

Coupled Computer Modeling to Accurately Predict Coastal Flooding

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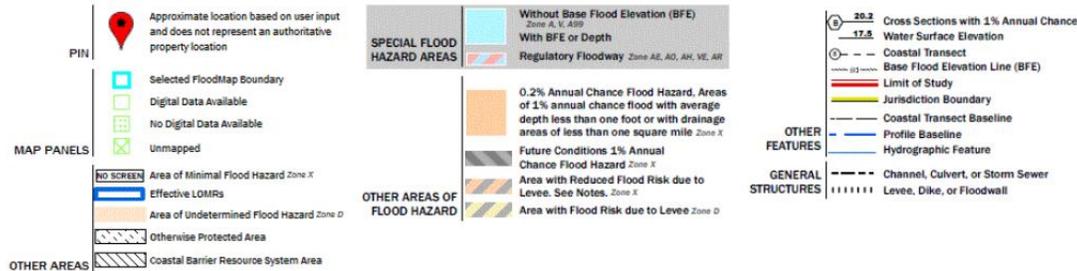
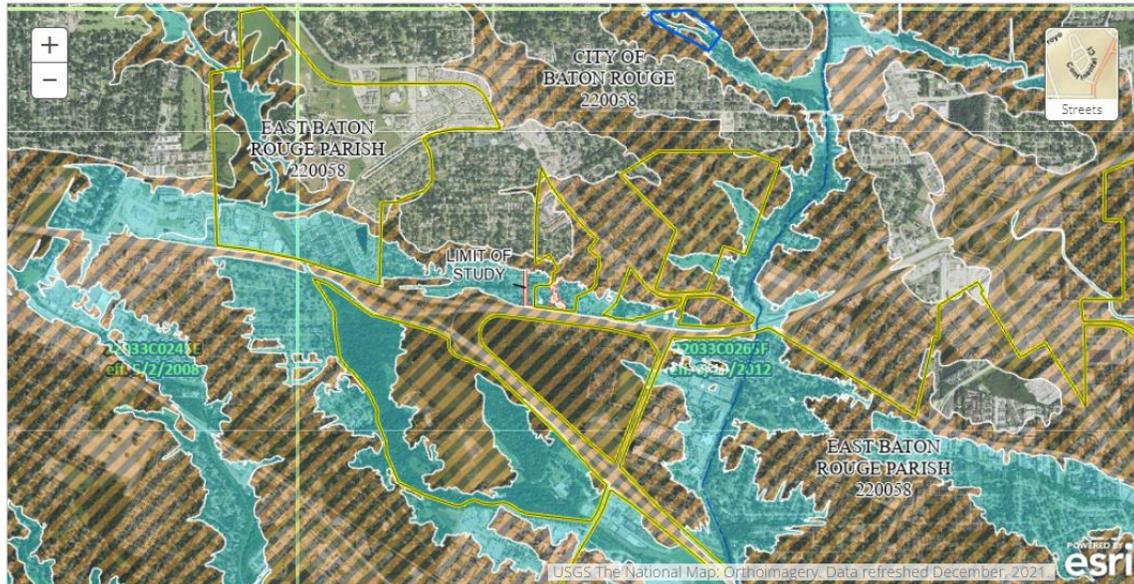
Crisis: 危机

Danger & Opportunity

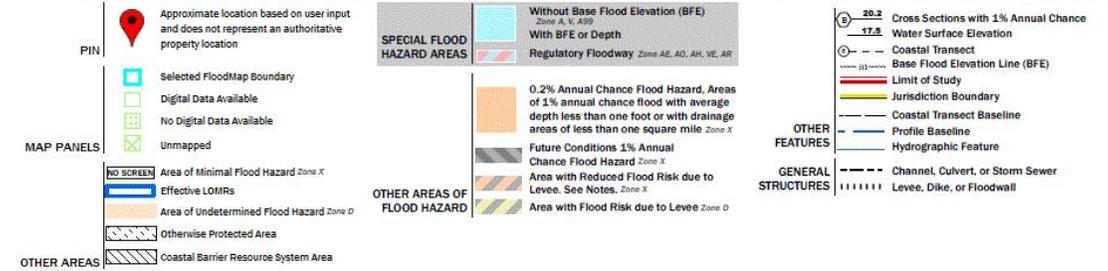


Flood Maps from FEMA (Federal Emergency Management Agency)

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

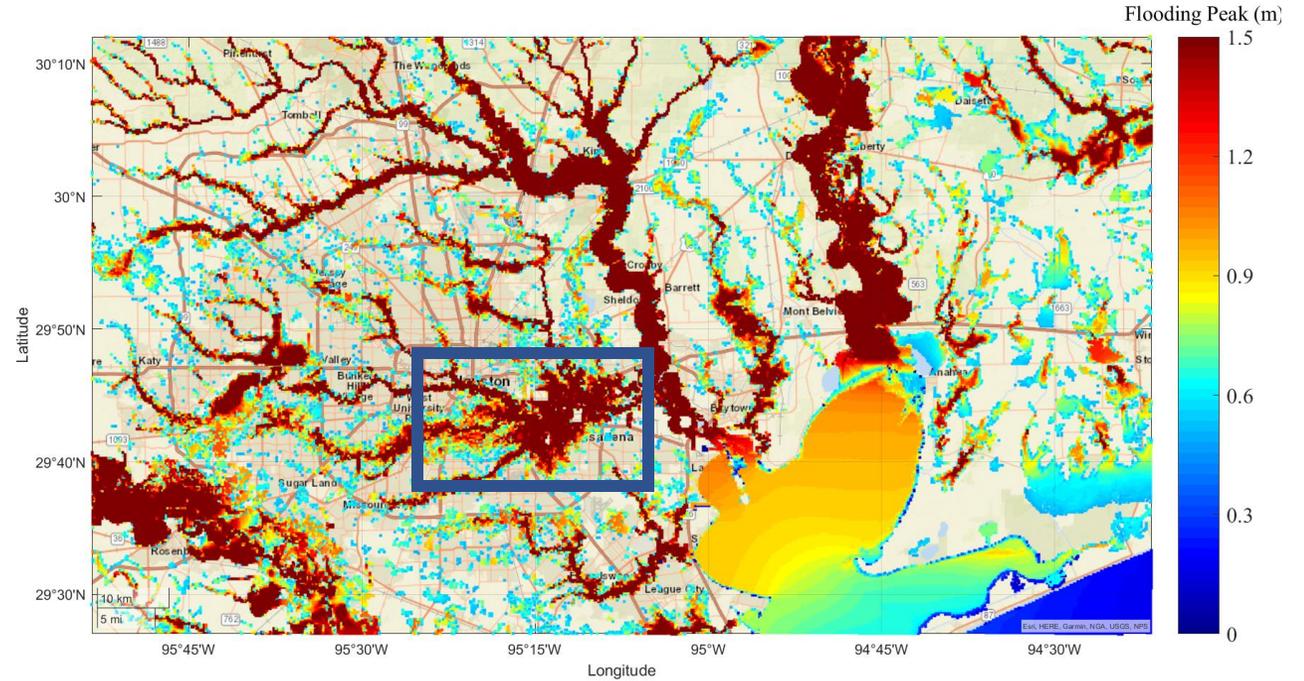
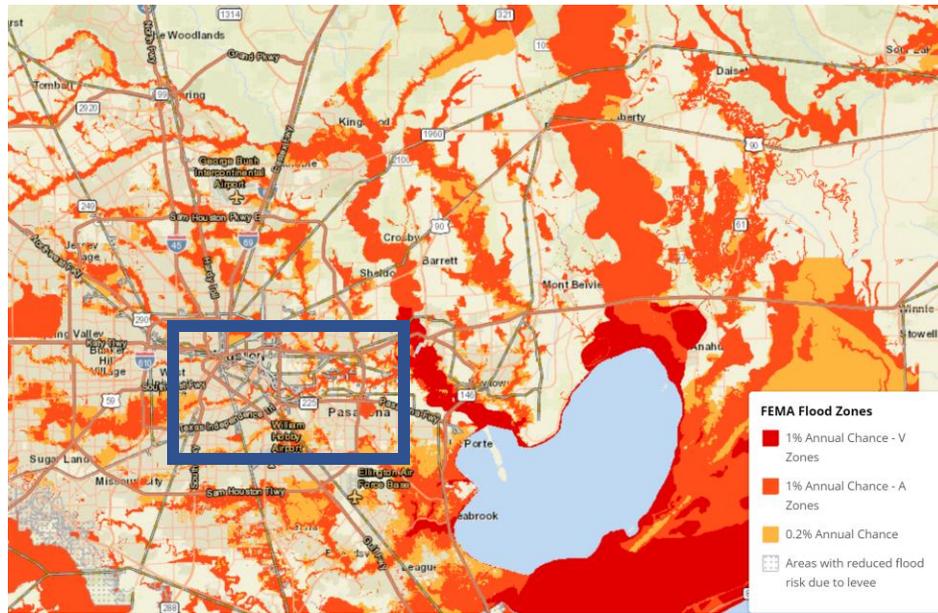


East Baton Rouge Parish



Jefferson Parish

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?

