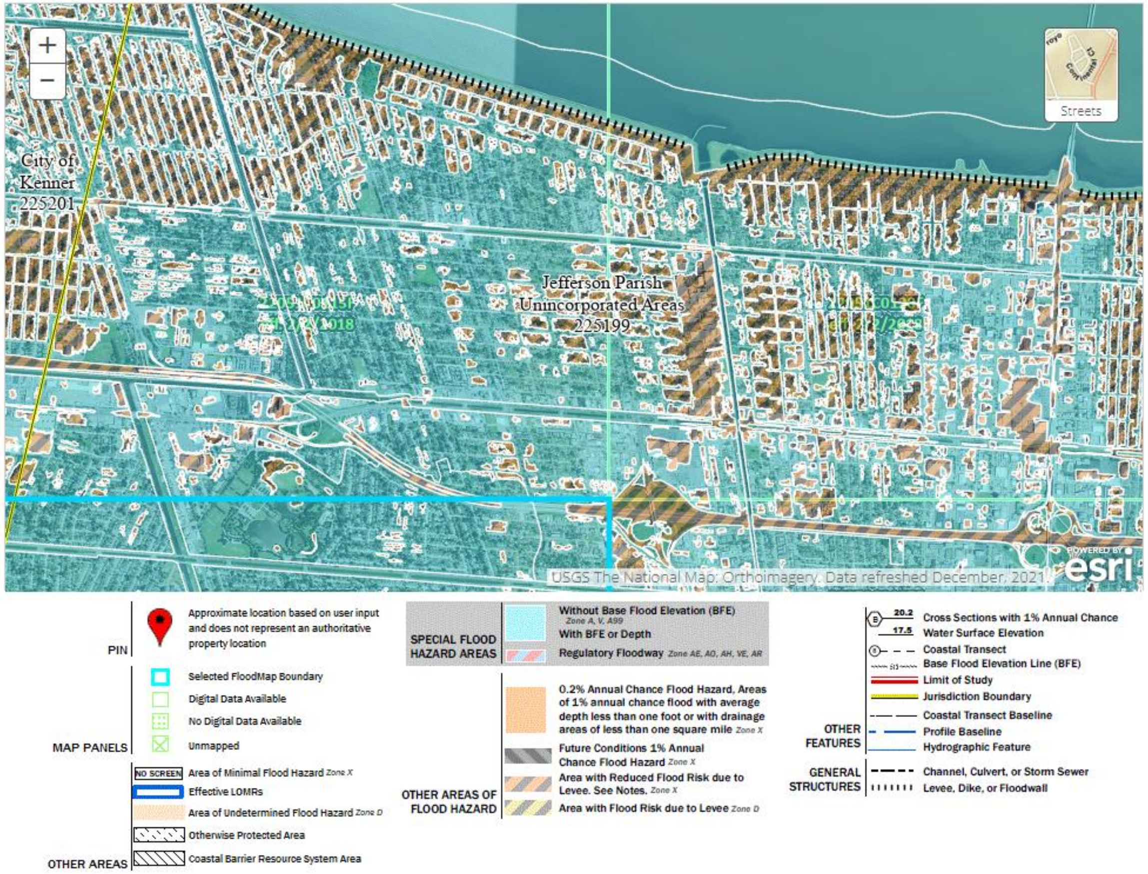
Z. George Xue
Dept. of Oceanography and Coastal Sciences
Center for Computation and Technology
Louisiana State University

Flood Maps from FEMA (Federal Emergency Management Agency)

Flood maps help mortgage lenders determine insurance requirements and help communities develop strategies for reducing their risk. https://www.fema.gov/flood-maps



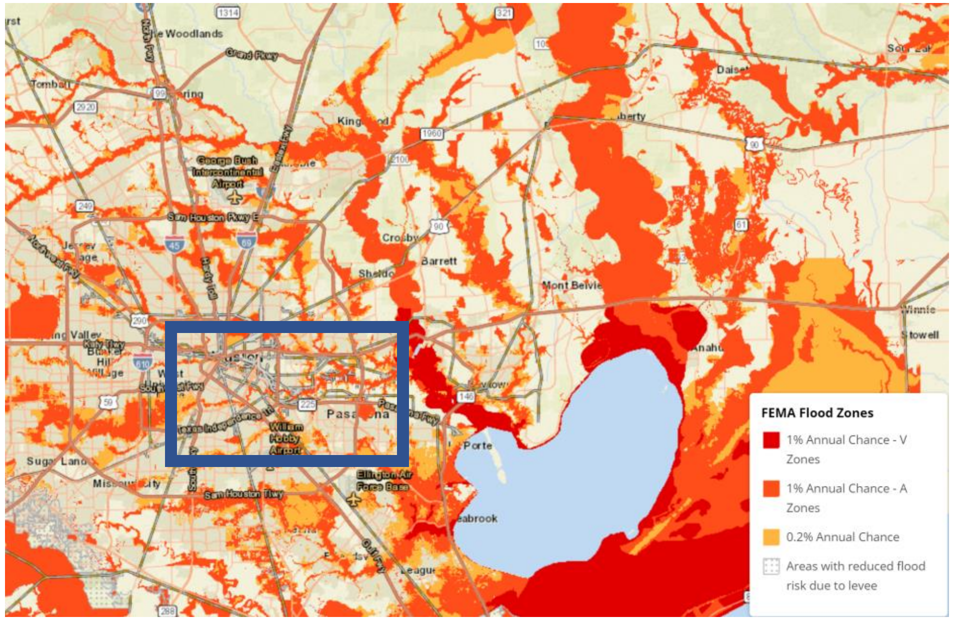
East Baton Rouge Parish

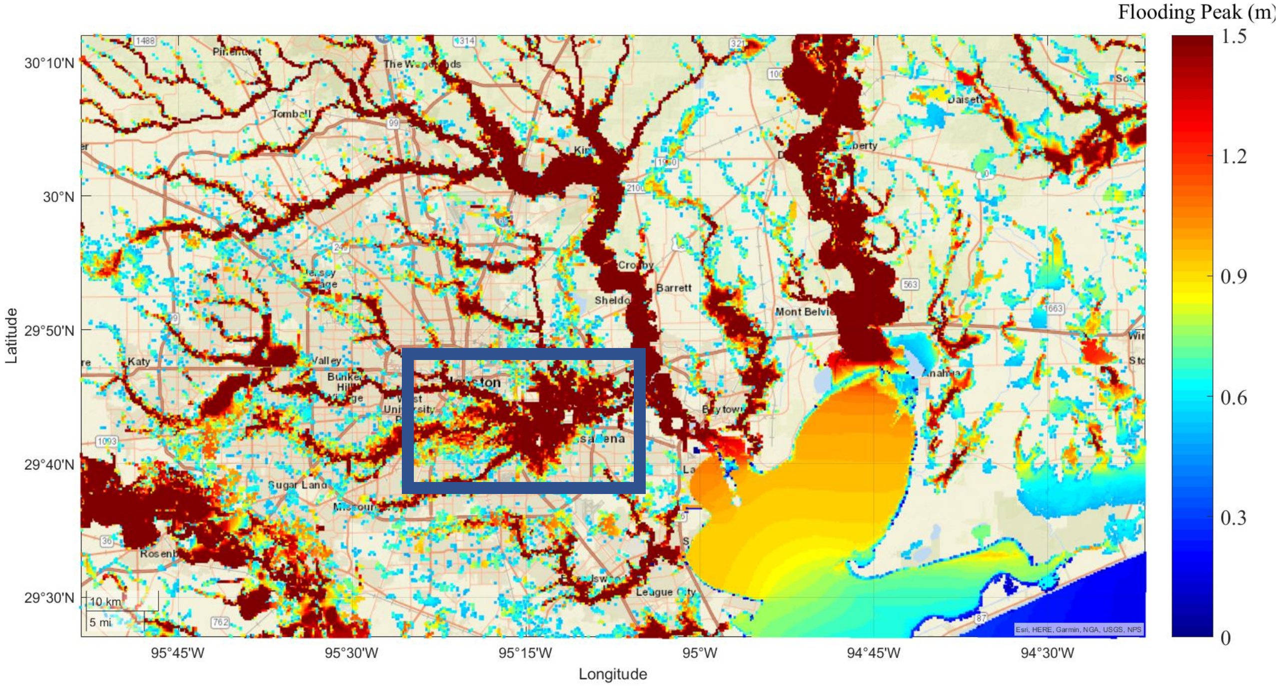


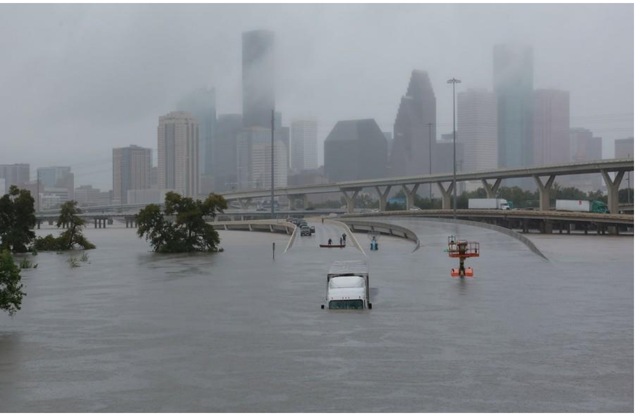
Jefferson Parish

https://msc.fema.gov/portal

Flood Zone vs Real-time Model







Photos showing the flooding in Houston during Harvey from https://www.theatlantic.com/photo/2017/08/hurricane-harvey-leaves-houston-under-water/538215/

How much can we trust Flood Zone?

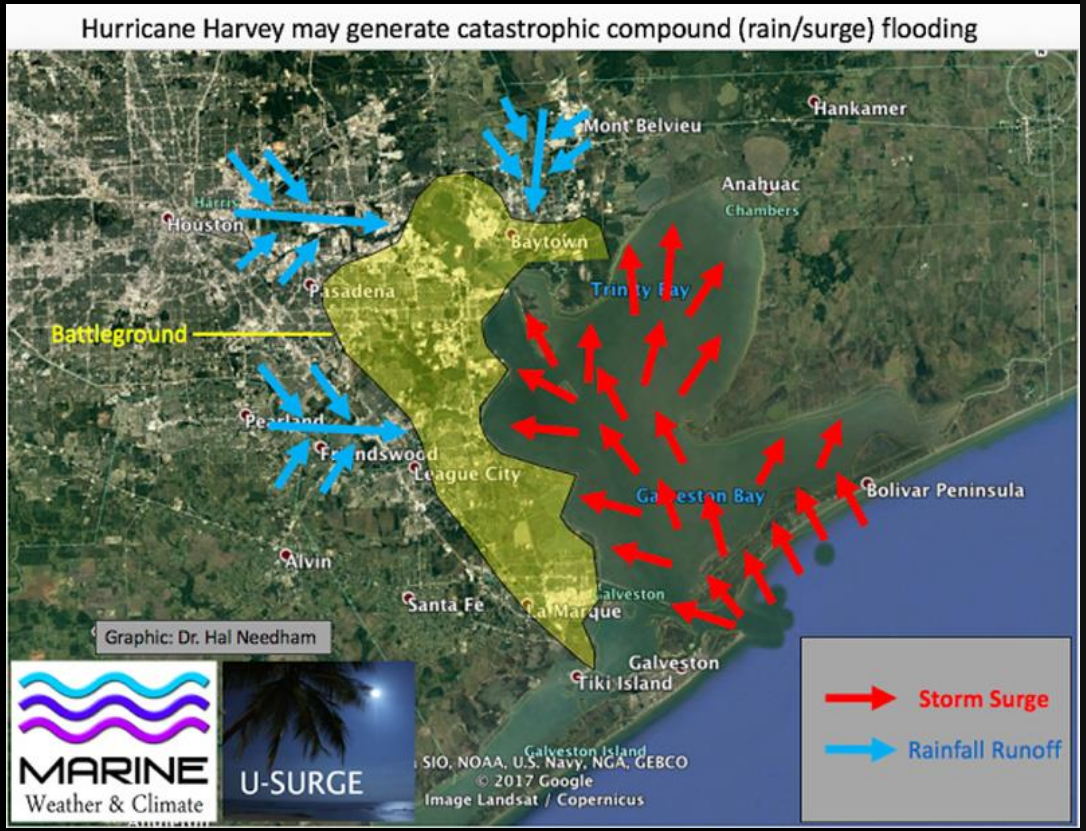
Table 1: Flooding in mapped flood zones

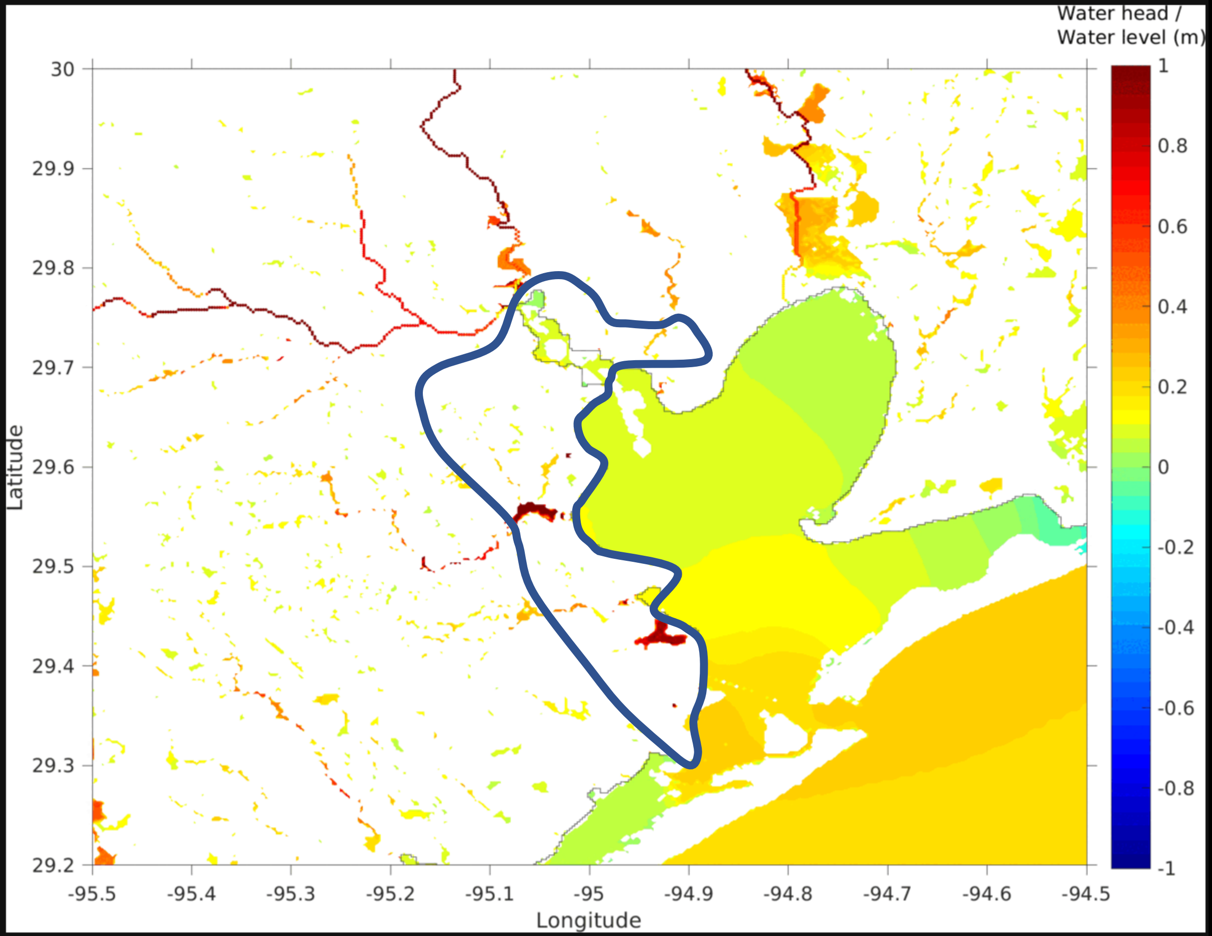
FEMA Flood Zone	Flooded Area (square miles) in analyzed images	Percent of Flooded Area (totals > 100%)
Floodway	26.37 mi^2	12.45%
Special Flood Hazard Area ("100 year" floodplain; zones A, AE, AH, AO)	89.40 mi^2	32.26%
VE (Coastal)	2.48 mi^2	0.89%
Shaded X zone ("500 year" floodplain)	37.23 mi^2	13.44%
"Minimal flood hazard"	147.94 mi^2	53.39%

over 50% of estimated inundation occurred outside of any mapped flood zone.

Application: Hurricane Harvey

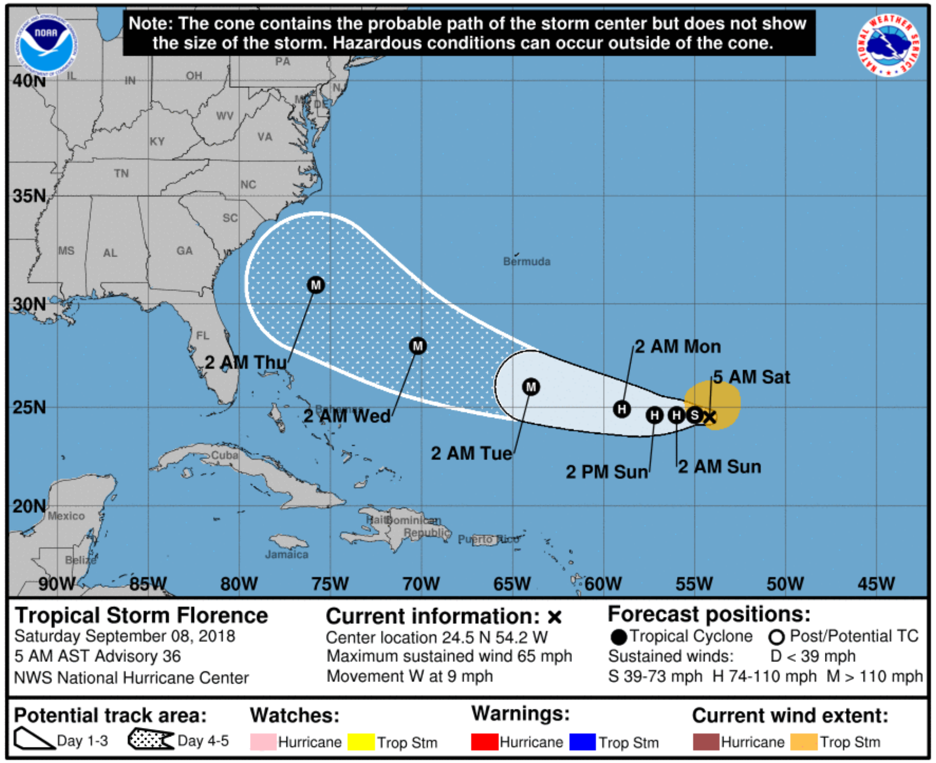
The coupled model simulates what was happening in the battle ground where fresh water and salt water could collide.