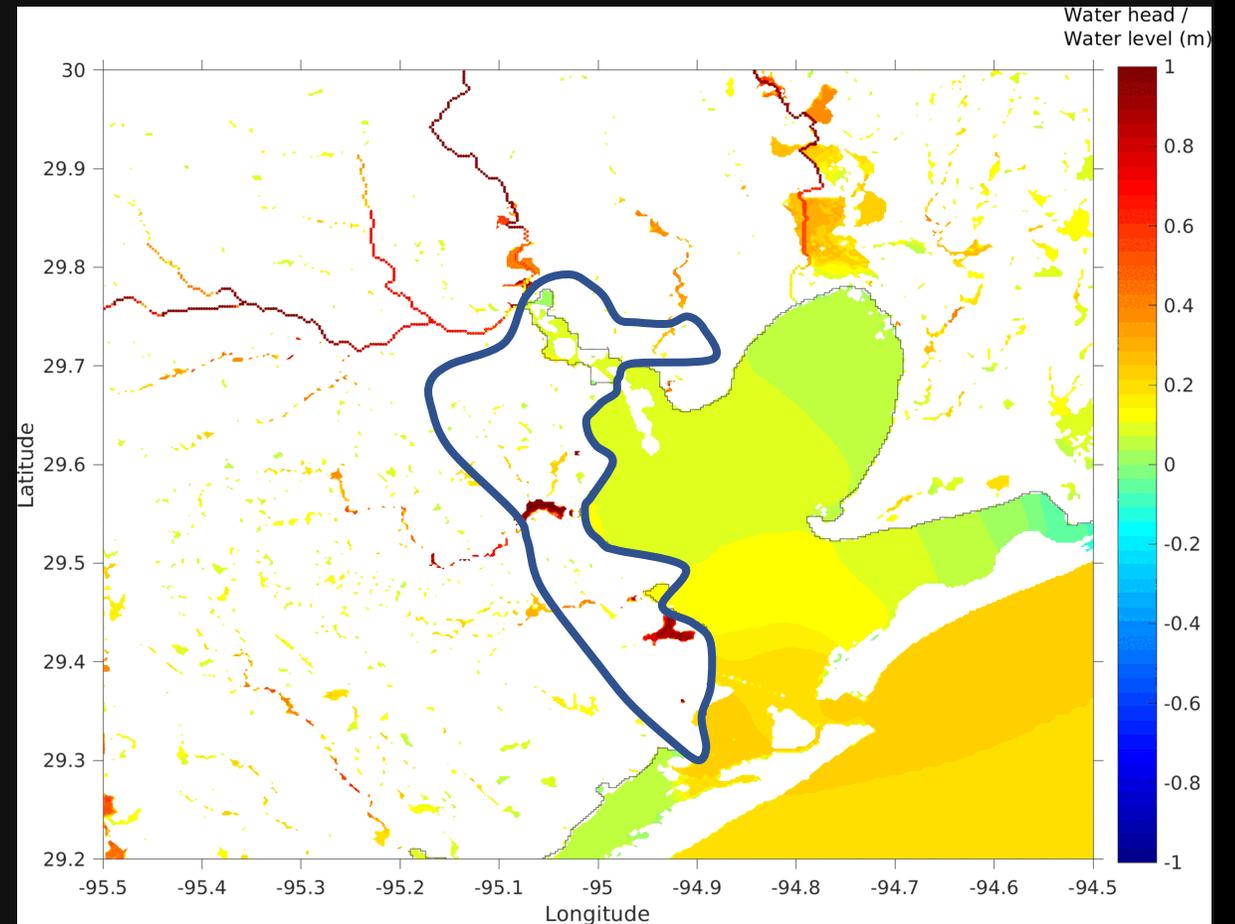
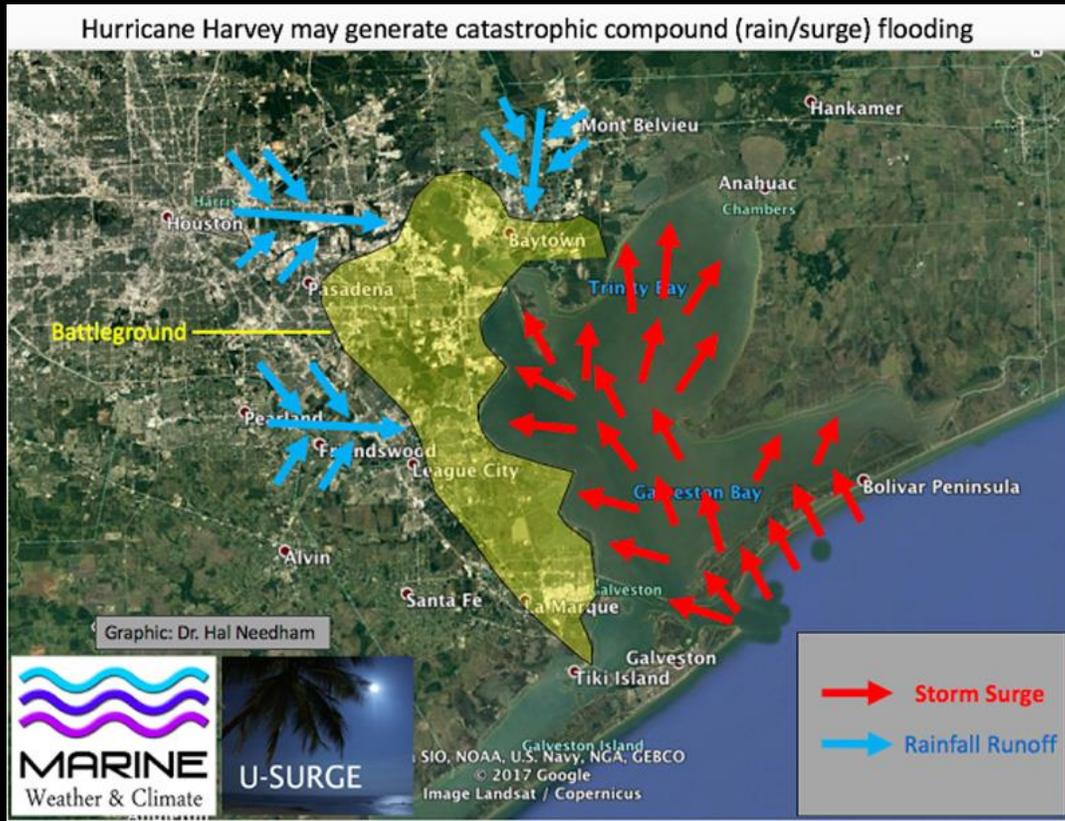
Table 1: Flooding in mapped flood zones

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%

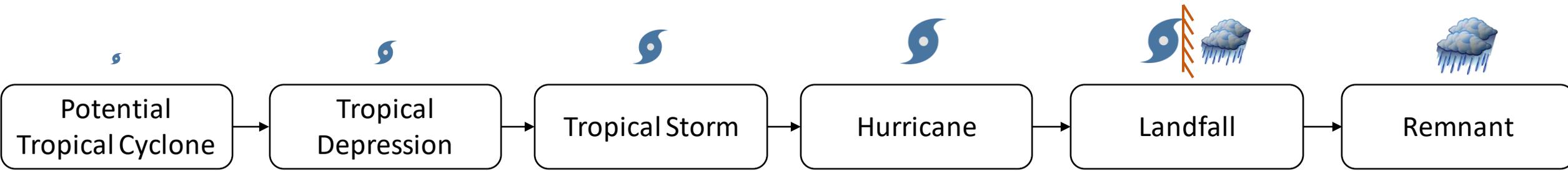
over 50% of estimated inundation occurred outside of any mapped flood zone.