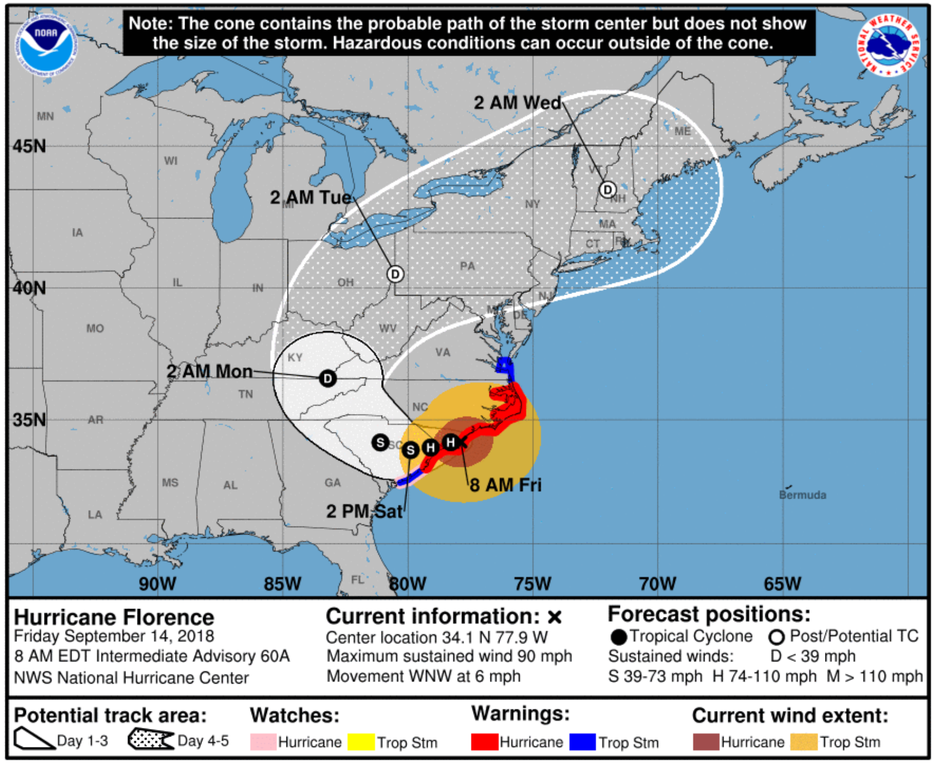




Hurricane Evolution

Potential Tropical Cyclone → Tropical Depression → Tropical Storm → Hurricane → Landfall → Remnant

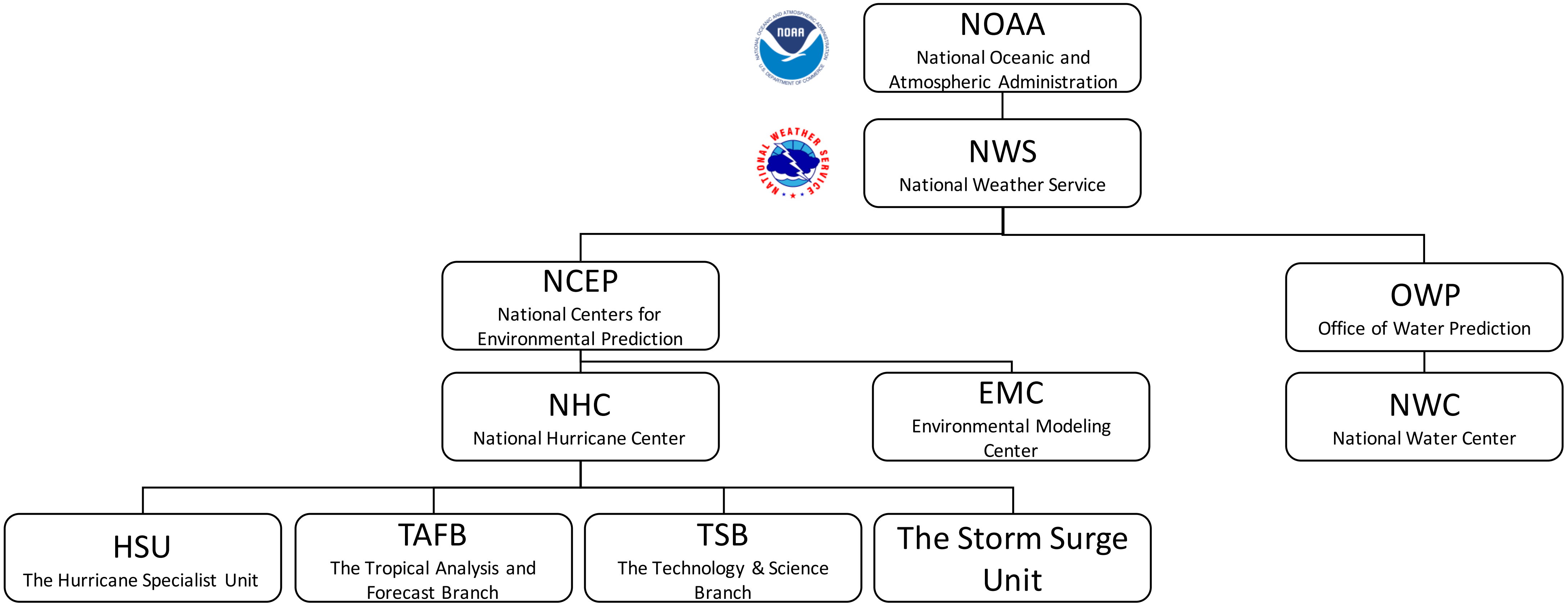


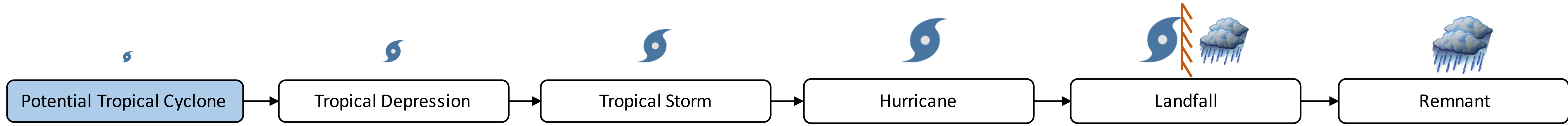


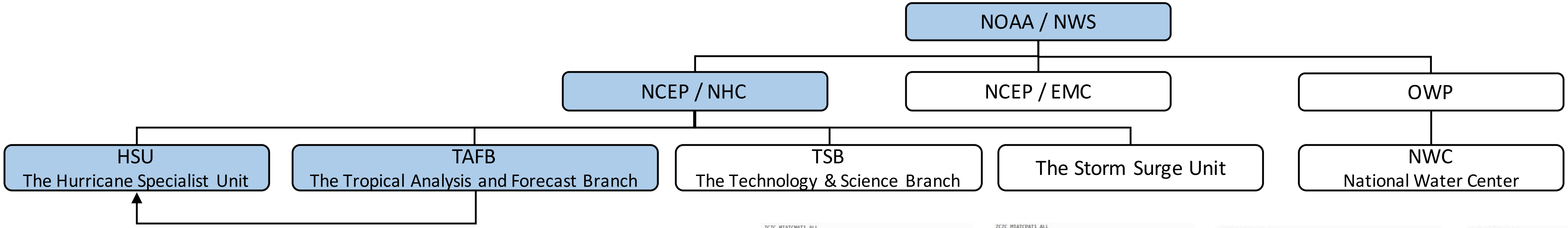
NOAA's Tropical Cyclone Track Forecast Cone and Watches/Warnings and Initial Wind Field for Hurricane Florence

On September 08, 2018 | On September 14, 2018

NOAA national Centers Related to Hurricane Flooding Forecast







Based on the observations from Satellite Imagery, Radar Imagery, Aircraft Reconnaissance, etc.

HSU issues:

Tropical Cyclone Forecast/Advisory (TCM)

Tropical Cyclone Public Advisory (TCP)

Tropical Cyclone Discussion (TCD)

Tropical Cyclone Surface Wind Speed Probabilities (PWS)

TCM, TCP, TCD and PWS when Florence was a Potential Tropical Cyclone on August 30,2018

https://www.nhc.noaa.gov/archive/2018/FLORENCE.shtml?

Potential Tropical Cyclone → Tropical Depression → Tropical Storm → Hurricane → Landfall → Remnant

NOAA / NWS

- NCEP / NHC
  - HSU — The Hurricane Specialist Unit
  - TAFB — The Tropical Analysis and Forecast Branch
  - TSB — The Technology & Science Branch
  - The Storm Surge Unit
- NCEP / EMC
- OWP
  - NWC — National Water Center

HSU keeps issuing TCM, TCP, TCD, PWS every 6 hours.

- **EMC** triggers HWRF and HMON four times daily producing 5-day forecasts of mainly track and intensity.
- **HSU** issues forecasts of track, intensity, and wind radii based on multiply model outputs.

Table 1. Summary of global and regional dynamical models for track, intensity, and wind radii.

ATCF ID	Global/Regional Model Name	Horizontal Resolution	Vertical Levels and Coordinates	Data Assimilation	Convective Scheme	Cycle/Run Frequency	NHC Forecast Parameter(s)
NVGM/NVGI	Navy Global Environmental Model	Spectral (~31km)	60 Hybrid Sigma-pressure	NAVDAS-AR 4D-VAR	Simplified Arakawa Schubert	6 hr (144 hr) 00/06/12/18 UTC	Track and intensity
AVNO/AVNI GFSO/GFSI	Global Forecast System (FV3-GFS)	Finite Volume Cube Sphere (~13km)	64 Hybrid Sigma-pressure	GSI/4D-VAR EnKF hybrid	Simplified Arakawa Schubert	6 hr (240 hr) 00/06/12/18 UTC	Track and intensity
*EMX/EMXI/EMX2	European Centre for Medium-Range Weather Forecasts	Spectral (~9km)	137 Hybrid Sigma-pressure	4D-VAR	Tiedke mass flux	12 hr (240 hr) 00/12 UTC	Track and intensity
EGRR/EGRI/EGR2	U.K. Met Office Global Model	Grid point (~10 km)	70 Hybrid Sigma-pressure	4D-VAR Ensemble Hybrid	UKMET	12 hr (144 hr) 00/12 UTC	Track and intensity
CMC/CMCI	Canadian Deterministic Prediction System	Grid point (~25 km)	80 Hybrid Sigma-pressure	4D-VAR Ensemble Hybrid	Kain-Fritsch	12 hr (240 hr) 00/12 UTC	Track and intensity
HWRF/HWFI	Hurricane Weather Research and Forecast system	Nested Grid point (13.5-4.5-1.5km)	75 Hybrid Sigma-pressure	4D-VAR Hybrid GDAS GFS IC/BC	Simplified Arakawa Schubert + GFS shallow convection (6 and 18km) 1.5km nest - none	6 hr (126 hr) 00/06/12/18 UTC *Runs on request from NHC/JTWC*	Track and intensity
CTCX/CTCI	NRL COAMPS-TC w/ GFS initial and boundary conditions	Nested Grid point (45-15-5 km)	42 Hybrid Sigma-pressure	3D-VAR (NAVDAS) EnKF DART	Kain-Fritsch	6 hr (126 hr) 00/06/12/18 UTC *Runs commence on 1st NHC/JTWC advisory*	Track and intensity
HMON/HMNI	Hurricane Multi-scale Ocean-coupled Non-hydrostatic model	Nested Grid point (18-6-2km)	51 Hybrid Sigma-pressure	GFS IC/BC	Simplified Arakawa Schubert + GFS shallow convection (6 and 18km) 2km nest - none	6 hr (126 hr) 00/06/12/18 UTC *Runs on request from NHC/JTWC*	Track and intensity

Table 2. Summary of ensembles and consensus aids for track and intensity.

ATCF ID	Model Name or Type	Horizontal Resolution	Vertical Levels and Coordinates	Data Assimilation	Pertubation or Consensus Methods	Cycle/Run Frequency	Ensemble Members	NHC Forecast Paramter(s)
AEMN/AEMI	Global Ensemble Forecast System	~33 km for 1st 192 hr ~55 km for 192-384 hr	64 Hybrid Sigma-pressure	GSI/3D-VAR EnKF hybrid	20 of 80 6 hr DA system hybrid EnKF members per cycle	6 hr (384 hr) 00/06/12/18 UTC	20	Track
*UEMN/UEMI	U.K. Met Office MOGREPS	~20 km	70 Hybrid Sigma-pressure	4D-VAR EnKF hybrid	44 member EnKF	12 hr (168 hr) 00/12 UTC	11	Track
*EEMN/EMN2	ECMWF EPS	~18 km	91 Hybrid Sigma-pressure	4D-VAR	Leading singluar vectors based initial pertubations	12 hr (360 hr) 00/12 UTC	50	Track
*FSSE	Florida State Super Ensemble				Corrected consensus	6 hr (120 hr) 00/06/12/18 UTC		Track and Intensity
*HCCA	HFIP Corrected Consensus Approach				Corrected consensus	6 hr (120 hr) 00/06/12/18 UTC	AEMI AVNI CTCI DSHP EGRI EMN2 EMXI HWFI LGEM	Track and Intensity
*GFEX	2 model consensus				Simple consensus	6 hr (120 hr) 00/06/12/18 UTC	AVNI EMXI	Track
TVCN (Atlantic) (TVCA)	Variable consensus				Simple consensus, minimum 2 members	6 hr (120 hr) 00/06/12/18 UTC	AVNI, EGRI, HWFI EMHI, CTCI, EMNI	Track
TVCN (E. Pacific) (TVCE)	Variable consensus				Simple consensus, minimum 2 members	6 hr (120 hr) 00/06/12/18 UTC	AVNI, EGRI, HWFI, EMHI CTCI, EMNI, HMNI	Track
TVCX	Variable consensus				Simple consensus, minimum 2 members, double-weighted EMXI	6 hr (120 hr) 00/06/12/18 UTC	AVNI EMXI HWFI CTCI EGRI	Track
RVCN	Wind Radii Consensus				Multi-model wind radii, bias corrected initial wind	6 hr (120 hr) 00/06/12/18 UTC	AHNI, HHFI, EHHI, CHCI (FV3GFS, HWRF, ECMWF, COAMPS-TC)	34-kt wind radii
ICON	Intensity consensus				Simple consensus, all 4 must be present	6 hr (120 hr) 00/06/12/18 UTC	DSHP, LGEM, HWFI, HMNI	Intensity
IVCN	Intensity variable consensus				Simple consensus, minimum 2 members	6 hr (120 hr) 00/06/12/18 UTC	DSHP, LGEM, HWFI, HMNI, CTCI	Intensity

Table 3. Summary of statistical models for track, intensity, and wind radii.

ATCF ID	Model Name or Type	Comments	Prediction Methodology	Cycle/Run Frequency	NHC Forecast Paramter(s)
CLP5 (OCD5)	CLIPER5 Climatology and Persistence	Used to measure skill in a set of track forecasts	Multiple regression technique. Inputs are current and past TC motion (previous 12-24hr), forward motion, date, latitude/longitude, and initial intensity	6 hr (120 hr) 00/06/12/18 UTC	Track
SHF5/DSF5 (OCD5)	Decay-SHIFOR5 Statistical Hurricane Intensity Forecast	Used to measure skill in a set of intensity forecasts, includes land decay rate component	Multiple regression technique using climatology and persistence predictors	6 hr (120 hr) 00/06/12/18 UTC	Intensity
TCLP	Trajectory-CLIPER	Used to measure skill in a set of track or intensity forecasts	Substitute for CLIPER and SHIFOR; similar predictors but uses trajectories based on reanalysis fields instead of linear regression	6 hr (168 hr) 00/06/12/18 UTC	Track and intensity
DRCL	Wind Radii CLIPER	Statistical parametric vortex model	Employs climatology with the paramaters determined from 13 coefficients and persistence to produce 34-kt, 50-kt, 64-kt wind radii estimates	6 hr (168 hr) 00/06/12/18 UTC	Wind radii
SHIP	Statistical Hurricane Intensity Prediction Scheme	Statistical-dynamical model based on standard multiple regression techniques	Climatology, persistence, environmental atmosphere parameters, and an ocean component	6 hr (168 hr) 00/06/12/18 UTC	Intensity
DSHP	Decay-Statistical Hurricane Intensity Prediction Scheme	Statistical-dynamical model based on standard multiple regression techniques	Climatology, persistence, environmental atmosphere parameters, oceanic input, and an inland decay component	6 hr (168 hr) 00/06/12/18 UTC	Intensity
LGEM	Logistic Growth Equation Model	Statistical intensity model based on a simplified dynamical prediction framework	A subset of SHIPS predictors, ocean heat content, and variability of the environment used to determine growth rate maximum wind coefficient	6 hr (168 hr) 00/06/12/18 UTC	Intensity

The National Hurricane Center (NHC) uses many models as guidance in the preparation of official track and intensity forecasts. The most commonly used models at NHC are summarized in the tables above.
https://www.nhc.noaa.gov/modelsummary.shtml

Potential Tropical Cyclone → Tropical Depression → Tropical Storm → Hurricane → Landfall → Remnant

- NOAA / NWS
  - NCEP / NHC
    - HSU: The Hurricane Specialist Unit
    - TAFB: The Tropical Analysis and Forecast Branch
    - TSB: The Technology & Science Branch
    - The Storm Surge Unit
  - NCEP / EMC
  - OWP
    - NWC: National Water Center

HSU keeps issuing TCM, TCD, PWS every 6 hours, TCP every 3 hours.

EMC keeps running HWRF and HMON four times daily producing 5-day forecasts of mainly track and intensity.

HSU keeps issuing forecasts of track, intensity, and wind radii based on multiply model outputs.

The Storm Surge Unit triggers SLOSH running to predict storm surge.