Application: Hurricane Harvey

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

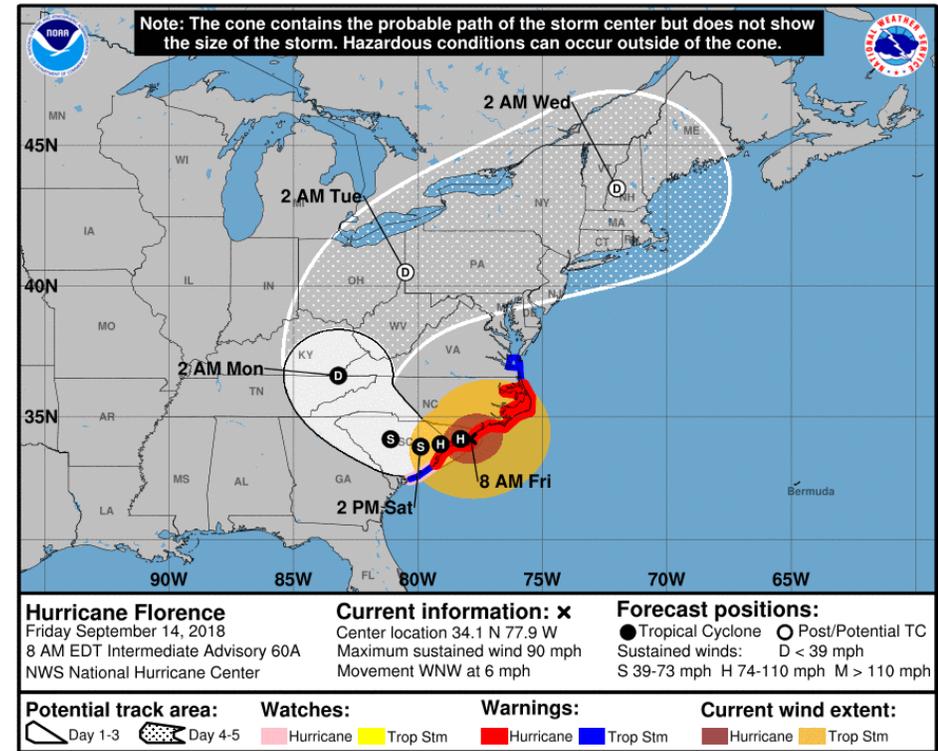


Hurricane Evolution



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



NOAA
National Oceanic and
Atmospheric Administration

NWS
National Weather Service

NCEP
National Centers for
Environmental Prediction

OWP
Office of Water Prediction

NHC
National Hurricane Center

EMC
Environmental Modeling
Center

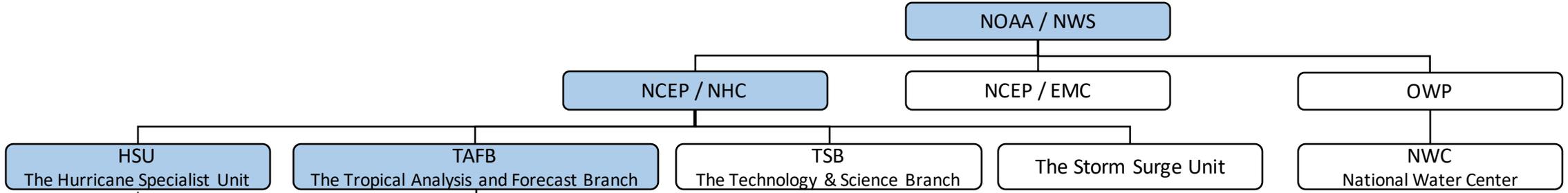
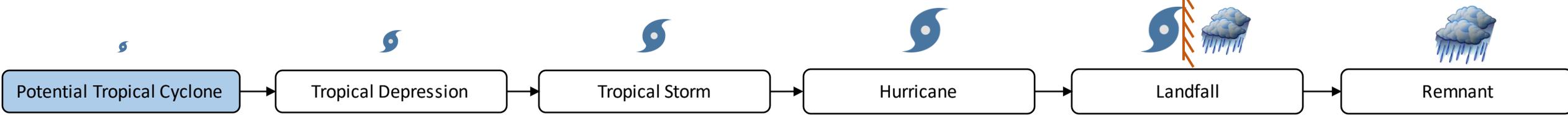
NWC
National Water Center

HSU
The Hurricane Specialist Unit

TAFB
The Tropical Analysis and
Forecast Branch

TSB
The Technology & Science
Branch

**The Storm Surge
Unit**



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)

ZCZC MHTCDP01 ALL
TTAA00 KNHC DDHFFF

POTENTIAL TROPICAL CYCLONE SIX FORECAST/ADVISORY NUMBER 1
NWS NATIONAL HURRICANE CENTER MIAMI FL ALO62018
1500 UTC THU AUG 30 2018

CHANGES IN WATCHES AND WARNINGS WITH THIS ADVISORY...

THE GOVERNMENT OF THE CABO VERDE ISLANDS HAS ISSUED A TROPICAL STORM WARNING FOR THE SOUTHERN ISLANDS OF SANTIAGO...FOGO AND BRAVA.

SUMMARY OF WATCHES AND WARNINGS IN EFFECT...

A TROPICAL STORM WARNING IS IN EFFECT FOR...
* SANTIAGO
* FOGO
* BRAVA

A TROPICAL STORM WARNING MEANS THAT TROPICAL STORM CONDITIONS ARE EXPECTED SOMEWHERE WITHIN THE WARNING AREA WITHIN 36 HOURS.

POTENTIAL TROP CYCLONE CENTER LOCATED NEAR 12.9N 18.4W AT 30/1500Z
POSITION ACCURATE WITHIN 30 NM

PRESENT MOVEMENT TOWARD THE WEST OR 280 DEGREES AT 10 KT

ESTIMATED MINIMUM CENTRAL PRESSURE 1007 MB
MAX SUSTAINED WINDS 25 KT WITH GUSTS TO 35 KT.
WINDS AND SEAS VARY GREATLY IN EACH QUADRANT. RADII IN NAUTICAL MILES ARE THE LARGEST RADII EXPECTED ANYWHERE IN THAT QUADRANT.

REPEAT...CENTER LOCATED NEAR 12.9N 18.4W AT 30/1500Z
AT 30/1200Z CENTER WAS LOCATED NEAR 12.0N 17.9W

FORECAST VALID 31/0000Z 13.2N 20.3W...TROPICAL DEPRESSION
MAX WIND 30 KT...GUSTS 40 KT.

FORECAST VALID 31/1200Z 12.5N 22.0W
MAX WIND 35 KT...GUSTS 45 KT.
34 KT...30NE 30SE 05W 30NW.

FORECAST VALID 01/0000Z 14.0N 24.0W
MAX WIND 45 KT...GUSTS 55 KT.
34 KT...50NE 40SE 30SW 50NW.

FORECAST VALID 01/1200Z 15.0N 27.0W
MAX WIND 55 KT...GUSTS 65 KT.
50 KT...50NE 50SE 05W 50NW.
34 KT...50NE 50SE 40SW 70NW.

FORECAST VALID 02/1200Z 16.5N 33.0W
MAX WIND 65 KT...GUSTS 80 KT.
50 KT...50NE 40SE 30SW 50NW.
34 KT...50NE 70SE 60SW 90NW.

EXTENDED OUTLOOK. NOTE...ERRORS FOR TRACK HAVE AVERAGED NEAR 150 NM ON DAY 4 AND 175 NM ON DAY 5...AND FOR INTENSITY NEAR 15 KT EACH DAY

OUTLOOK VALID 03/1200Z 18.5N 38.0W
MAX WIND 65 KT...GUSTS 80 KT.

OUTLOOK VALID 04/1200Z 20.0N 42.0W
MAX WIND 65 KT...GUSTS 80 KT.

REQUEST FOR 3 HOURLY SHEP REPORTS WITHIN 300 MILES OF 12.9N 18.4W

NEXT ADVISORY AT 30/2100Z

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FORECASTER AVILA

NNNN

ZCZC MHTCDP01 ALL
TTAA00 KNHC DDHFFF

BULLETIN
Potential Tropical Cyclone Six Advisory Number 1
NWS National Hurricane Center Miami FL ALO62018
1100 AM AST THU AUG 30 2018

...TROPICAL STORM CONDITIONS EXPECTED OVER THE SOUTHERN CABO VERDE ISLANDS ON FRIDAY...

SUMMARY OF 1100 AM AST...1500 UTC...INFORMATION

LOCATION...12.9N 18.4W
ABOUT 425 NM...680 NM ESE OF THE SOUTHERNMOST CABO VERDE ISLANDS
MAXIMUM SUSTAINED WINDS...30 MPH...45 KNOTS
PRESENT MOVEMENT...W OR 280 DEGREES AT 12 MPH...19 KMPH
MINIMUM CENTRAL PRESSURE...1007 MB...29.74 INCHES

WATCHES AND WARNINGS

A TROPICAL STORM WARNING IS IN EFFECT FOR...
* Santiago
* Fogo
* Brava

A Tropical Storm Warning means that tropical storm conditions are expected somewhere within the warning area within 36 hours.

For storm information specific to your area, please monitor products issued by your national meteorological service.

DISCUSSION AND OUTLOOK

AT 1100 AM AST (1500 UTC), the disturbance was centered near latitude 12.9 north, longitude 18.4 west. The system is moving toward the west near 12 mph (19 km/h), and this general motion with a gradual turn toward the west-northwest is expected to continue during the next few days. On the forecast track, the disturbance is expected to move near or over the southern Cabo Verde Islands on Friday.

Maximum sustained winds are near 30 mph (45 km/h) with higher gusts. Some strengthening is forecast during the next 48 hours, and the disturbance is expected to become a tropical storm during the next day or so.

Environmental conditions are favorable for the system to become a tropical cyclone tonight or Friday.

- Formation chance through 48 hours...high...80 percent
- Formation chance through 5 days...high...50 percent

The estimated minimum central pressure is 1007 mb (29.74 inches).

HAZARDS AFFECTING LAND

RAINFALL: The system could produce total rain accumulations of 4 to 8 inches across the southern Cabo Verde Islands. These rains could produce life-threatening flash floods.

WINDS: Tropical storm conditions are expected in the southern Cabo Verde Islands on Friday.

NEXT ADVISORY

Next intermediate advisory at 200 PM AST.
Next complete advisory at 500 PM AST.

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FORECASTER AVILA

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ZCZC MHTCDP01 ALL
TTAA00 KNHC DDHFFF

Potential Tropical Cyclone Six Discussion Number 1
NWS National Hurricane Center Miami FL ALO62018
1100 AM AST THU AUG 30 2018

The area of low pressure that moved off the coast of Africa has continued to become better organized, and is producing a large area of disturbed weather with gusty winds, but currently lacks a well-defined center. Environmental conditions are favorable for additional development, and a tropical depression or a tropical storm could form on any time today or Friday. Given the high chances that this system could bring tropical storm conditions to a portion of the southern Cabo Verde Islands, advisories have been initiated on Potential Tropical Cyclone Six. Most of the intensity guidance calls for strengthening and so does the NHC forecast.

The system is embedded within the westerly trades and this flow pattern will steer the disturbance toward the west or west-northwest during the next few days. By the end of the forecast period, a turn toward the northeast should begin as the system reaches a weakness in the subtropical high. This is consistent with the output of the global models.

FORECAST POSITIONS AND MAX WINDS

12N11	30/1500Z	12.9N	18.4W	25	KT	30	MPH	...POTENTIAL TROP CYCLONE
12N11	31/0000Z	13.2N	20.1W	30	KT	35	MPH	...TROPICAL DEPRESSION
24N	31/1200Z	13.5N	22.0W	35	KT	40	MPH	
36N	01/0000Z	14.0N	24.0W	45	KT	50	MPH	
48N	01/1200Z	15.0N	27.0W	55	KT	65	MPH	
72N	02/1200Z	16.5N	33.0W	65	KT	75	MPH	
94N	03/1200Z	18.5N	38.0W	65	KT	75	MPH	
120N	04/1200Z	20.0N	42.0W	65	KT	75	MPH	

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Forecaster Avila

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ZCZC MHTCDP01 ALL
TTAA00 KNHC DDHFFF

POTENTIAL TROPICAL CYCLONE SIX WIND SPEED PROBABILITIES NUMBER 1
NWS NATIONAL HURRICANE CENTER MIAMI FL ALO62018
1500 UTC THU AUG 30 2018

2 INDICATES COORDINATED UNIVERSAL TIME (GREENWICH)
ATLANTIC STANDARD TIME (AST)...SUBTRACT 4 HOURS FROM 2 TIME
EASTERN DAYLIGHT TIME (EDT)...SUBTRACT 4 HOURS FROM 2 TIME
CENTRAL DAYLIGHT TIME (CDT)...SUBTRACT 5 HOURS FROM 2 TIME

WIND SPEED PROBABILITY TABLE FOR SPECIFIC LOCATIONS
CHANCES OF SUSTAINED (1-HOUR AVERAGE) WIND SPEEDS OF AT LEAST
...34 KT (39 MPH)...63 MPH)...
...50 KT (58 MPH)...93 MPH)...
...64 KT (74 MPH)...119 MPH)...

FOR LOCATIONS AND TIME PERIODS DURING THE NEXT 5 DAYS

PROBABILITIES FOR LOCATIONS ARE GIVEN AS O(CEP) WHERE
O= 0% IS THE PROBABILITY OF THE EVENT BEGINNING DURING
AN INDIVIDUAL TIME PERIOD (ONSET PROBABILITY)
(CP) IS THE PROBABILITY OF THE EVENT OCCURRING BETWEEN
12Z THU AND THE FORECAST HOUR (CUMULATIVE PROBABILITY)

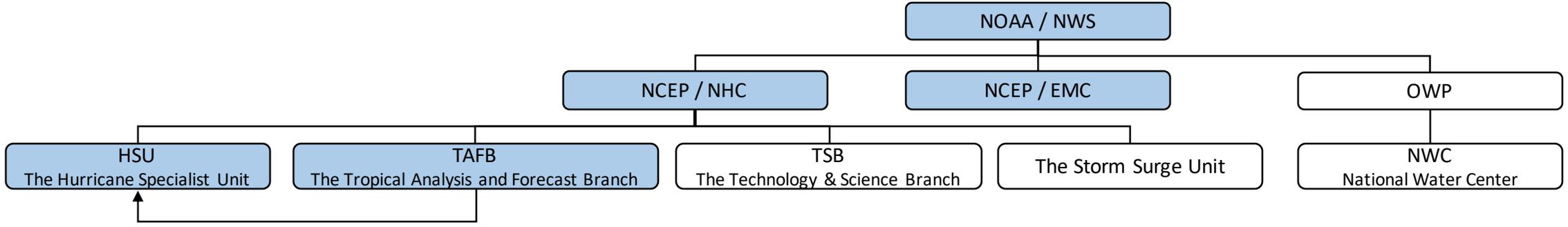
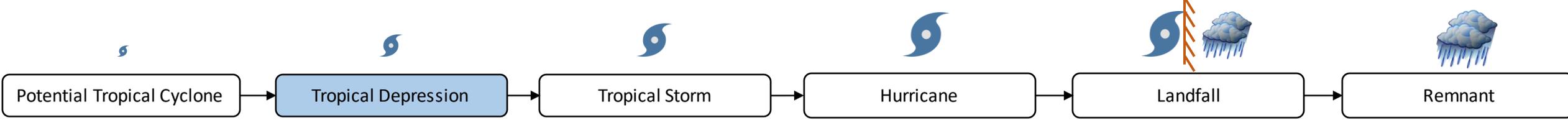
PROBABILITIES ARE GIVEN IN PERCENT
X INDICATES PROBABILITIES LESS THAN 1 PERCENT
PROBABILITIES FOR 34 KT AND 50 KT ARE SHOWN AT A GIVEN LOCATION WHEN
THE 5-DAY CUMULATIVE PROBABILITY IS AT LEAST 3 PERCENT
PROBABILITIES FOR 34...50...64 KT SHOWN WHEN THE 5-DAY
64-KT CUMULATIVE PROBABILITY IS AT LEAST 1 PERCENT.

... WIND SPEED PROBABILITIES FOR SELECTED LOCATIONS ...

PERIODS	FROM THU		FROM FRI		FROM SAT		FROM SUN		FROM MON		FROM TUE		
	12Z	00Z	12Z	00Z	12Z	00Z	12Z	00Z	12Z	00Z	12Z	00Z	
LOCATIONS	(12)	(24)	(36)	(48)	(72)	(96)	(120)						
REIENA GABARR	34	X	X	2	2	12	14	2	16	X	16	X	
PRADA CVI	34	X	2	2	30	32	7	39	1	40	X	40	
PRADA CVI	50	X	X	4	4	2	6	1	7	X	7	X	
SANTA ANA CVI	34	X	2	2	12	14	1	17	1	18	X	18	

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FORECASTER AVILA

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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	GS14D-VAR EnKF hybrid	Simplified Arakawa Schubert	6 hr (240 hr) 00/06/12/18 UTC	Track and intensity
*EMX/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
EGR/EGR/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 (16.6-2km)	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.

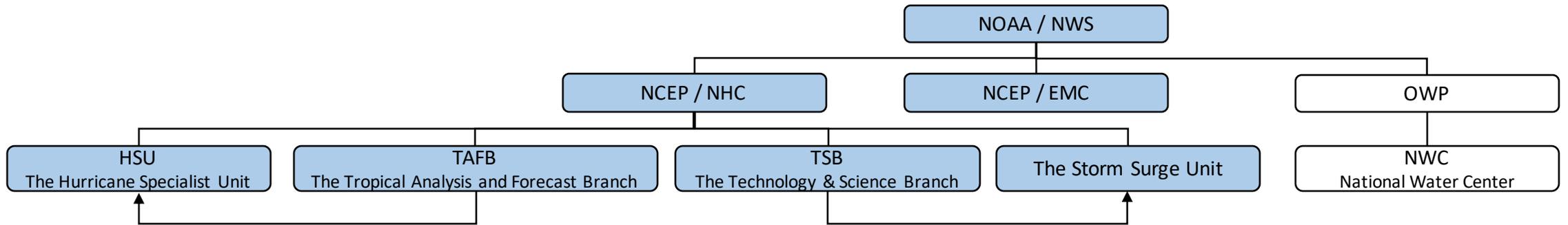
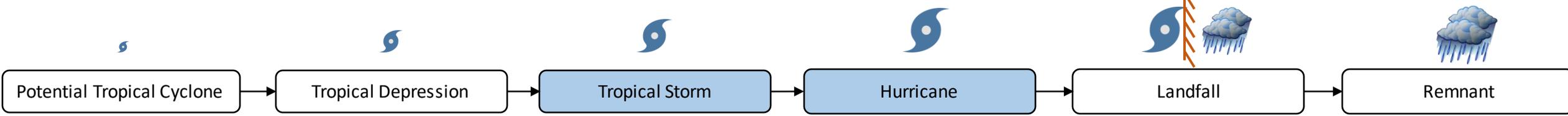
ATCF ID	Model Name or Type	Horizontal Resolution	Vertical Levels and Coordinates	Data Assimilation	Perturbation or Consensus Methods	Cycle/Run Frequency	Ensemble Members	NHC Forecast Parameter(s)
AEMNAEM	Global Ensemble Forecast System	~33 km for 1st 192 hr ~53 km for 192-384 hr	64 Hybrid Sigma-pressure	OSI3D-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
*UEMNUEM	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
*EEMNEEM2	ECMWF EPS	~18 km	91 Hybrid Sigma-pressure	4D-VAR	Leading singular vectors based initial perturbations	6 hr (120 hr) 00/06/12/18 UTC	50	Track and intensity
*FSSE	Florida State Super Ensemble				Corrected consensus	6 hr (120 hr) 00/06/12/18 UTC		Track and intensity
*HCCA	HIP Corrected Consensus Approach				Corrected consensus	6 hr (120 hr) 00/06/12/18 UTC	AEM/AVNI CTX/DSHP EGR/EMX2 HWRF LOEM	Track and intensity
*GFEX	2 model consensus				Simple consensus	6 hr (120 hr) 00/06/12/18 UTC	AVNI EMX1	Track
TYCN (Atlantic) (TYCA)	Variable consensus				Simple consensus, minimum 2 members	6 hr (120 hr) 00/06/12/18 UTC	AVNI EGR/ HWRF EMI/ CTX/ EMNI	Track
TYCN (E. Pacific) (TYCE)	Variable consensus				Simple consensus, minimum 2 members	6 hr (120 hr) 00/06/12/18 UTC	AVNI EGR/ HWRF EMI/ CTX/ EMNI, HMI	Track
TVCX	Variable consensus				Simple consensus, minimum 2 members, double-weighted EMX1	6 hr (120 hr) 00/06/12/18 UTC	AVNI EMX1 HWRF CTX/ EPS	Track
RVCN	Wind Radii Consensus				Multi-model wind radii, bias corrected initial wind	6 hr (120 hr) 00/06/12/18 UTC	AHNI, HWFI, EMI, CHCI (FY20F3, HWRF, ECMWF, COAMPS-TC)	34-kt wind radii
ICCN	Intensity consensus				Simple consensus, all 4 must be present	6 hr (120 hr) 00/06/12/18 UTC	DSHP, LOEM, HWFI, HMNI	Intensity
IVCN	Intensity variable consensus				Simple consensus, minimum 2 members	6 hr (120 hr) 00/06/12/18 UTC	DSHP, LOEM, HWFI, HMNI, CTX	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 Parameter(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 parameters 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>