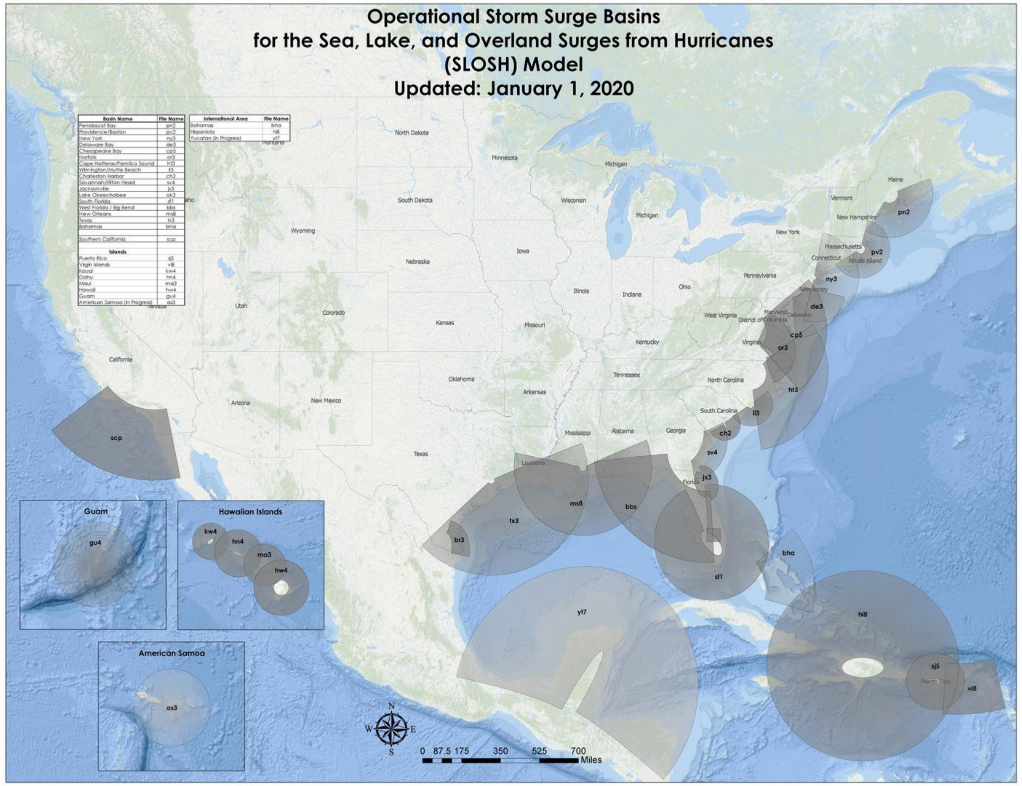
SLOSH: The Sea, Lake and Overland Surges from Hurricanes model

Strengths:

- computationally efficient.
- resolves flow through barriers, gaps, and passes and models deep passes .
- resolves inland inundation and the overtopping of barrier systems, levees, and roads.
- resolves coastal reflections of surges such as coastally trapped Kelvin waves.

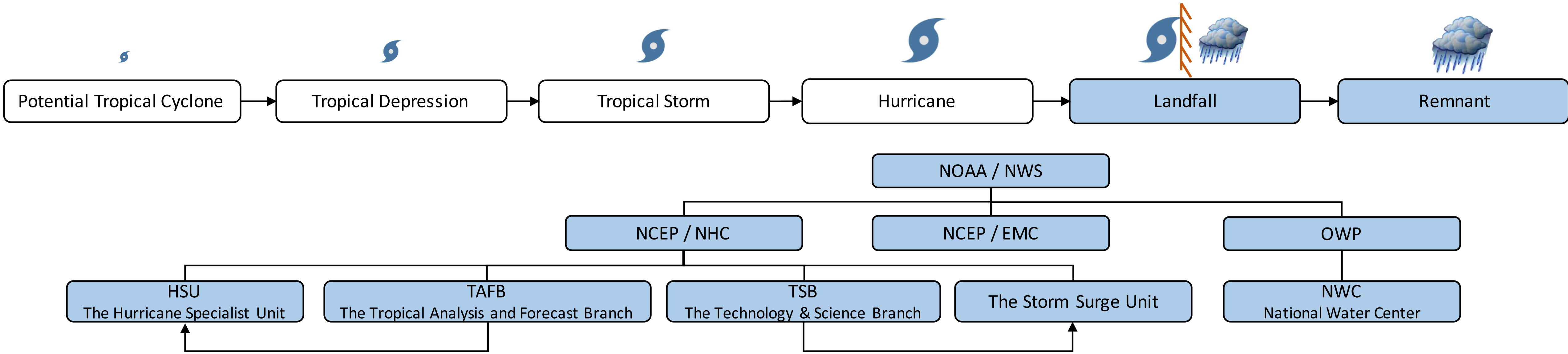
Limitations:

- **no wave.**
- **no river flow / rain.**



SLOSH model coverage

https://www.nhc.noaa.gov/surge/slosh.php



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The Storm Surge Unit keeps running SLOSH to predict storm surge.

⇨ Hurricane-induced river flooding started to be predicted by NWM operated by **NWC**.

NWM: National Water Model:

provides streamflow for 2.7 million river reaches and other hydrologic information over the entire continental United States (CONUS).

Strengths:

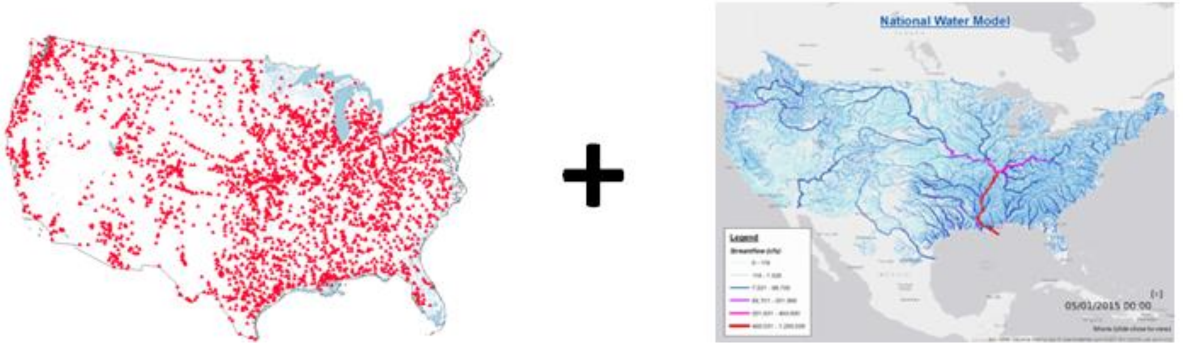
- the core of the NWM (WRF-Hydro) is process-based hydrological model.
- ingests forcing from a variety of sources including MRMS, Stage IV , MPE, radar observation, HRRR, RAP, NAM-Nest, GFS, CFS and NWP.
- capability of being run in six configurations (Standard / Extended / Long-Range Analysis, Short-Range / Medium-Range / Long-Range Forecast).

Limitations:

- no overbank flooding.
- unstable on low topography terrain.

Current River Forecast Points (~3,600)

NWM Streamflow Output Points (~2.7 mil)



https://water.noaa.gov/about/nwm

Different types of flooding during hurricane

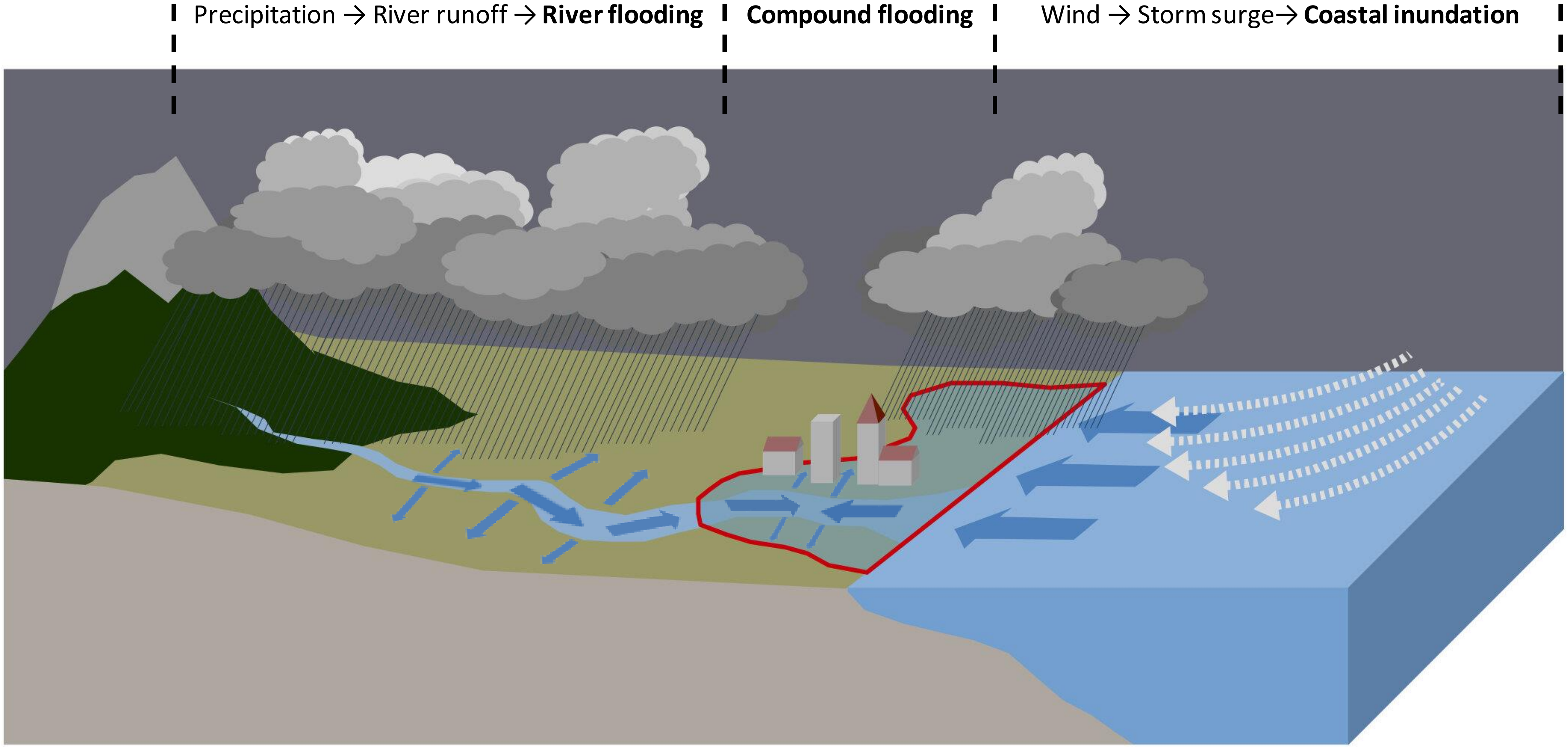


Image originally published on phys.org: https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html
Credit: Douglas Maraun

Modeling of hurricane-induced flooding

Ocean model

- Only covers open ocean and part of transition zone.
- Require accurate upper boundary conditions.
- Examples: NOAA SLASH, ADCIRC, SCHIMS, FVCOM, ROMS , etc.

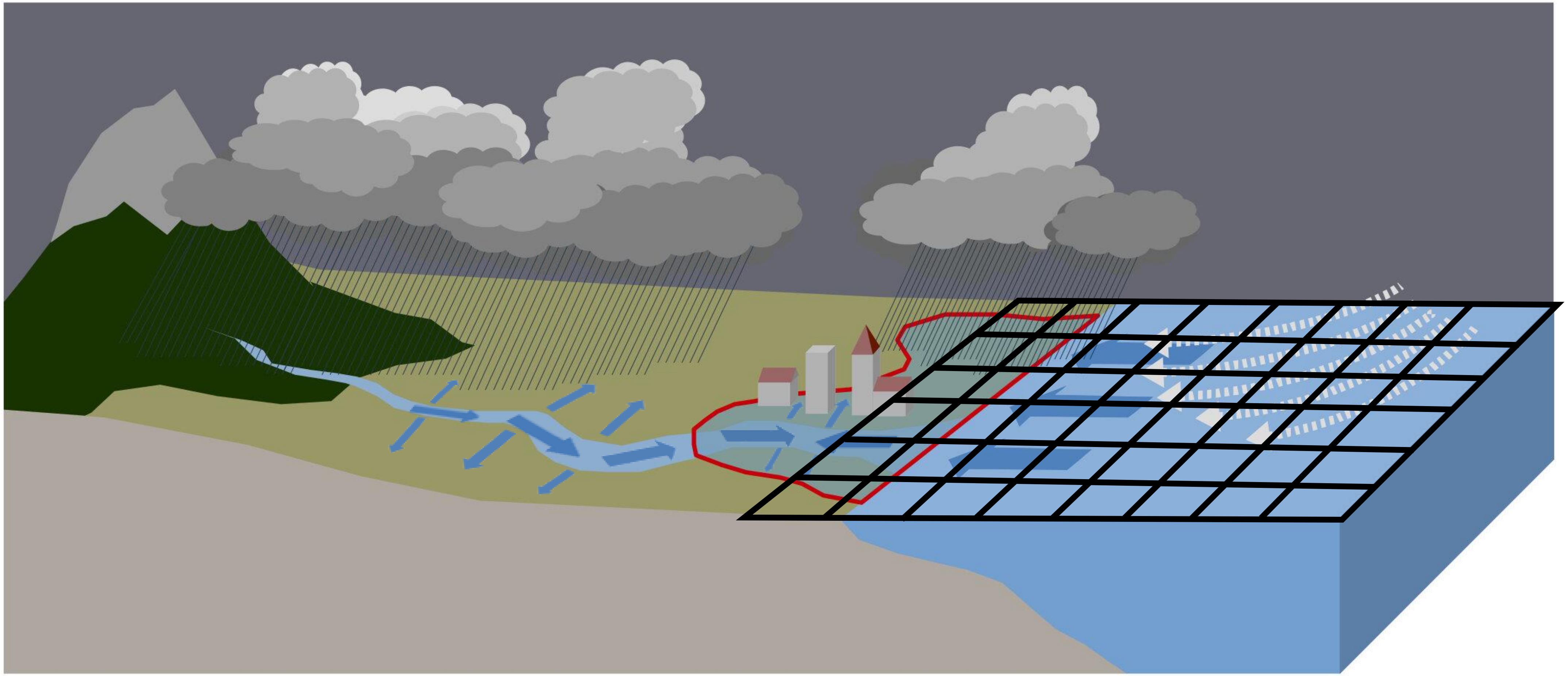


Image originally published on phys.org: https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html
Credit: Douglas Maraun

Modeling of hurricane-induced flooding

Hydrological model

- Only covers drainage basin and part of transition zone.
- Require accurate lower boundary conditions.
- Examples: NOAA NWM, HEC-REC, VIC, CASC2D, etc.

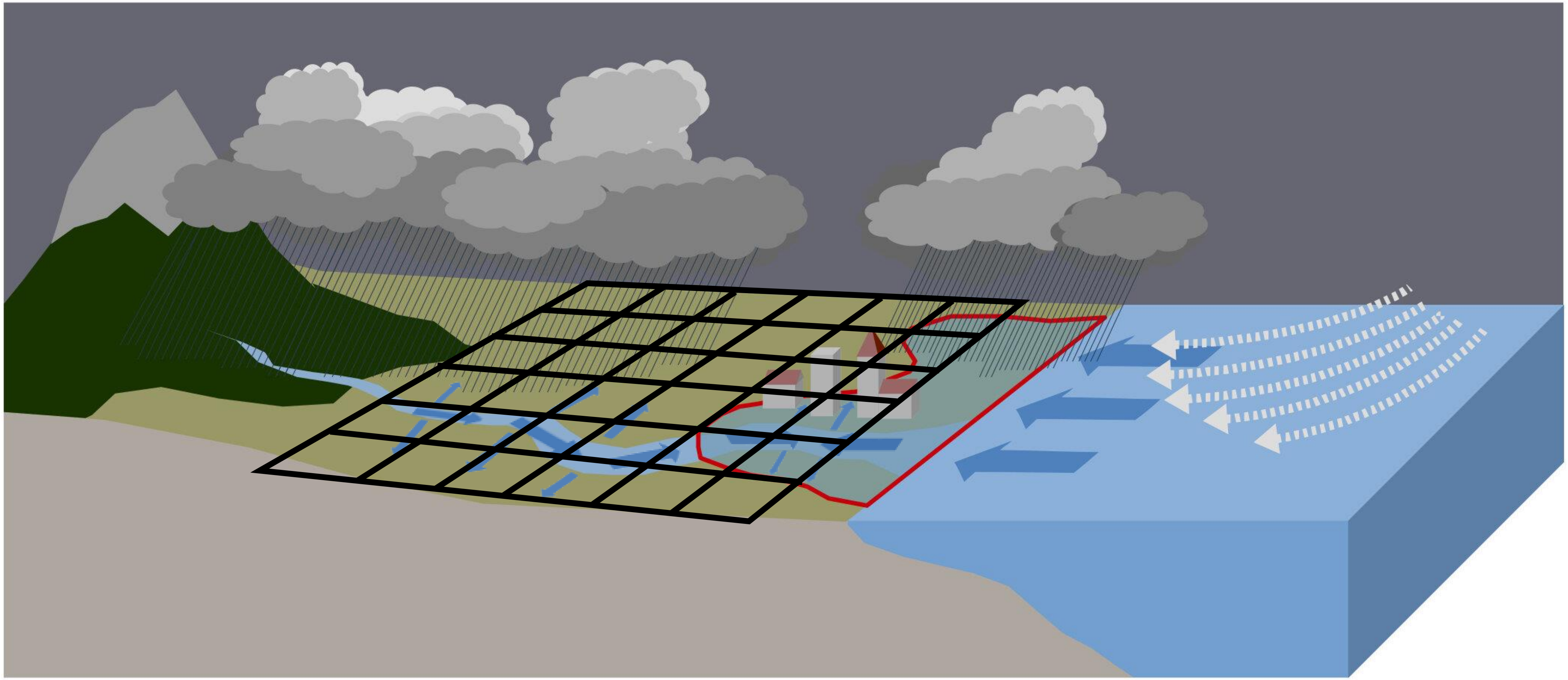
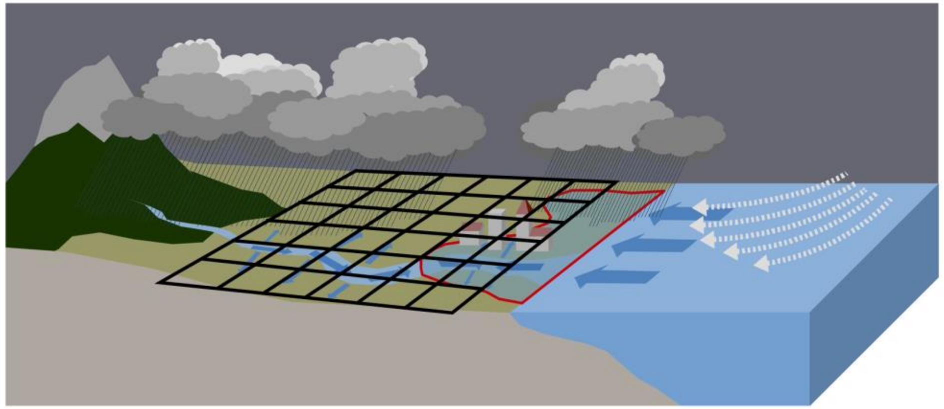


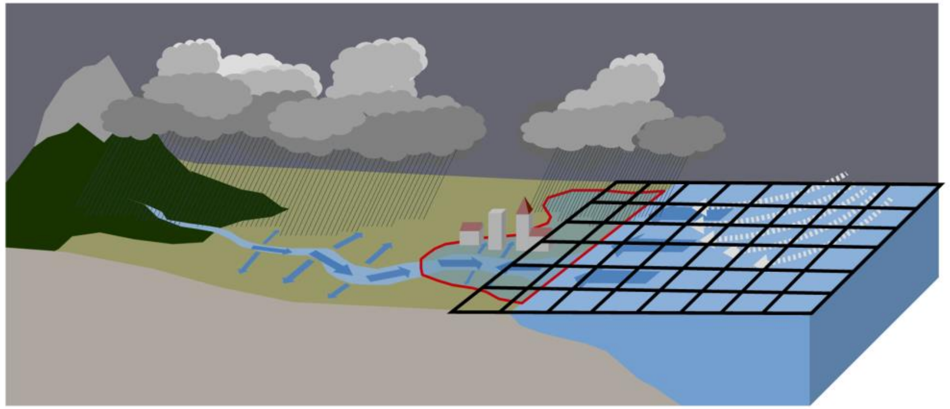
Image originally published on phys.org: https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html
Credit: Douglas Maraun

Modeling of hurricane-induced flooding

Single model is unable to accurately simulate what is happening in the transition zone and thus losses compound flooding information.