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.

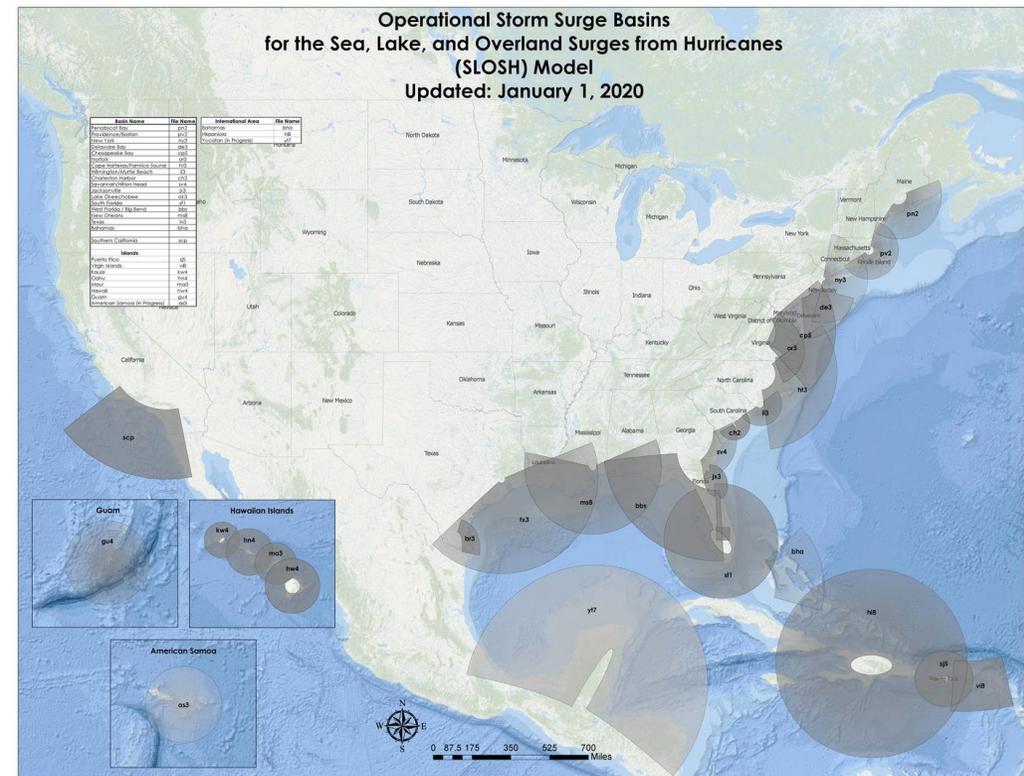
SLOSH: The Sea, Lake and Overland Surges from Hurricanes model

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.

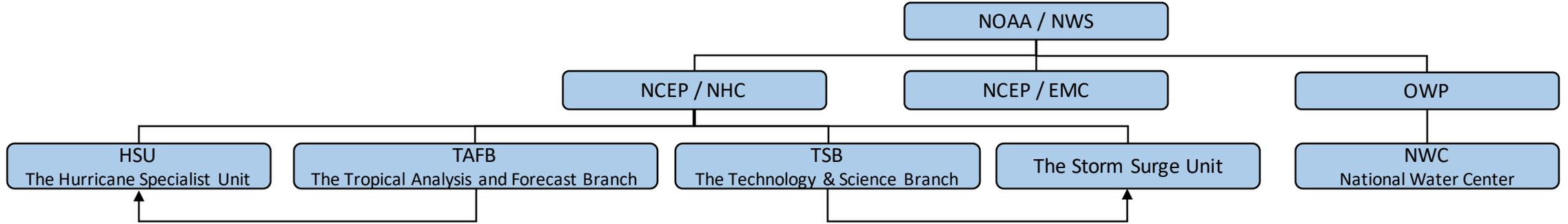
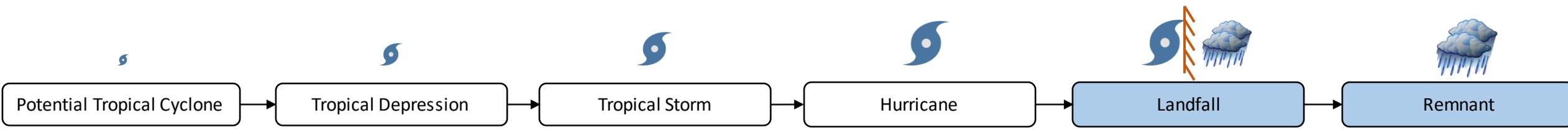
Limitations:

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



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

SLOSH model coverage



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 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)



+

Different types of flooding during hurricane

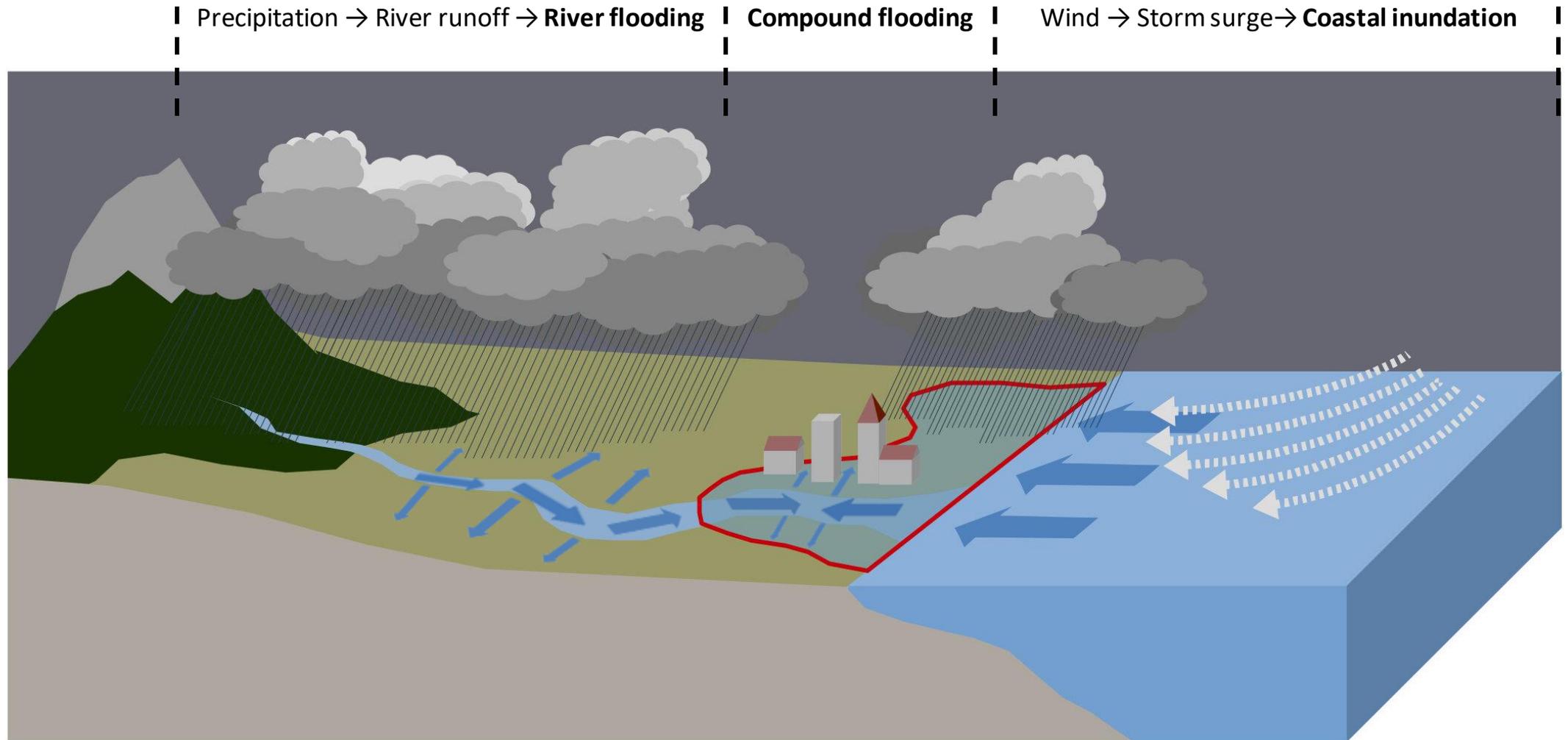


Image originally published on phys.org: <https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html>
Credit: Douglas Maraun

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.

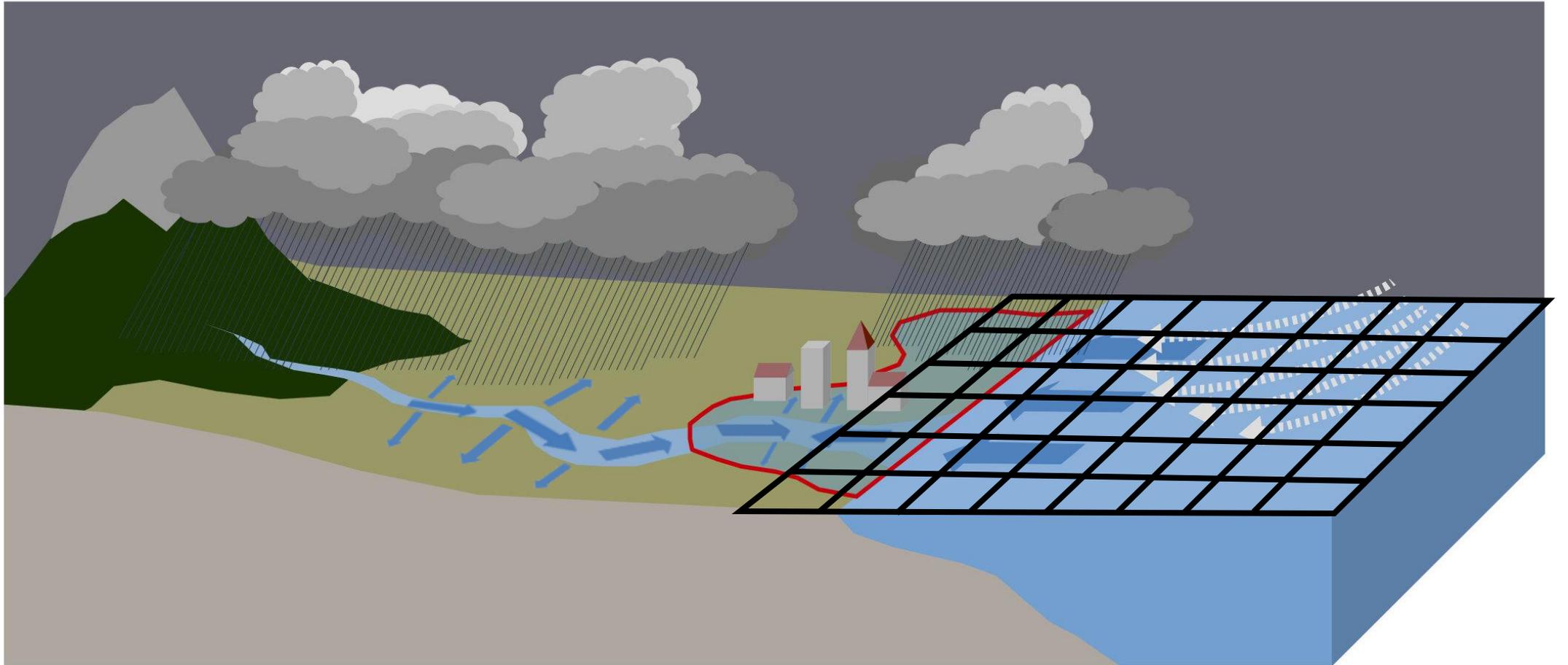


Image originally published on phys.org: <https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html>
Credit: Douglas Maraun

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.

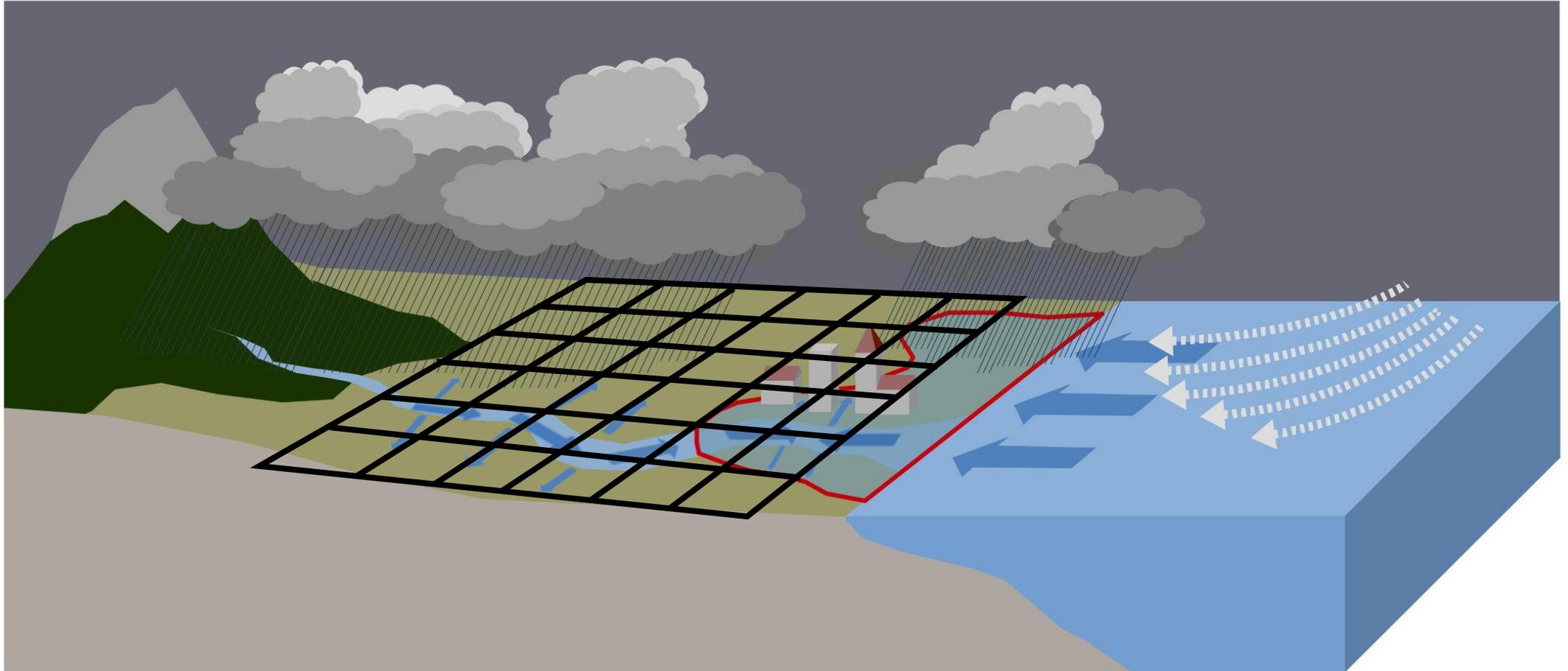
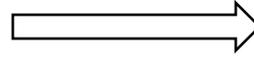