Highlight the need for an integrated modeling system to simulate the flooding event on the land and in the ocean simultaneously.





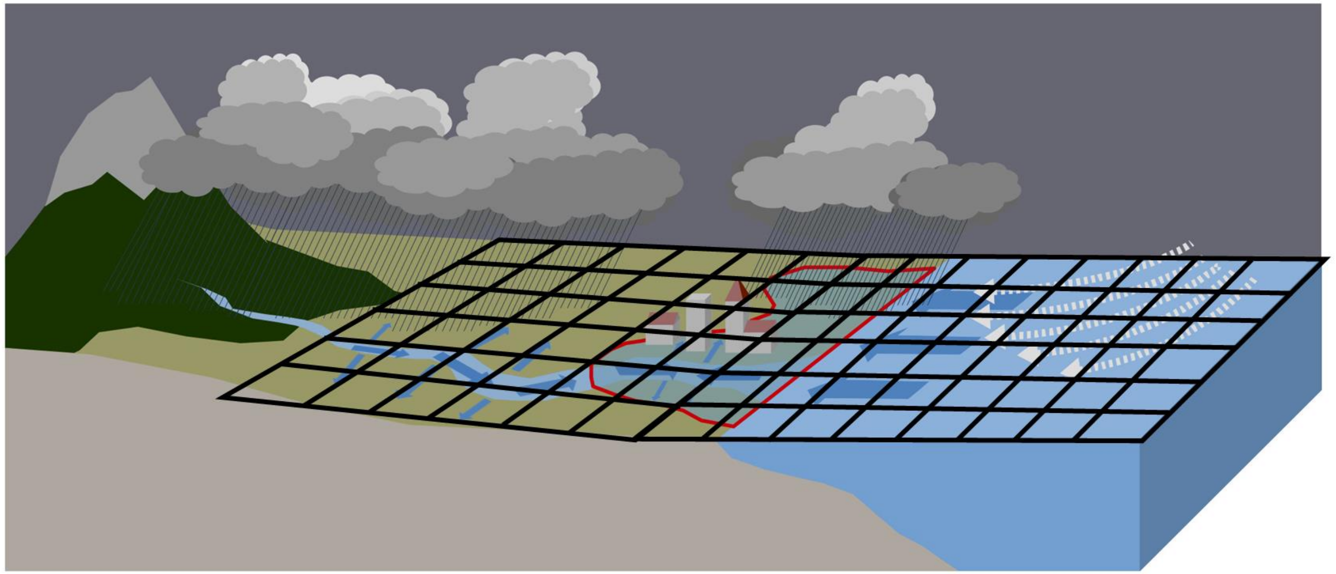
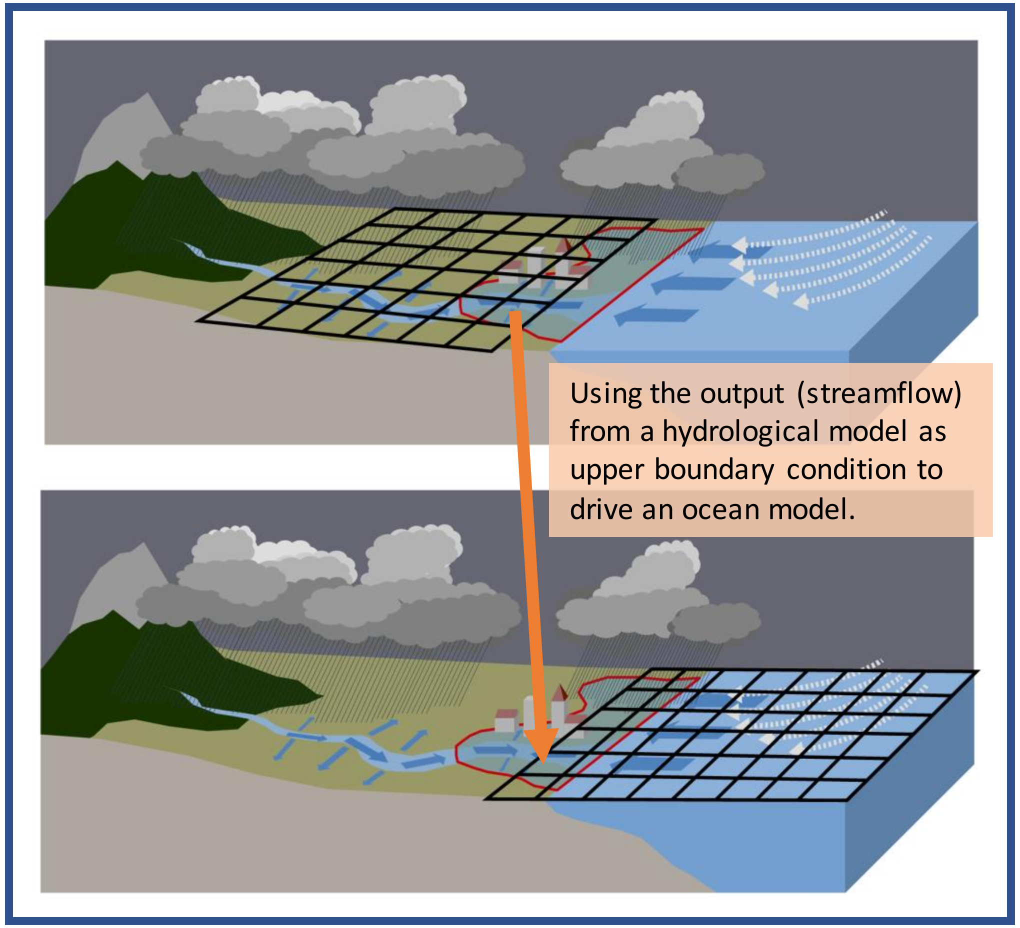


Image originally published on phys.org: https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html
Credit: Douglas Maraun

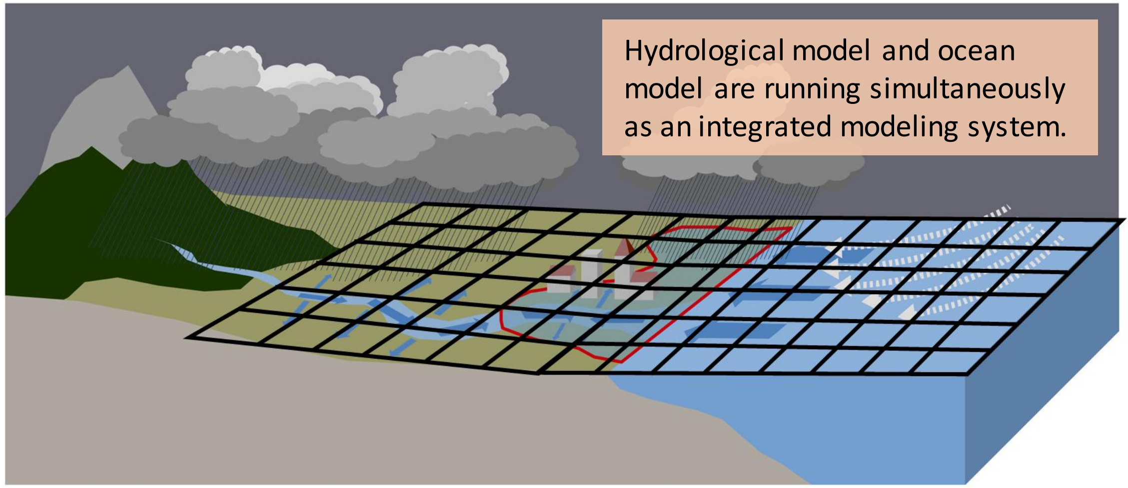
Modeling of hurricane-induced flooding

NOAA / NOS / Office of Coast Survey is developing required infrastructure to perform inland-coastal coupling for the NOS' operational coastal ocean models.
They are coupling hydrological model (mainly NWM) with ocean models ADCIRC, ROMS, FVCOM and SELFE/SCHISM (currently through one-way coupling approach).
https://coastaloceanmodels.noaa.gov/coupling/02_inland_coastal_coupling.html



One-way coupling

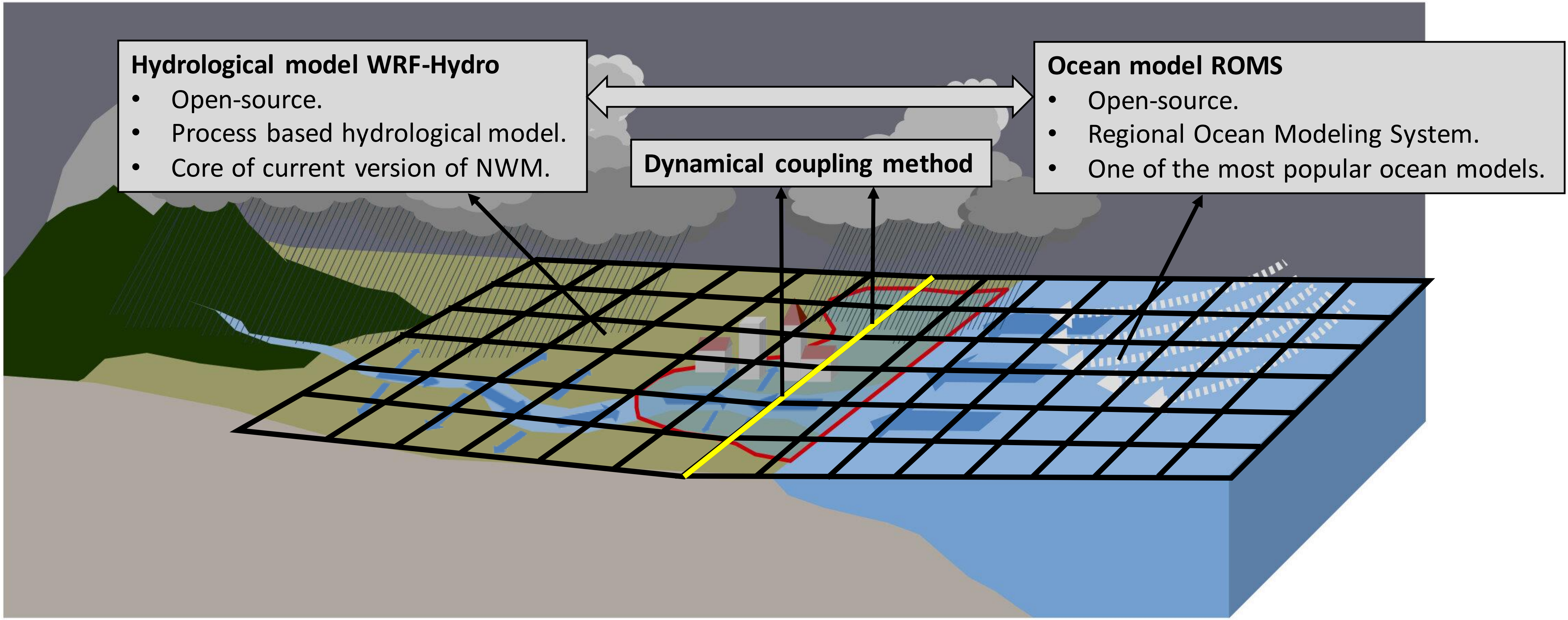
vs



Two-way coupling

Image originally published on phys.org: https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html
Credit: Douglas Maraun

Dynamically coupled hydrological-ocean modeling system



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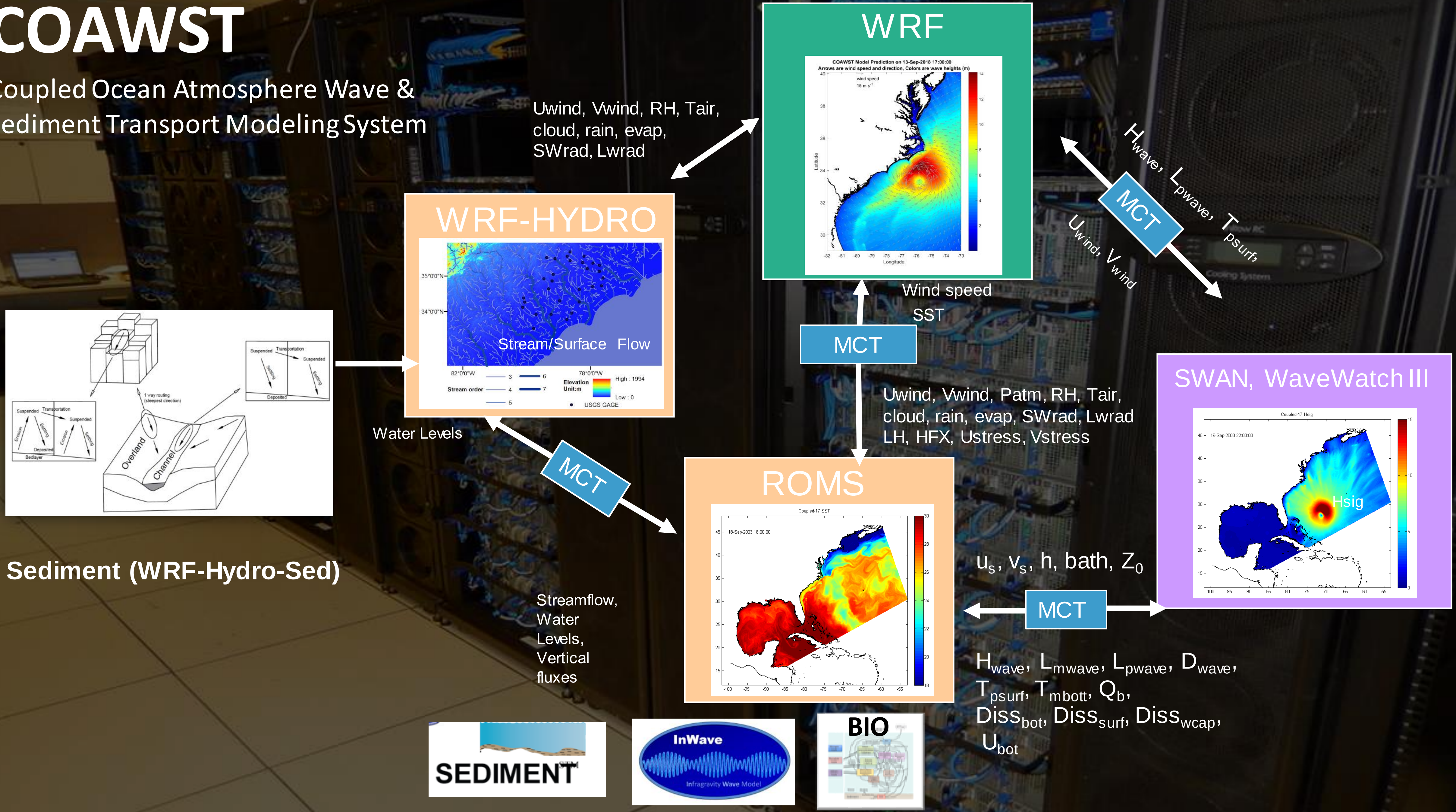
Credit: Douglas Maraun

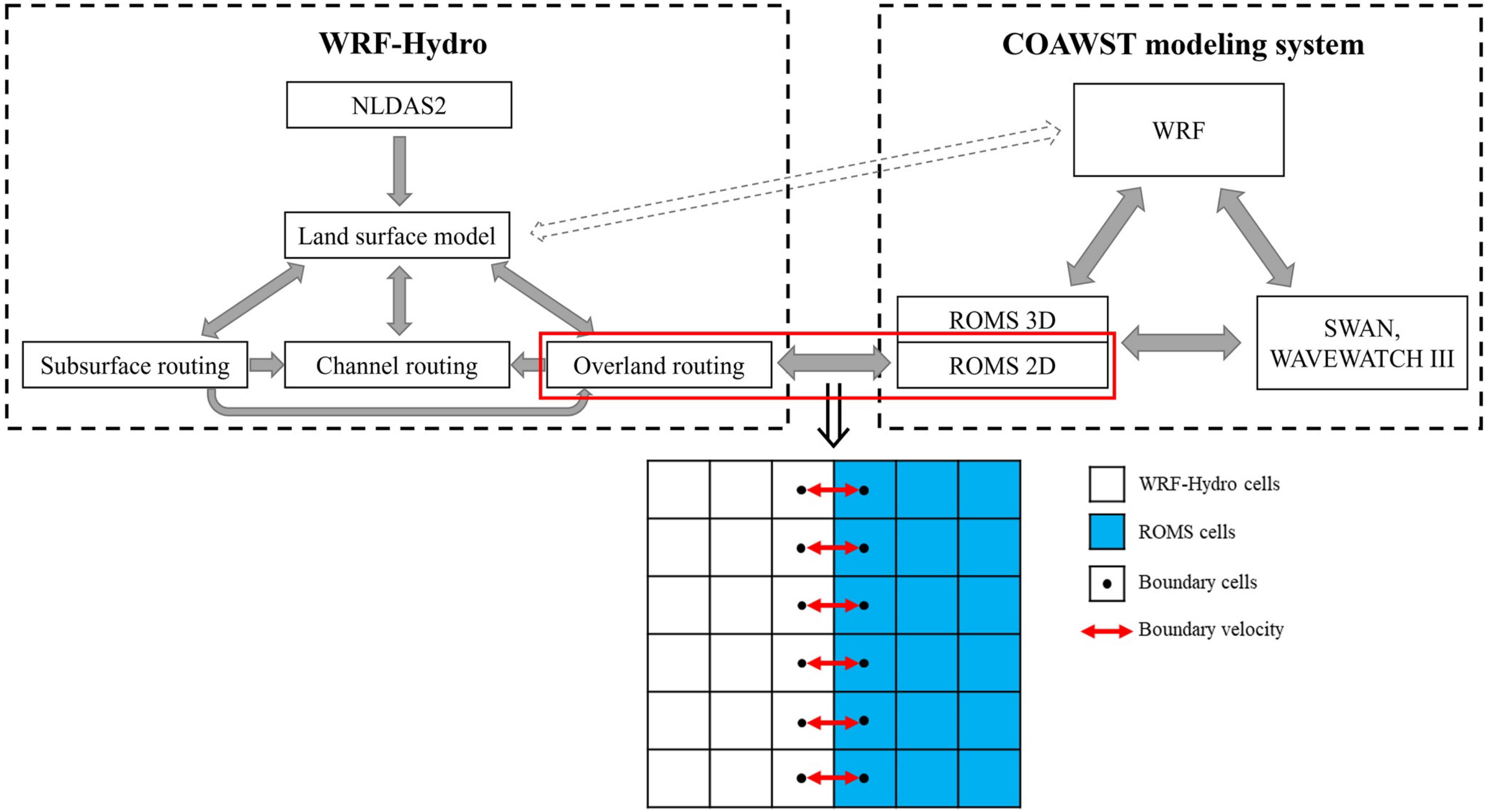
COAWST

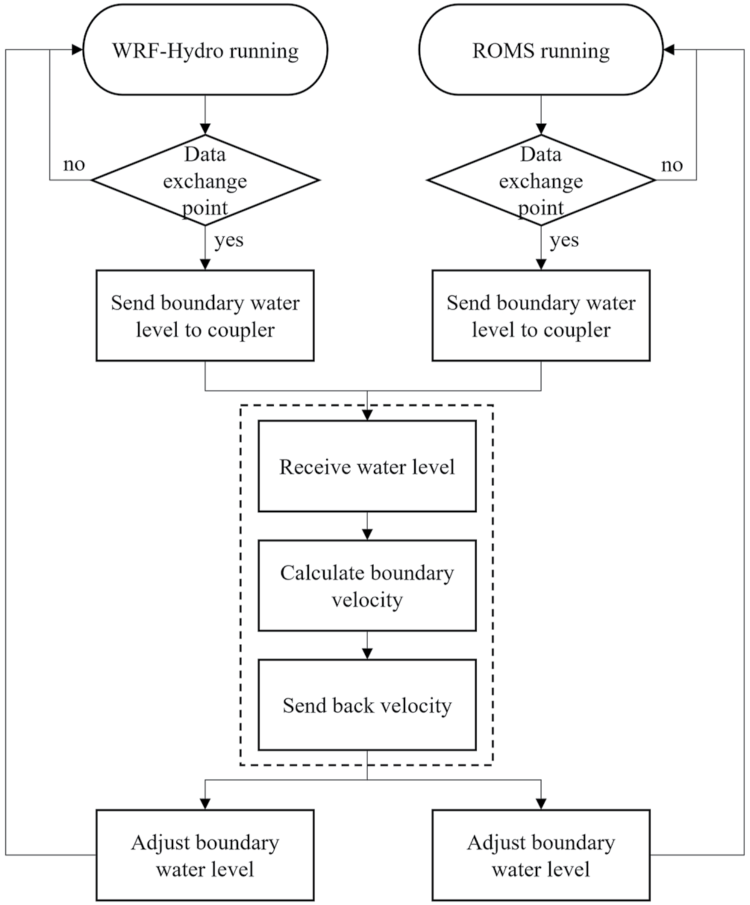
Coupled Ocean Atmosphere Wave & Sediment Transport Modeling System



Dynamically coupled hydrological-ocean modeling system

- Computation domain is divided into two subdomains- one for WRF-Hydro and the other for ROMS.
- The two models exchange water level information on every connected cell along the boundary.
- A coupler is applied to assure the two models have the same velocity along the interface boundary.
- The dynamic coupling is built on the platform of COAWST (Warner et al., 2010) .



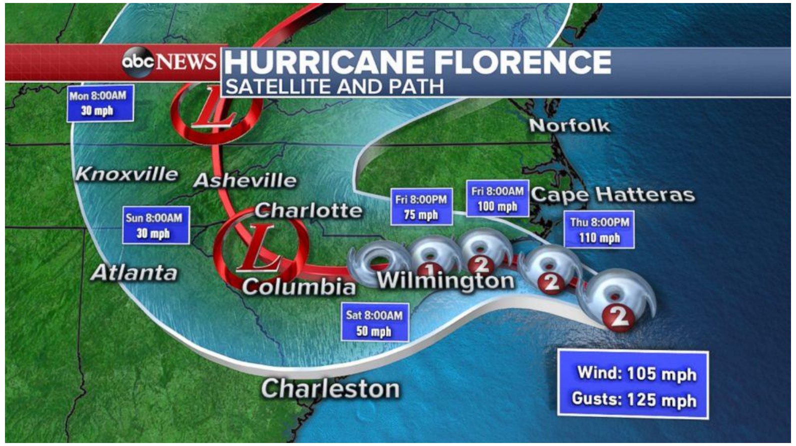


Bao, D., Xue, Z. G., Warner, J. C., Moulton, M., Yin, D., Hegermiller, C. A., et al. (2022). A numerical investigation of Hurricane Florence-induced compound flooding in the Cape Fear Estuary using a dynamically coupled hydrological-ocean model. Journal of Advances in Modeling Earth Systems, 14, e2022MS003131.
Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. (2010). Development of a coupled ocean–atmosphere–wave–sediment transport (COAWST) modeling system. Ocean modelling, 35(3), 230-244.

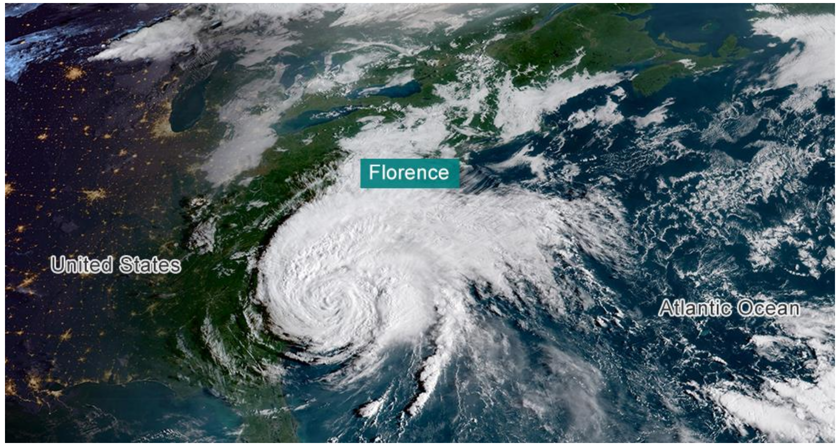
Application: Hurricane Florence

Hurricane Florence

- The sixth hurricane and the first major hurricane of the 2018 Atlantic hurricane season.
- Made landfall near Wrightsville Beach, North Carolina on 14 September.
- Introduced huge precipitation in the Cape Fear River Basin and set new records of peak flows in most of the channels and tributaries therein.
- generated a huge storm surge, and the inundation heights along the North Carolina coast reached 2.5–3.4 m (8–11 ft).



The projected path of Hurricane Florence
https://abcnews.go.com/US/160000-power-hurricane-florence-lashes-north-carolina-coast/story?id=57791726

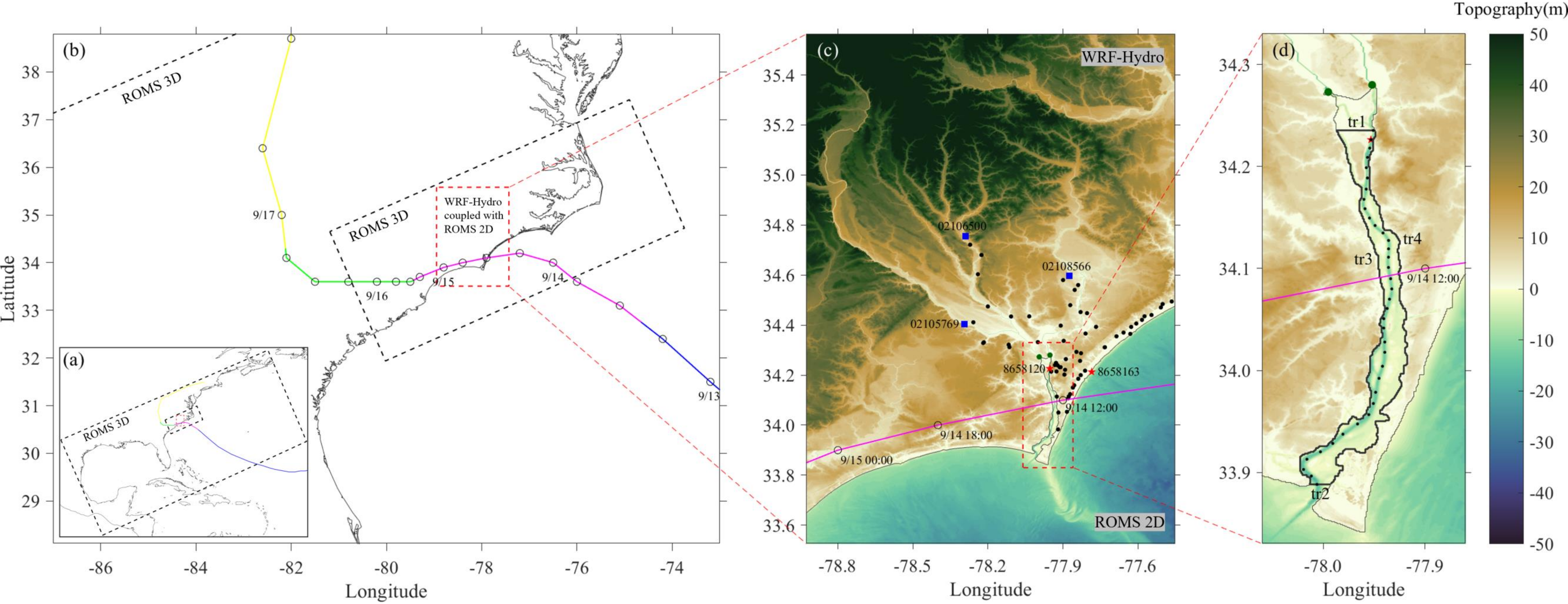


Satellite image of Florence.
https://www.bbc.com/news/world-us-canada-45511312

Drone photo of Florence-induced flooding.
https://www.greenvilleonline.com/story/news/2018/09/15/tropical-storm-florence-track-path-sc-nc-greenville-asheville-charlotte-columbia-myrtle-spartanburg/1309148002/