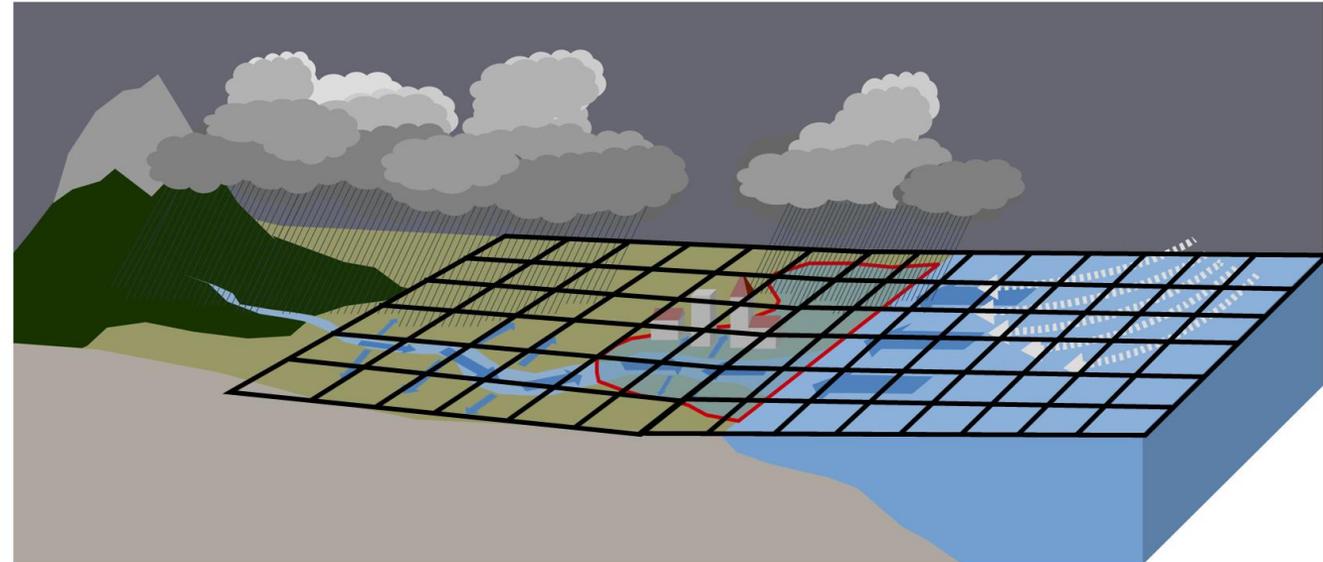
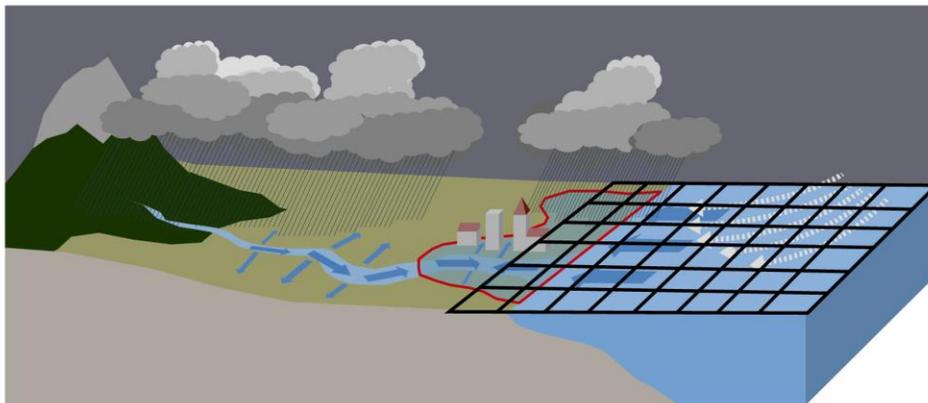
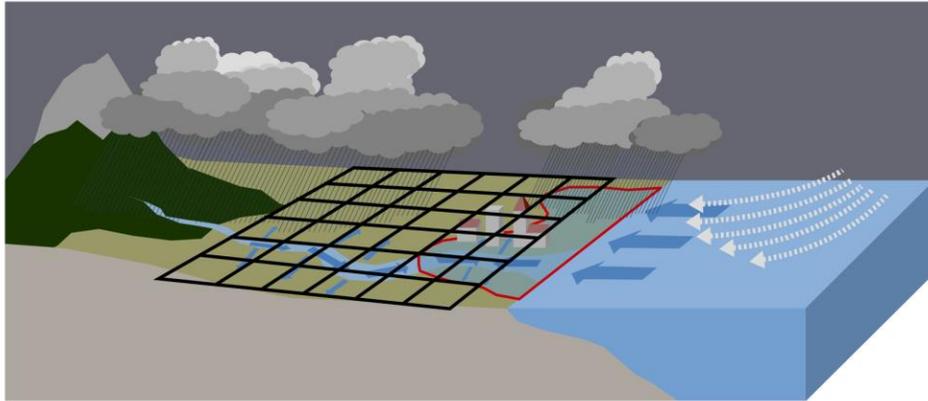
Image originally published on phys.org: <https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html>
Credit: Douglas Maraun

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.

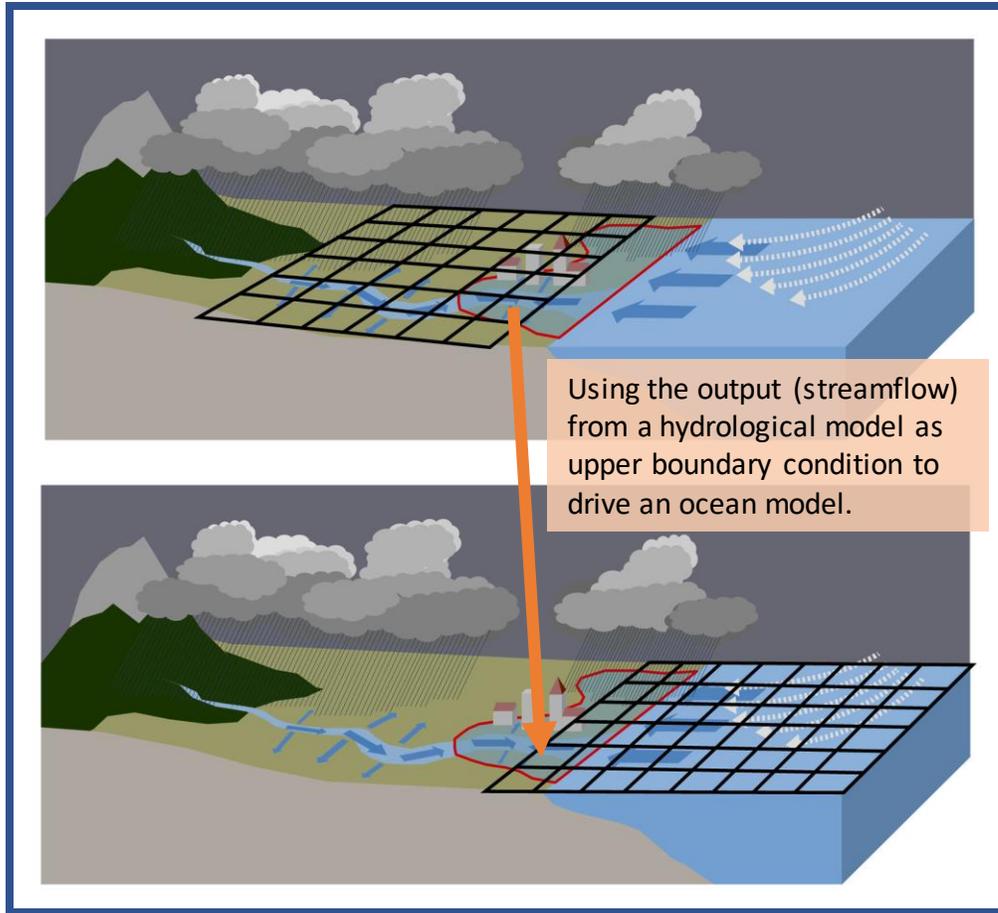


Highlight the need for an integrated modeling system to simulate the flooding event on the land and in the ocean simultaneously.