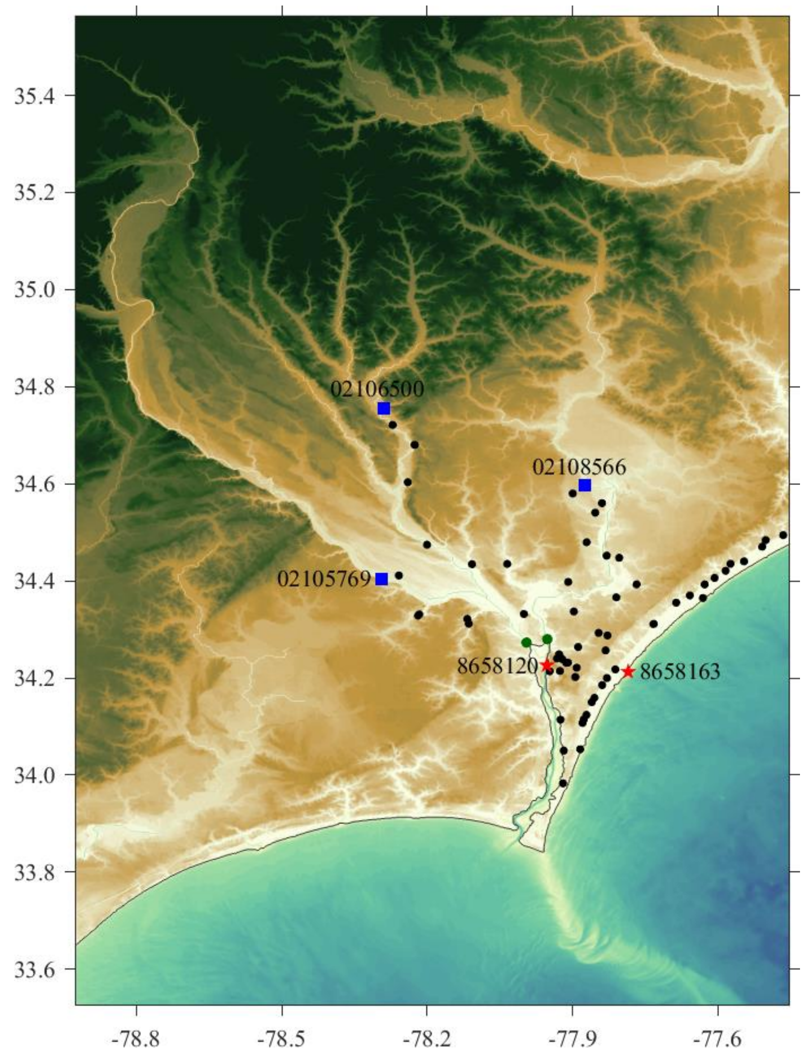
Application: Hurricane Florence

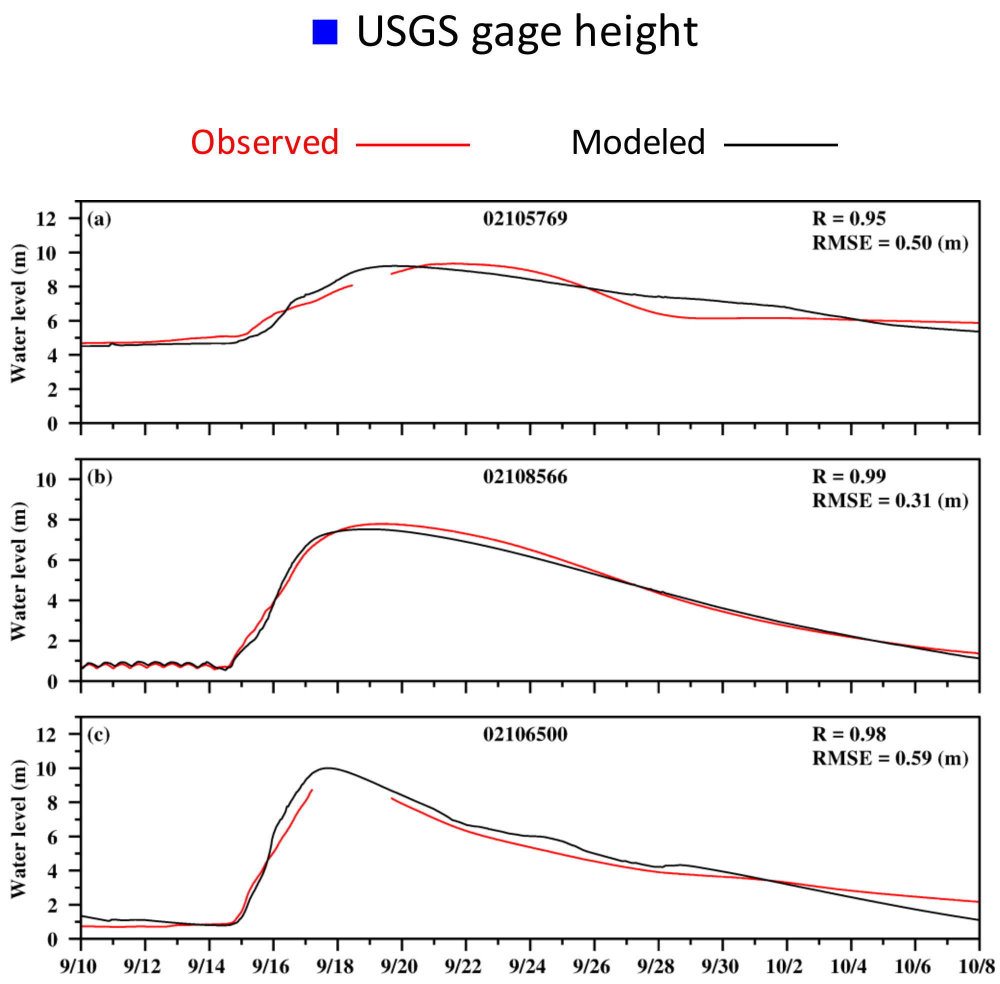
Model set-up



Application: Hurricane Florence

Model validation

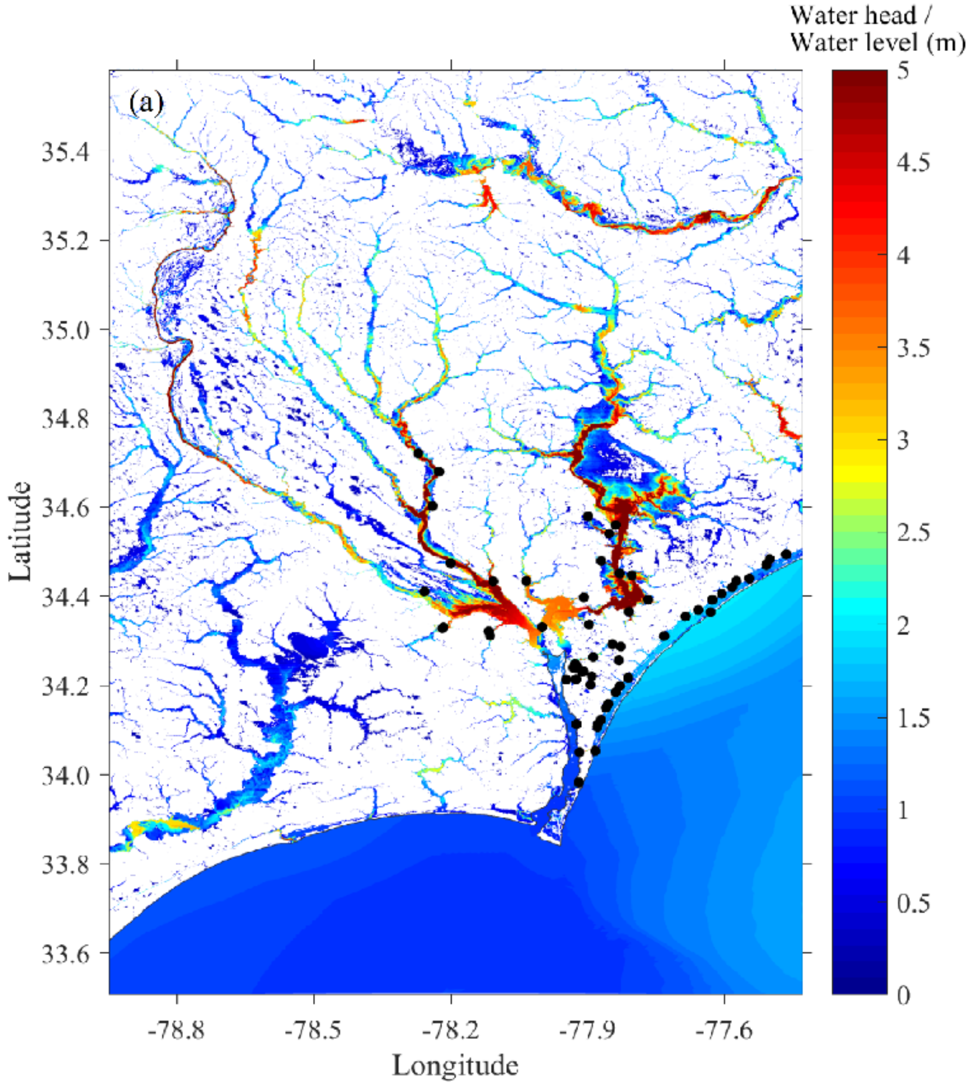


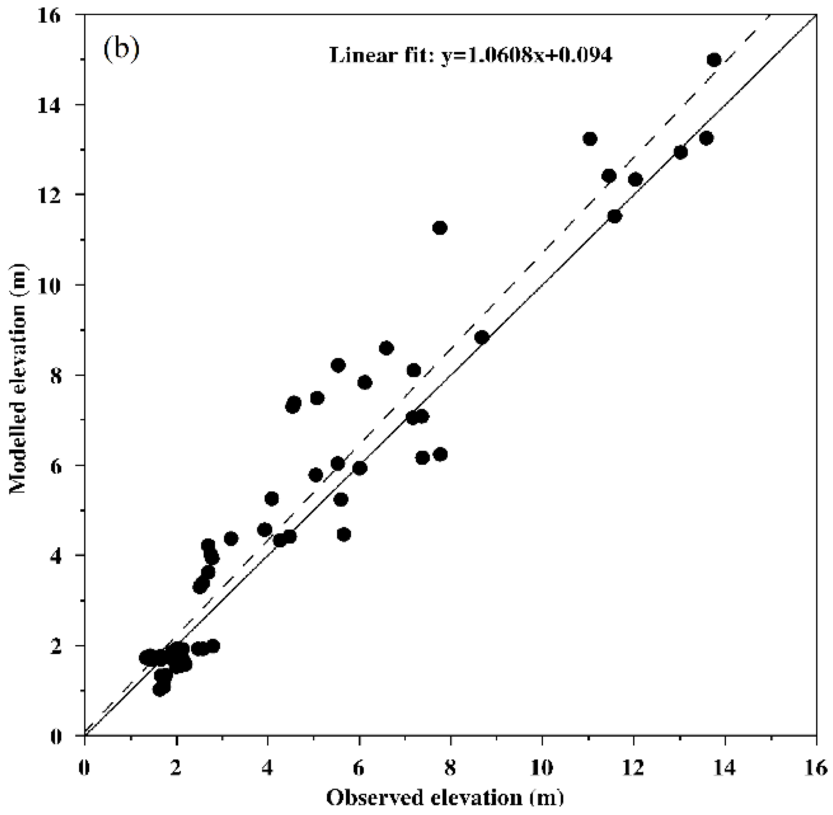


Application: Hurricane Florence

Model validation

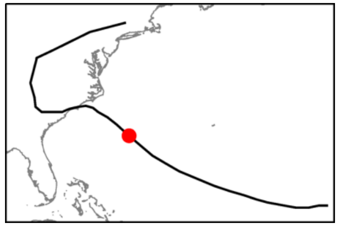
● High water marks

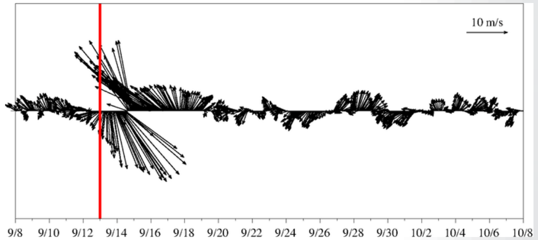




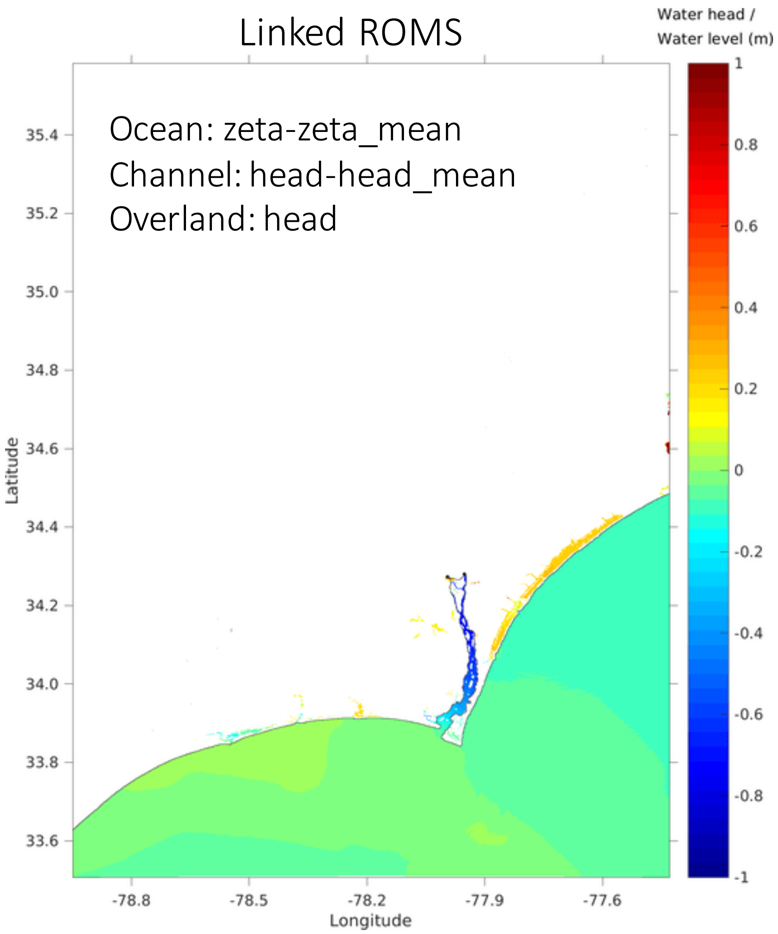
River-Ocean Coupling

Dynamical (two-way) vs. One-way Coupling

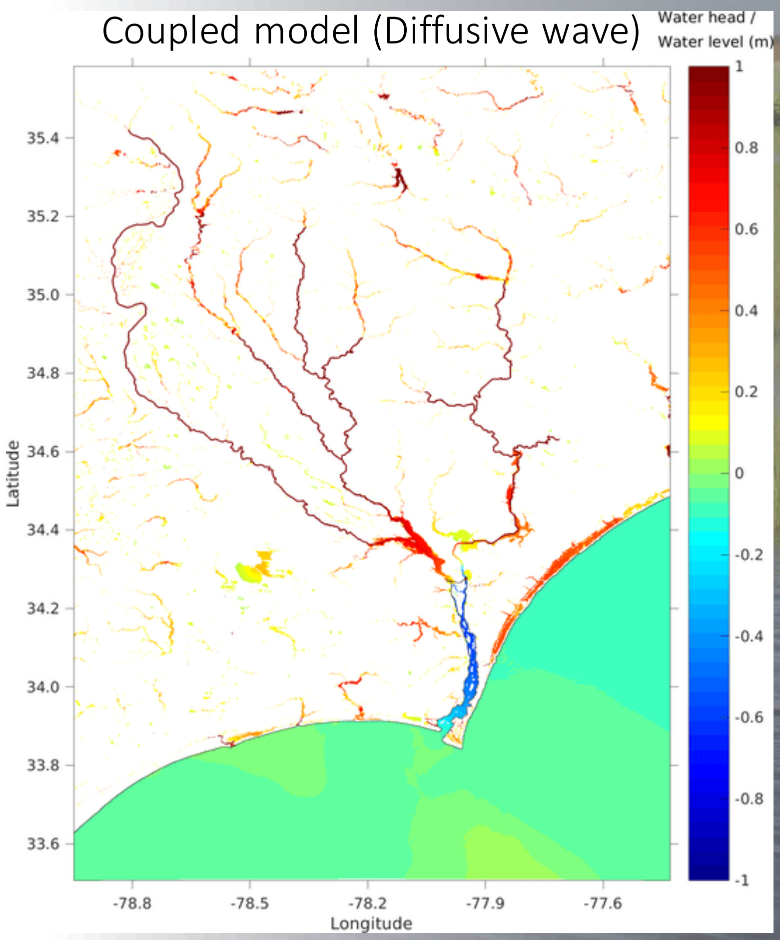




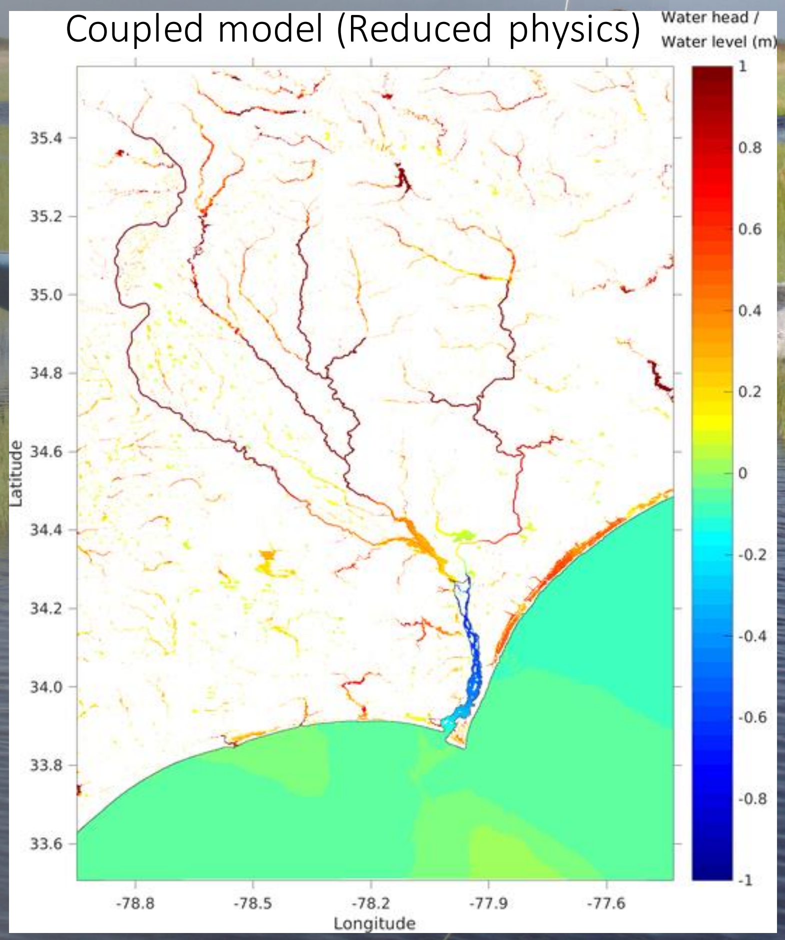
Linked ROMS



Coupled model (Diffusive wave)

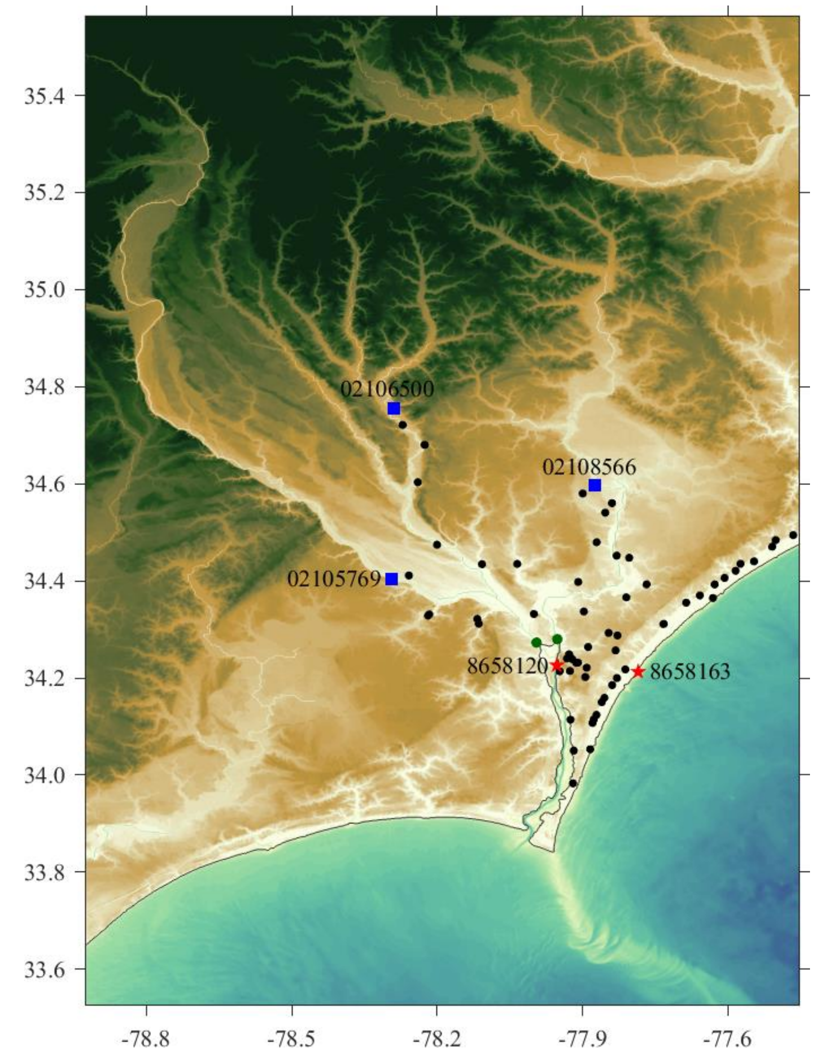


Coupled model (Reduced physics)

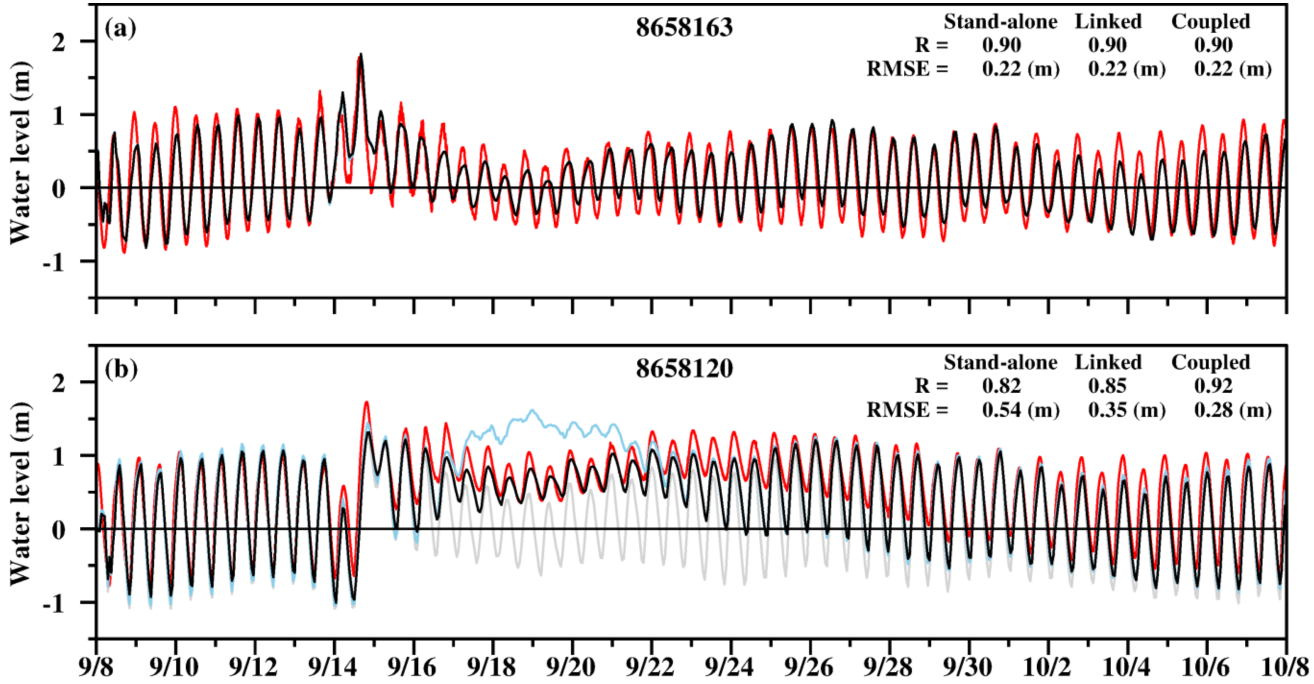


Application: Hurricane Florence

Model validation

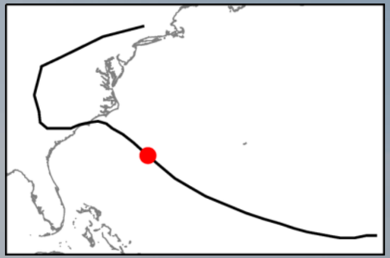


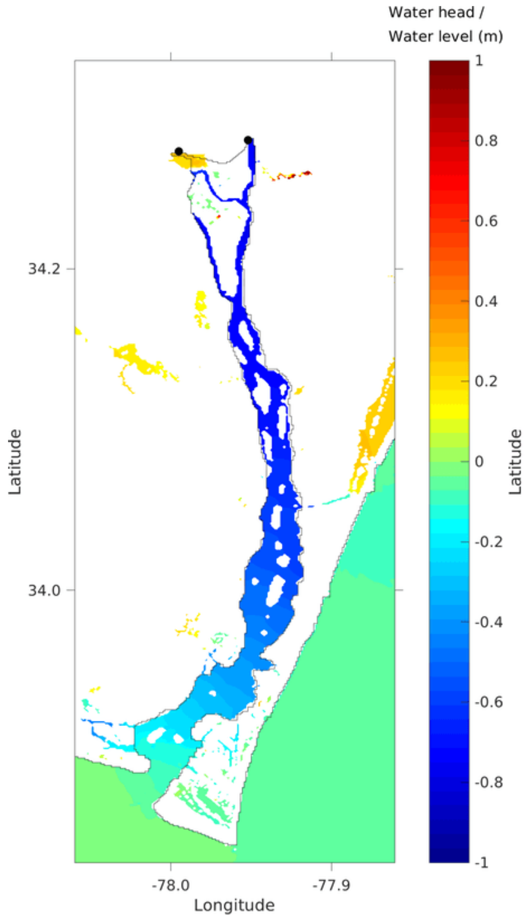
★ NOAA tide station



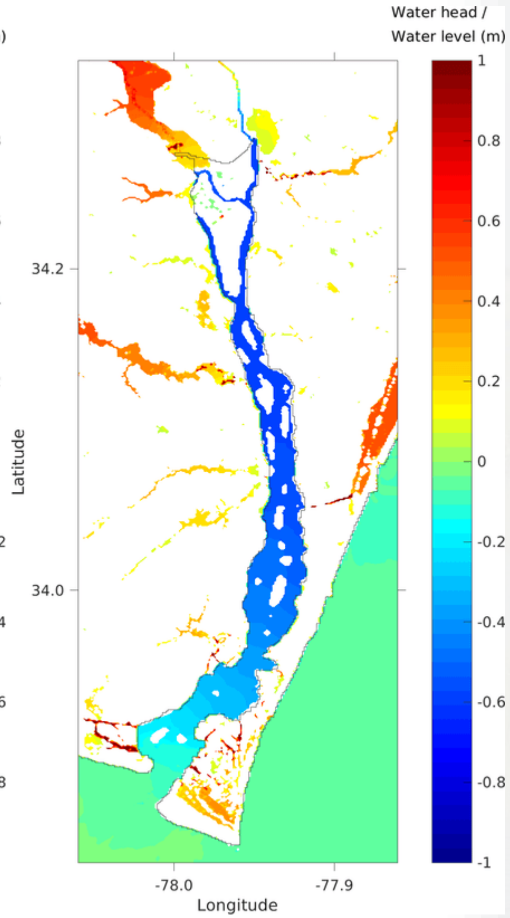
Name	Coupling Method
OBS	
Exp1	Stand-alone ROMS
Exp2	Linked ROMS
Exp3	Dynamic Coupling

River-Ocean Coupling
Dynamical (two-way) vs. One-way Coupling

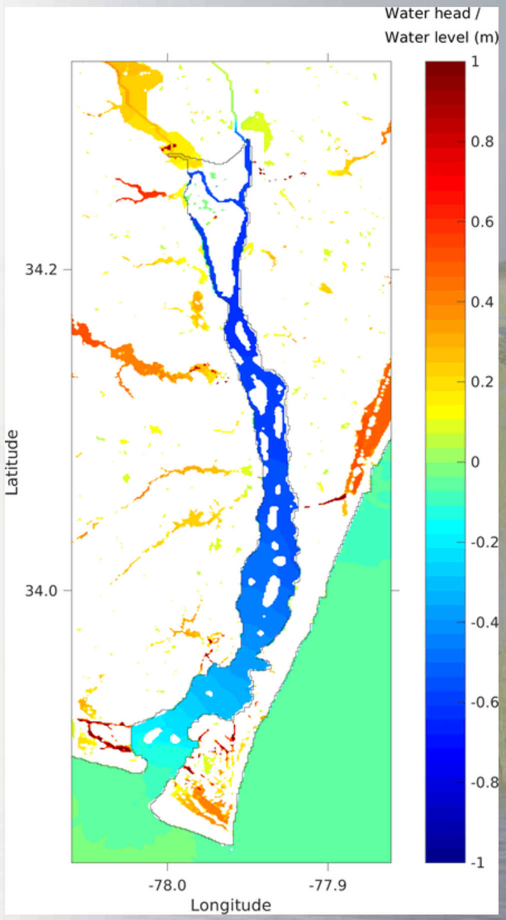




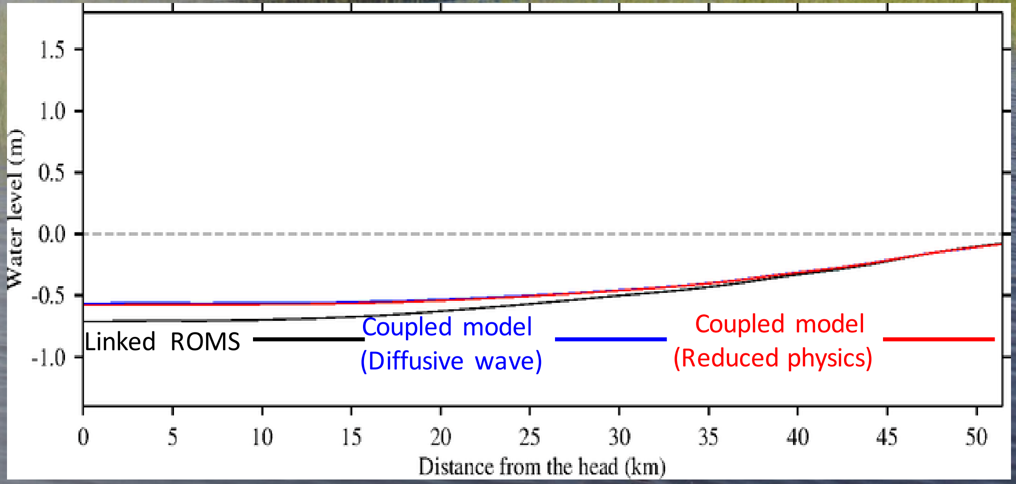
Linked ROMS



Coupled model
(Diffusive wave)



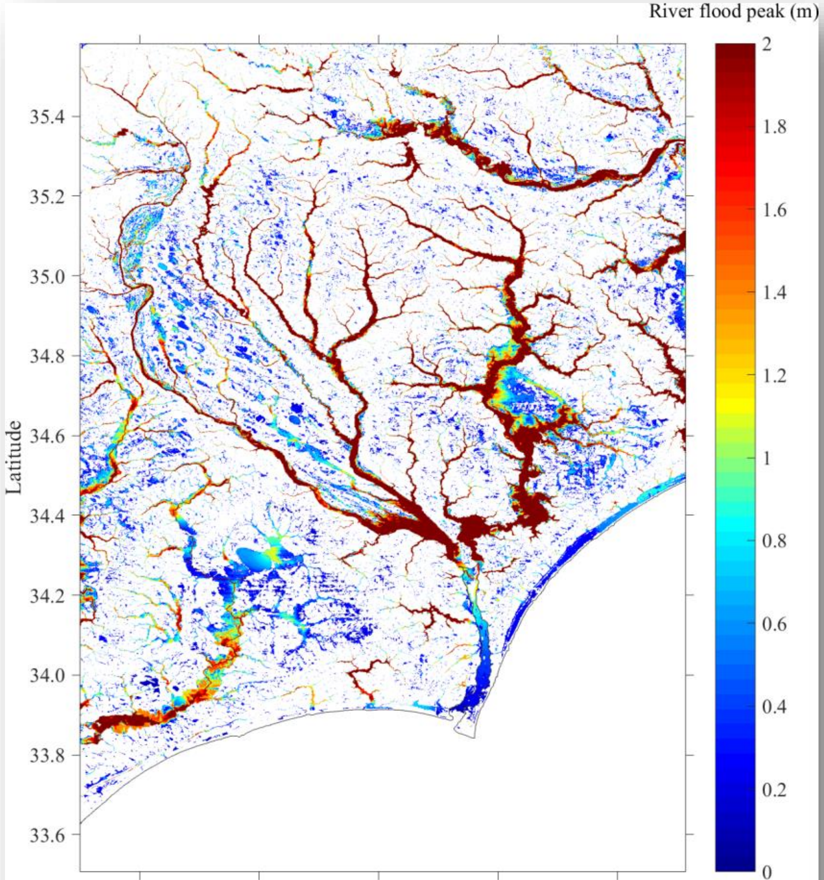
Coupled model
(Reduced physics)



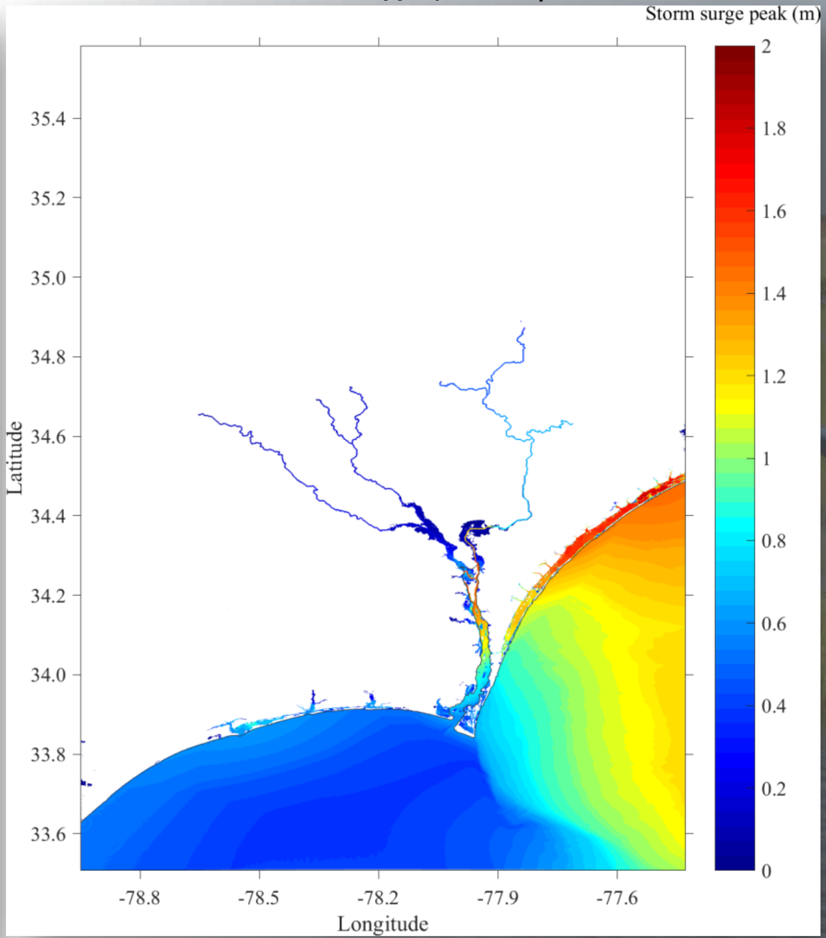
River vs. Surge

R = river
W = wind
T = tide

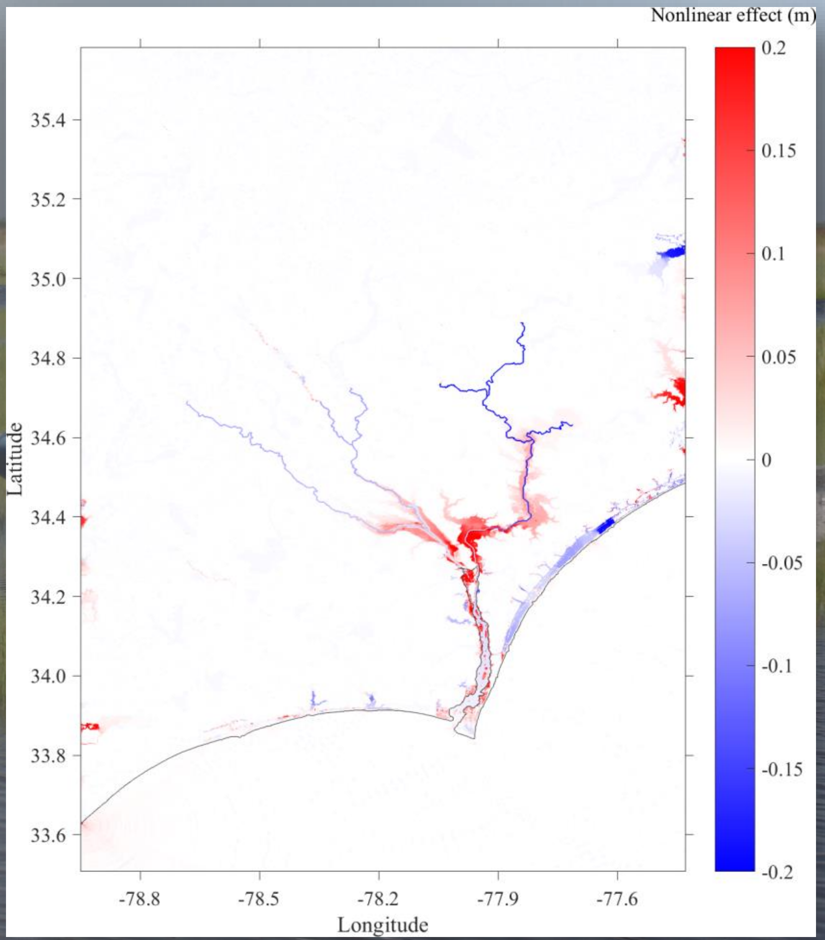
River flood peak
Exp4 - Exp6
R+T T



Storm surge peak
Exp5 - Exp6
W+T T



Nonlinear effect
Exp3 - (Exp4+Exp5-Exp6)
R+W+T R+T W+T T

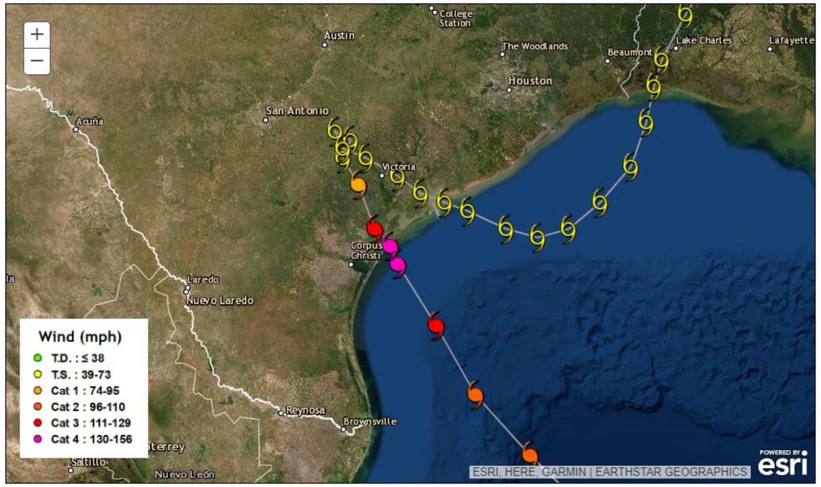


Name	Coupling Method	Precipitation	Wind
Exp1	Stand-alone ROMS	--	Yes
Exp2	Linked ROMS	Yes	Yes
Exp3	Dynamic Coupling	Yes	Yes
Exp4	Dynamic Coupling	Yes	No
Exp5	Dynamic Coupling	No	Yes
Exp6	Dynamic Coupling	No	No

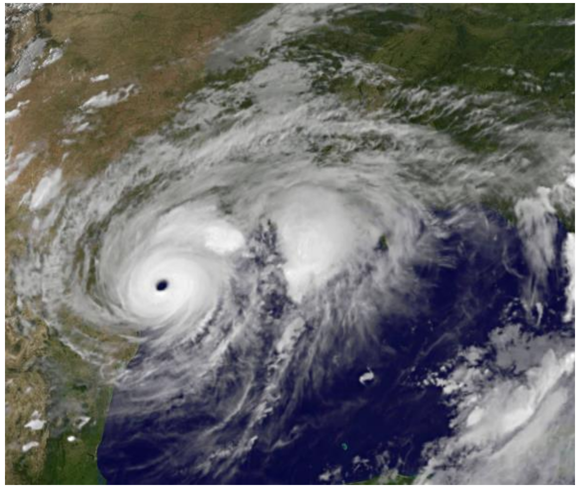
Application: Hurricane Harvey

Hurricane Harvey

- Second-Costliest Hurricane to Hit the United States (https://geology.com/hurricanes/largest-hurricane/).
- One of the deadliest hurricanes in the last 12 years (Sarkar et al., 2018).
- The most significant tropical cyclone rainfall event in United States history (Blake & Zelinsky, 2018).
- The wettest storm in the history of the United States (Valle-Levinson et al., 2020).
- The return period of three-day precipitation exceeds 1000 years (van Oldenborgh et al., 2017).



Hurricane Harvey track from National Weather Service https://www.weather.gov/crp/hurricane_harvey



An image of Hurricane Harvey captured on Aug. 26, 2017, by GOES-East satellite. (Image: NOAA)

Floodwaters brought on by Hurricane Harvey in Houston overwhelmed the Addicks Reservoir in August 2017.Credit...David J. Phillip/Associated Press

Blake, E. S., & Zelinsky, D. A. (2018). National Hurricane Center tropical cyclone report: Hurricane Harvey (AL092017). *National Hurricane Center*, *May*, 1–77.

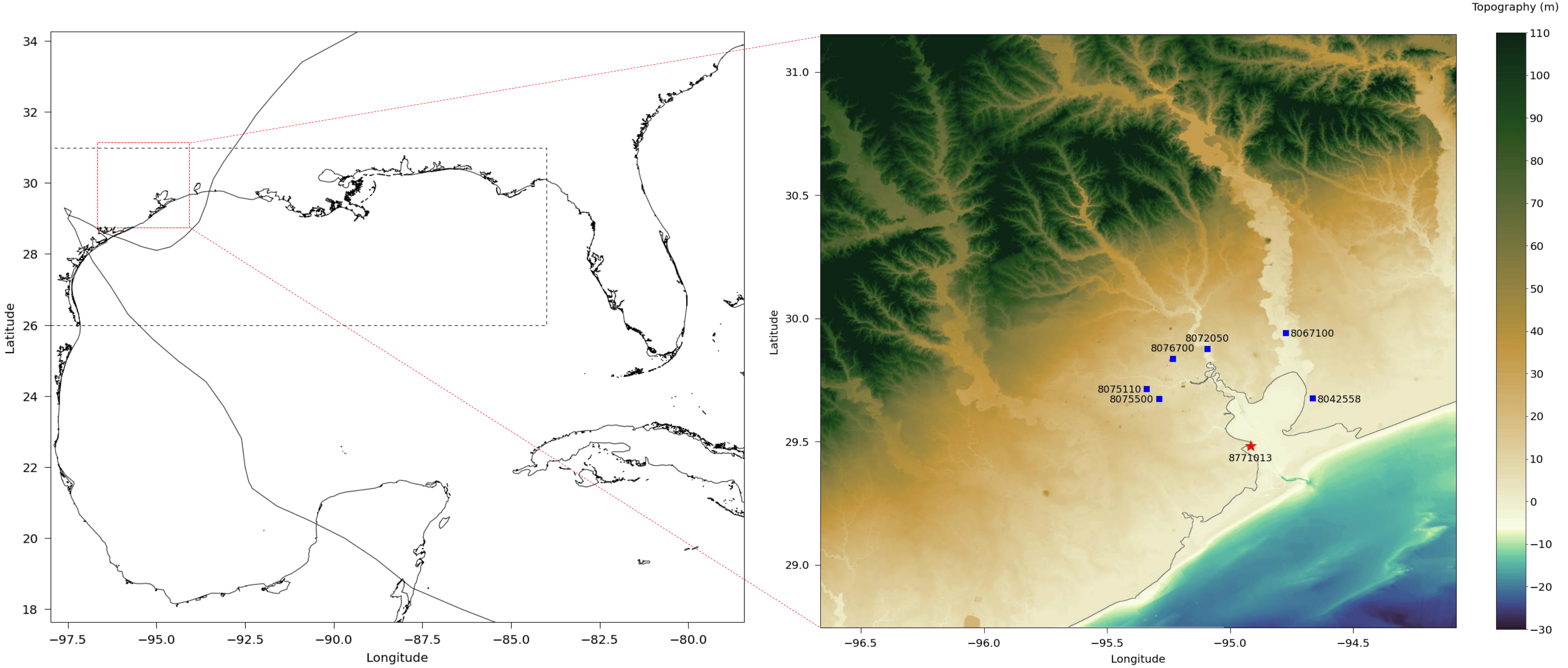
Van Oldenborgh, G. J., Van Der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G., & Cullen, H. (2017). Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, *12*(12), 124009.

Sarkar, S., Singh, R. P., & Chauhan, A. (2018). Anomalous changes in meteorological parameters along the track of 2017 Hurricane Harvey. *Remote Sensing Letters*, *9*(5), 487-496.

Souri, A. H., Choi, Y., Kodros, J. K., Jung, J., Shpund, J., Pierce, J. R., Lynn, B. H., Khain, A., & Chance, K. (2020). Response of Hurricane Harvey's rainfall to anthropogenic aerosols: A sensitivity study based on spectral bin microphysics with simulated aerosols. *Atmospheric Research*, *242*, 104965.

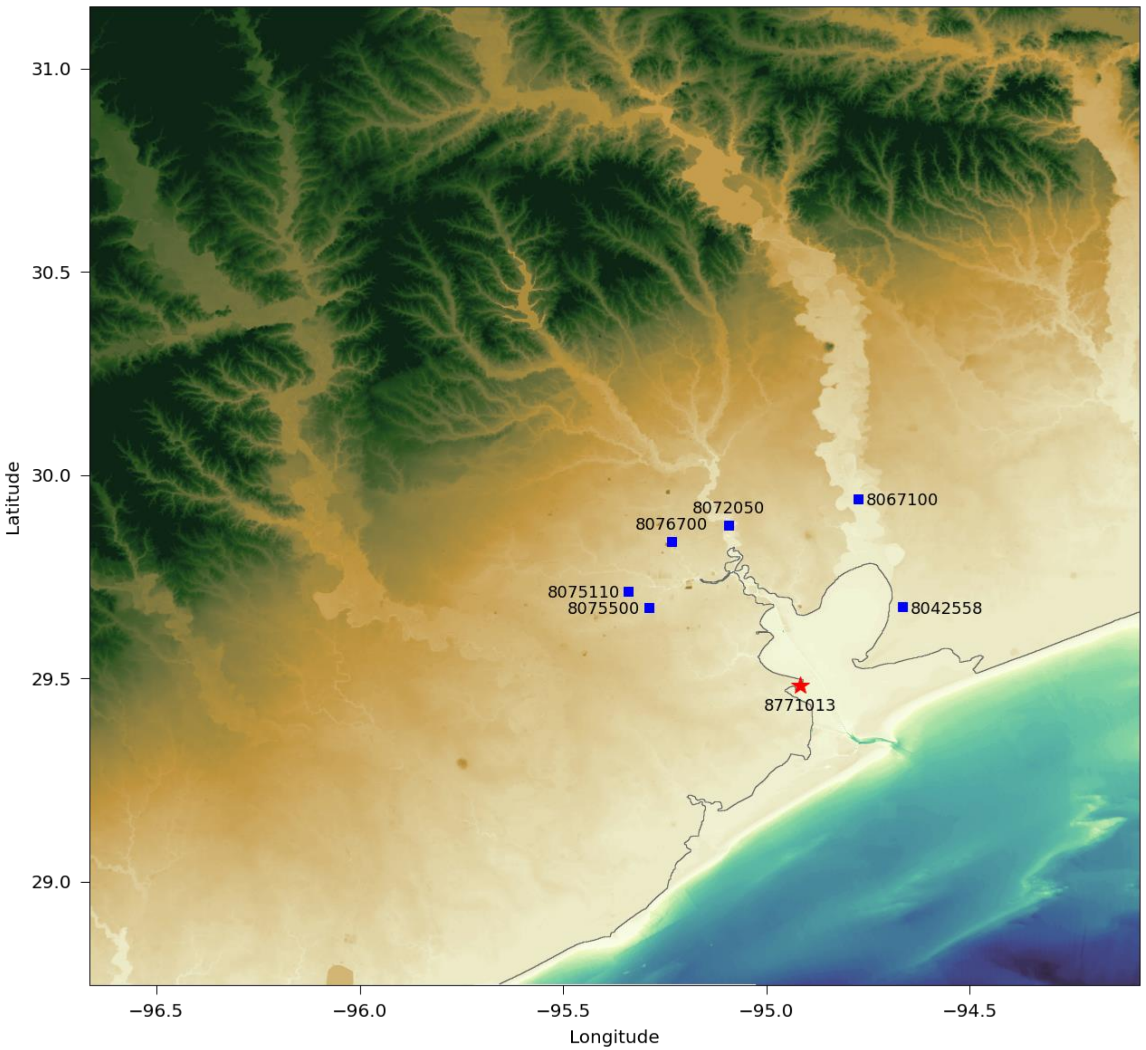
Application: Hurricane Harvey

Model set-up



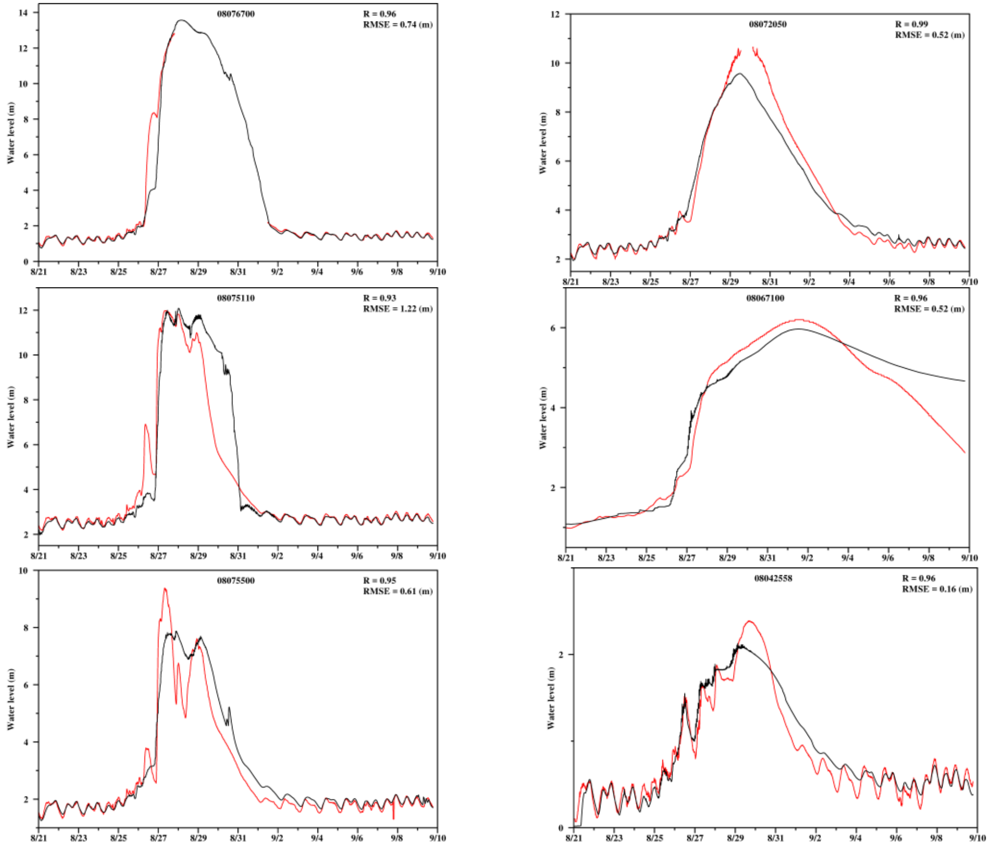
Application: Hurricane Harvey

Model validation

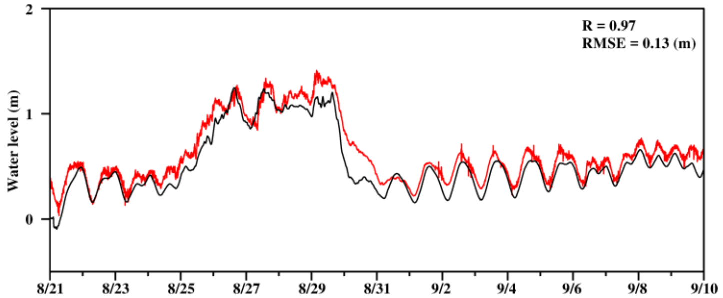


Observed ——— Modeled ———

USGS gage height

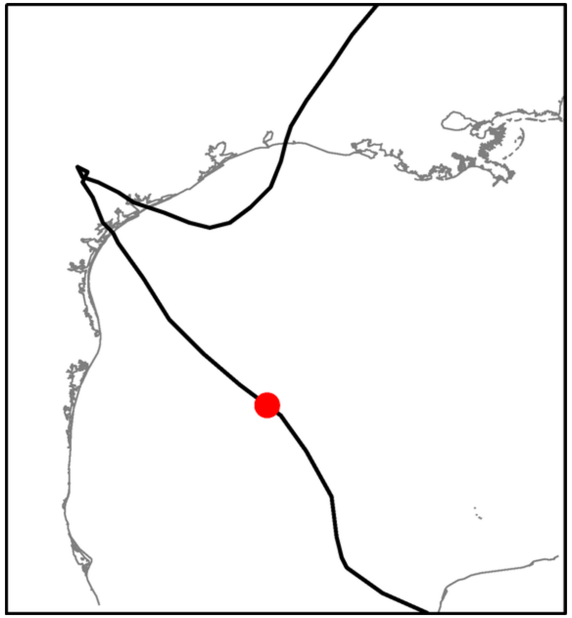


NOAA tide station

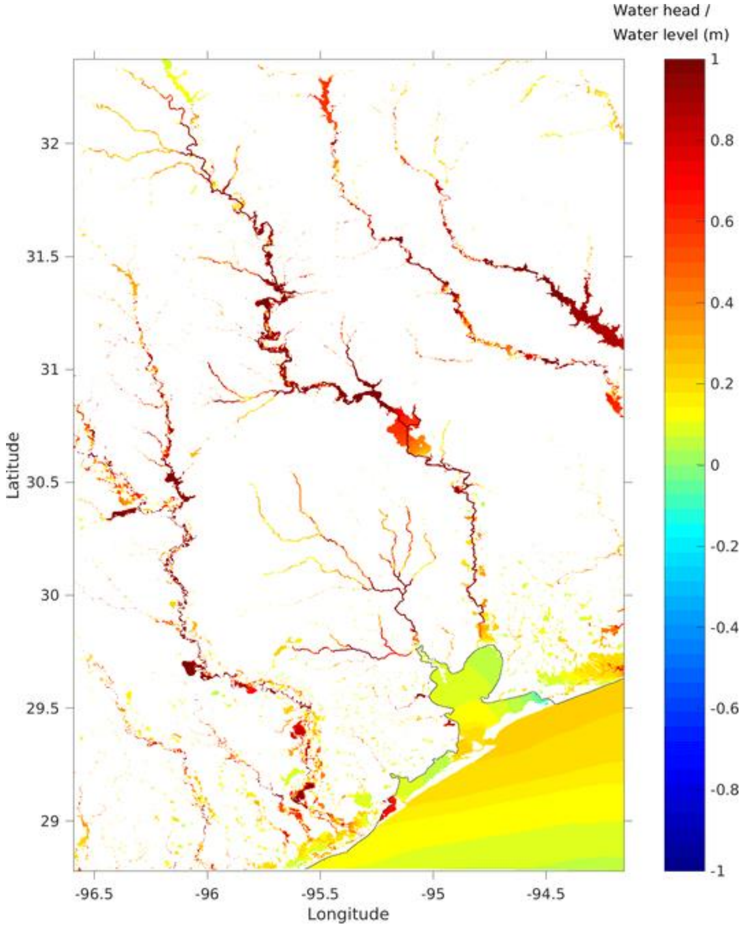


Application: Hurricane Harvey

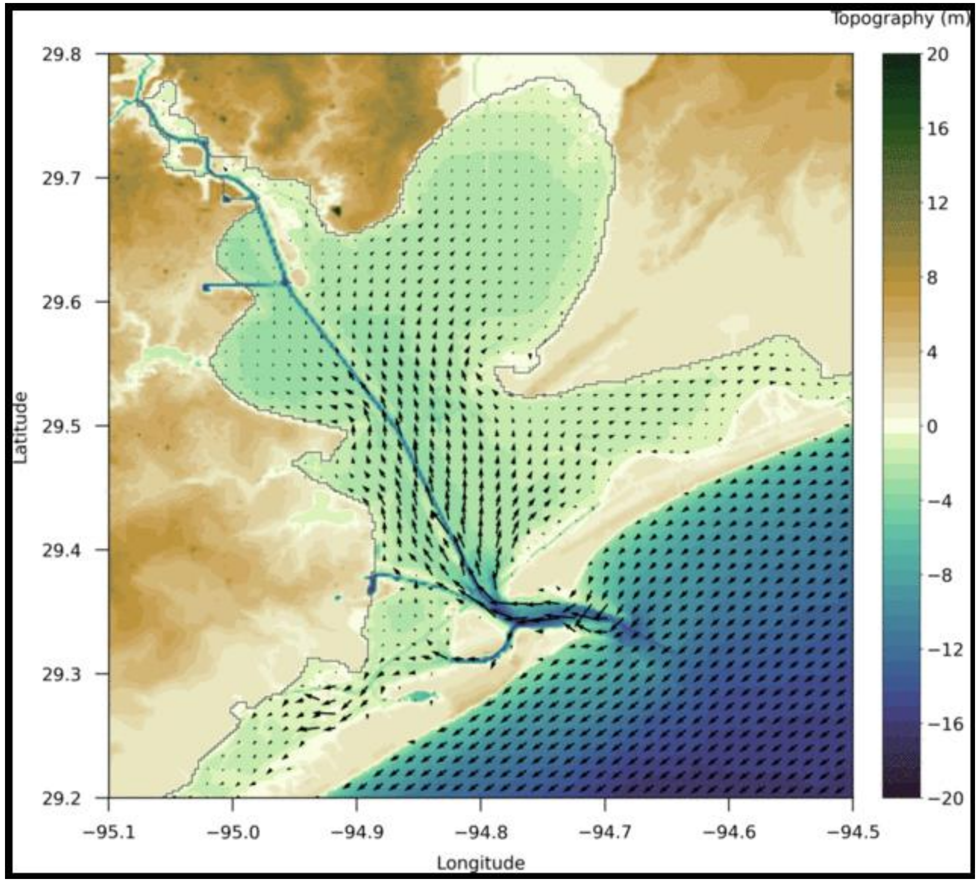
Model results



Hurricane Harvey track



Simulated flooding



Simulated velocity in the Bay

Flood Zone vs Real-time Model

Flood Zone:

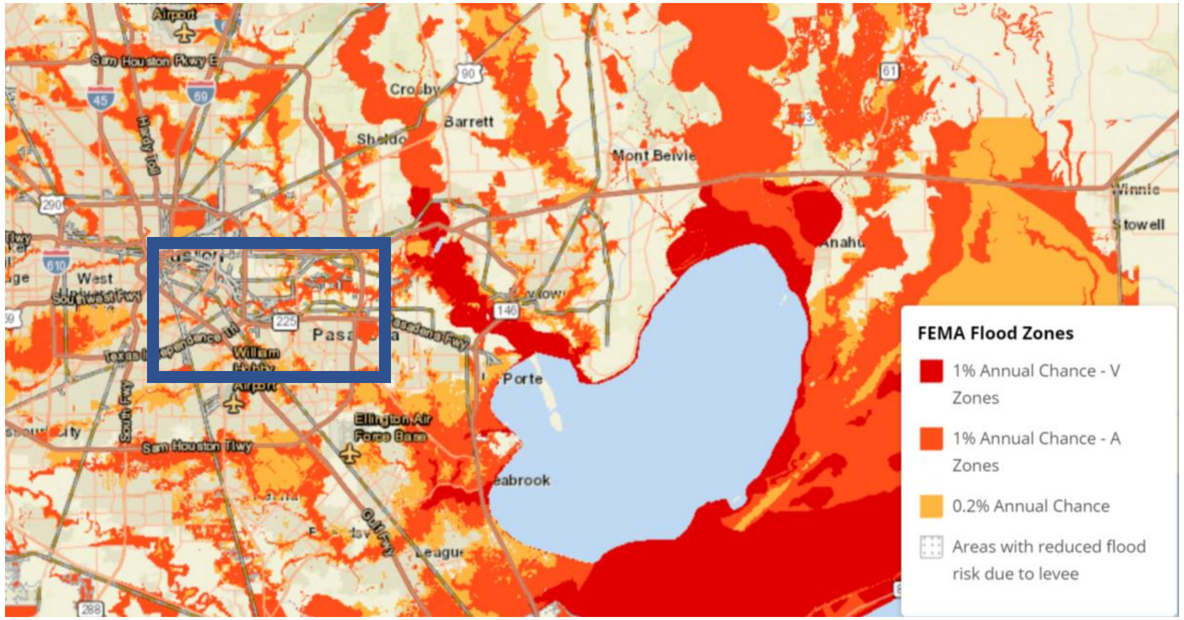
Input: historical data

Output: flooding probability

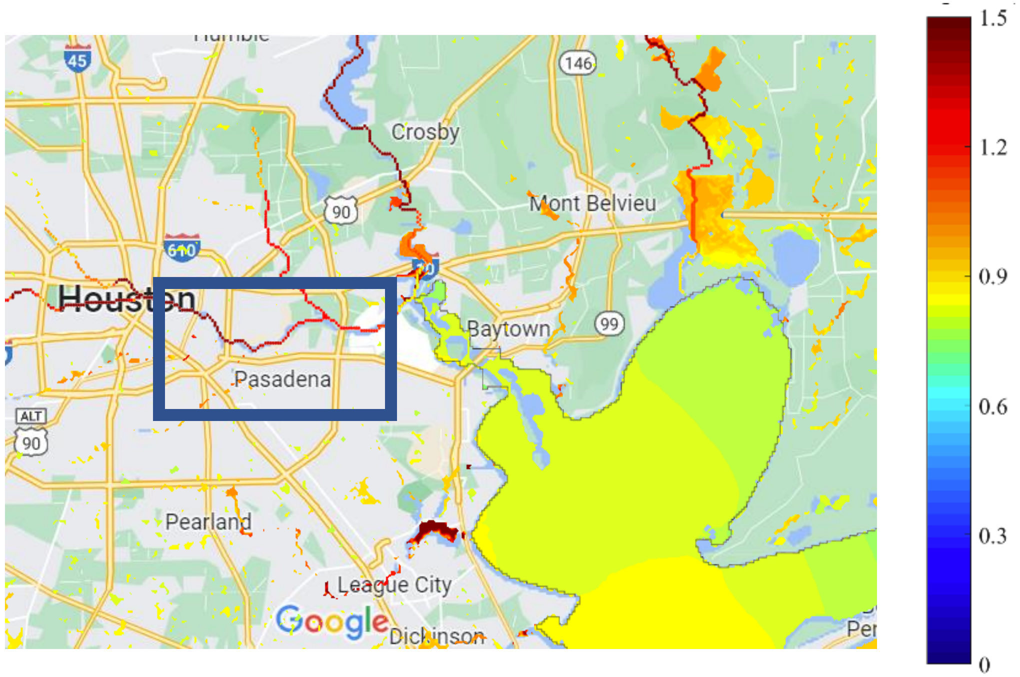
Real-time Model:

Input: real-time data

Output: real-time water level



FEMA Flood Zone Map from https://coast.noaa.gov/floodexposure/



Simulated flooding peak during Harvey

The return period of Harvey's three-day precipitation exceeds 1000 years !

What if Hurricane Harvey happens in Louisiana?