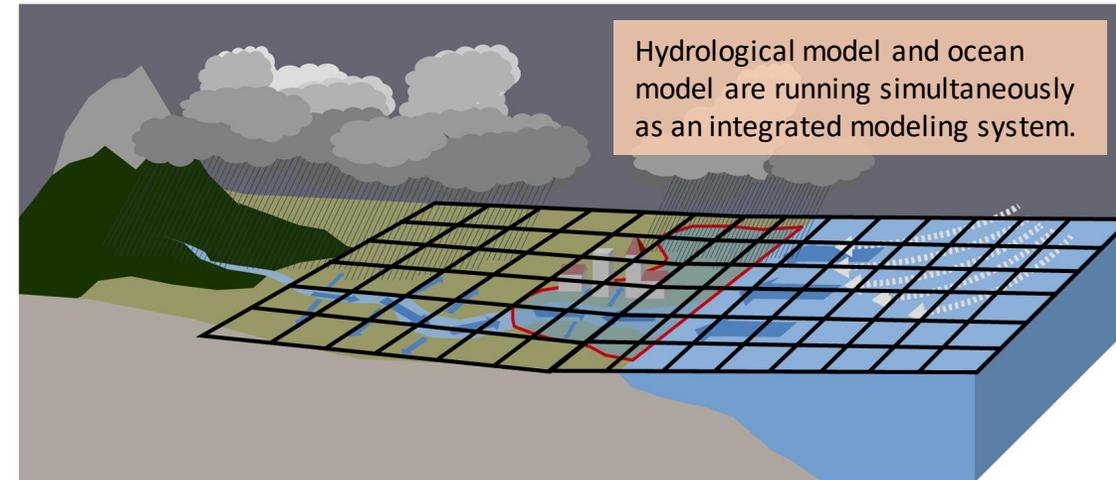
Modeling of hurricane-induced flooding

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

Dynamically coupled hydrological-ocean modeling system

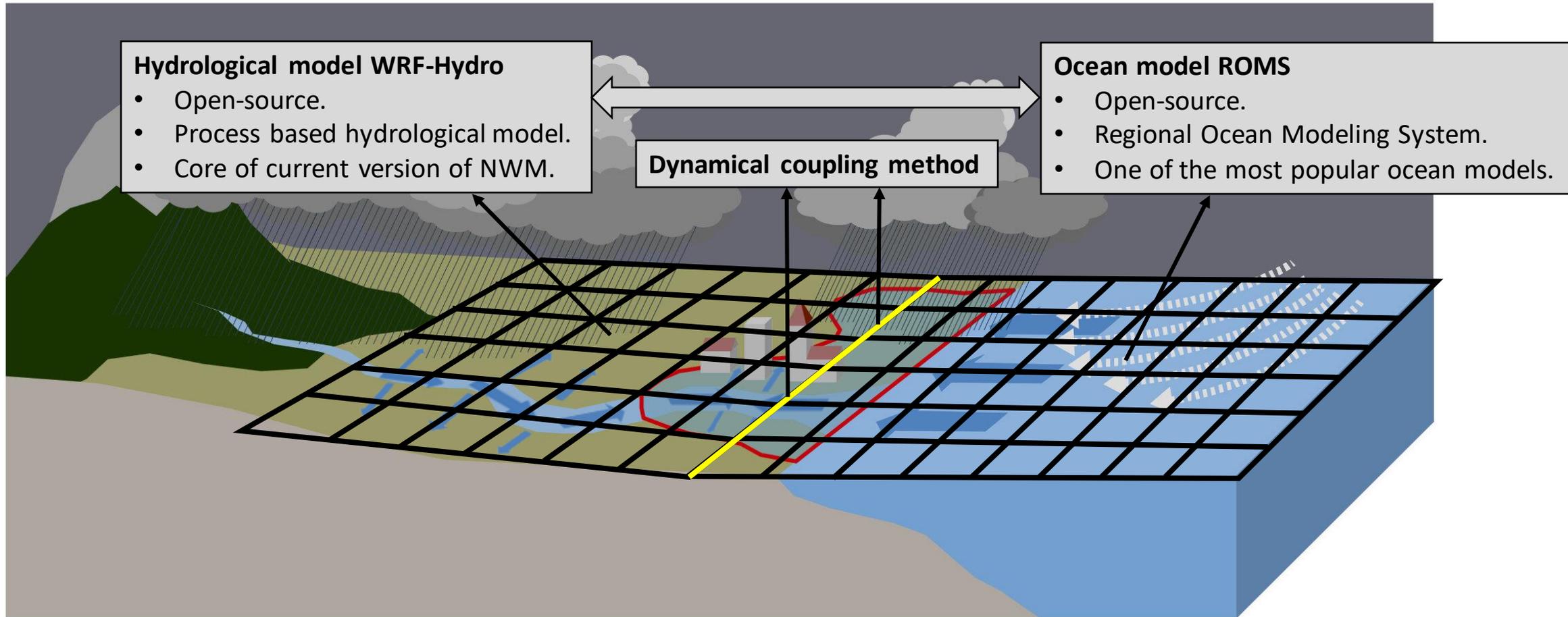
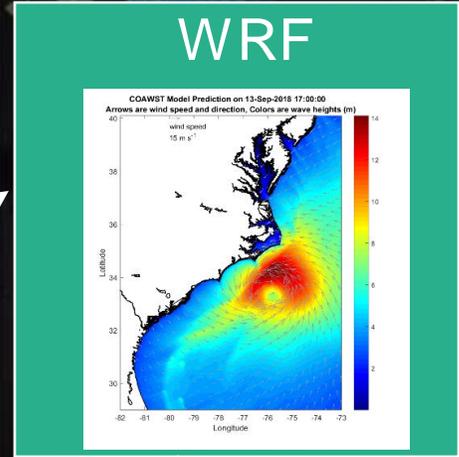


Image originally published on phys.org: <https://phys.org/news/2019-09-global-simulations-uk-northern-europe.html>
Credit: Douglas Maraun

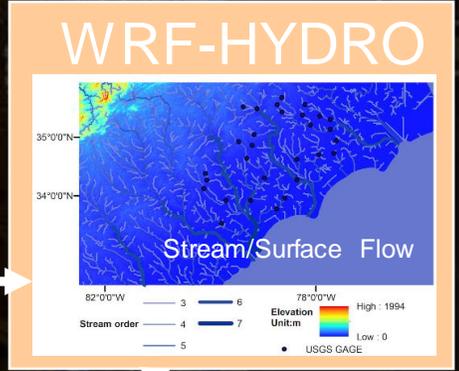
COAWST

Coupled Ocean Atmosphere Wave & Sediment Transport Modeling System

U_{wind} , V_{wind} , RH, T_{air} ,
cloud, rain, evap,
SWrad, Lwrad



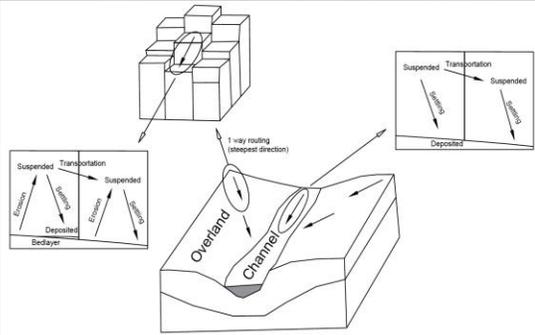
H_{wave} , L_{pwave} , T_{psurf}
MCT
 U_{wind} , V_{wind}



MCT

Wind speed
SST

U_{wind} , V_{wind} , P_{atm} , RH, T_{air} ,
cloud, rain, evap, SWrad, Lwrad
LH, HFX, U_{stress} , V_{stress}

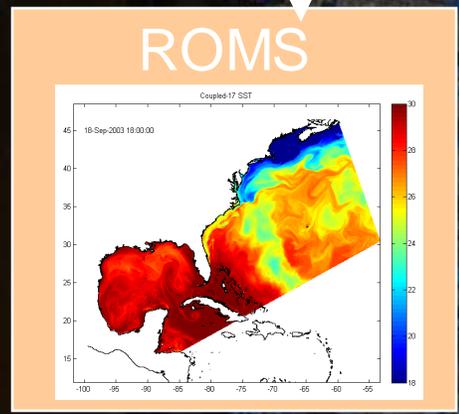


Water Levels

MCT

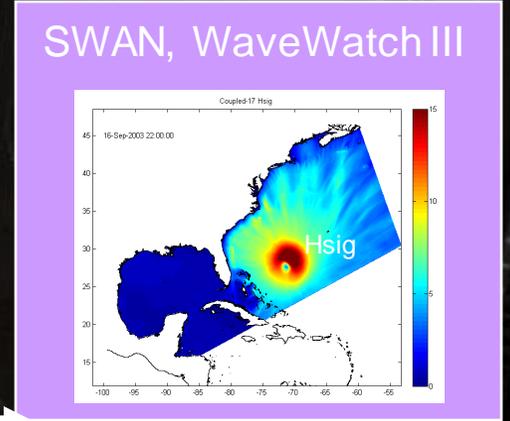
Sediment (WRF-Hydro-Sed)

Streamflow,
Water
Levels,
Vertical
fluxes

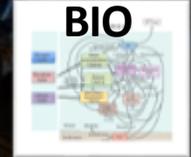


u_s , v_s , h , bath, Z_0

MCT

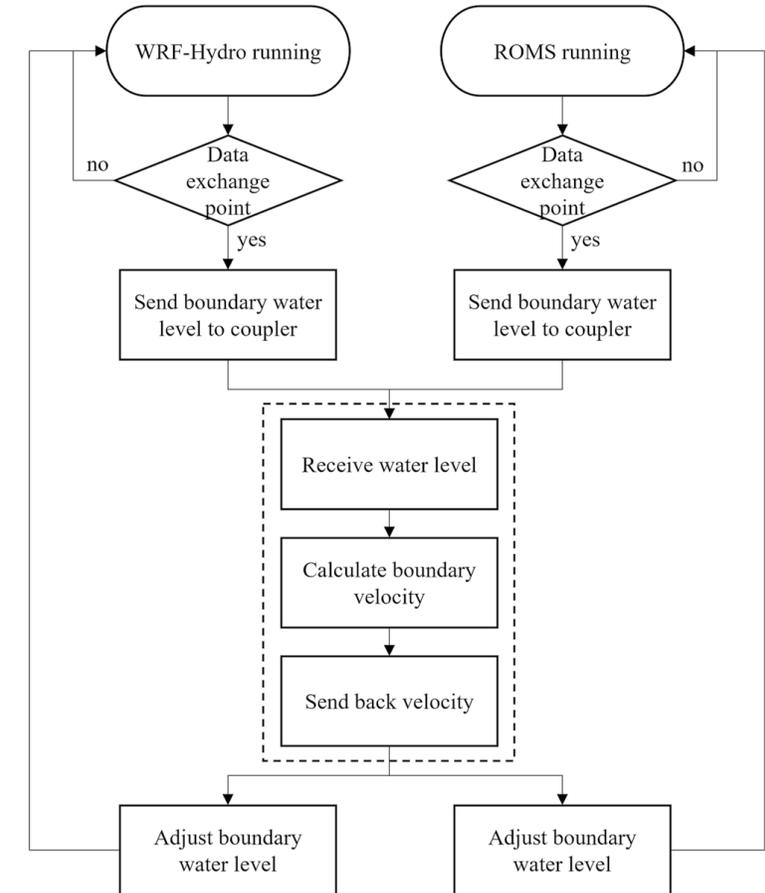
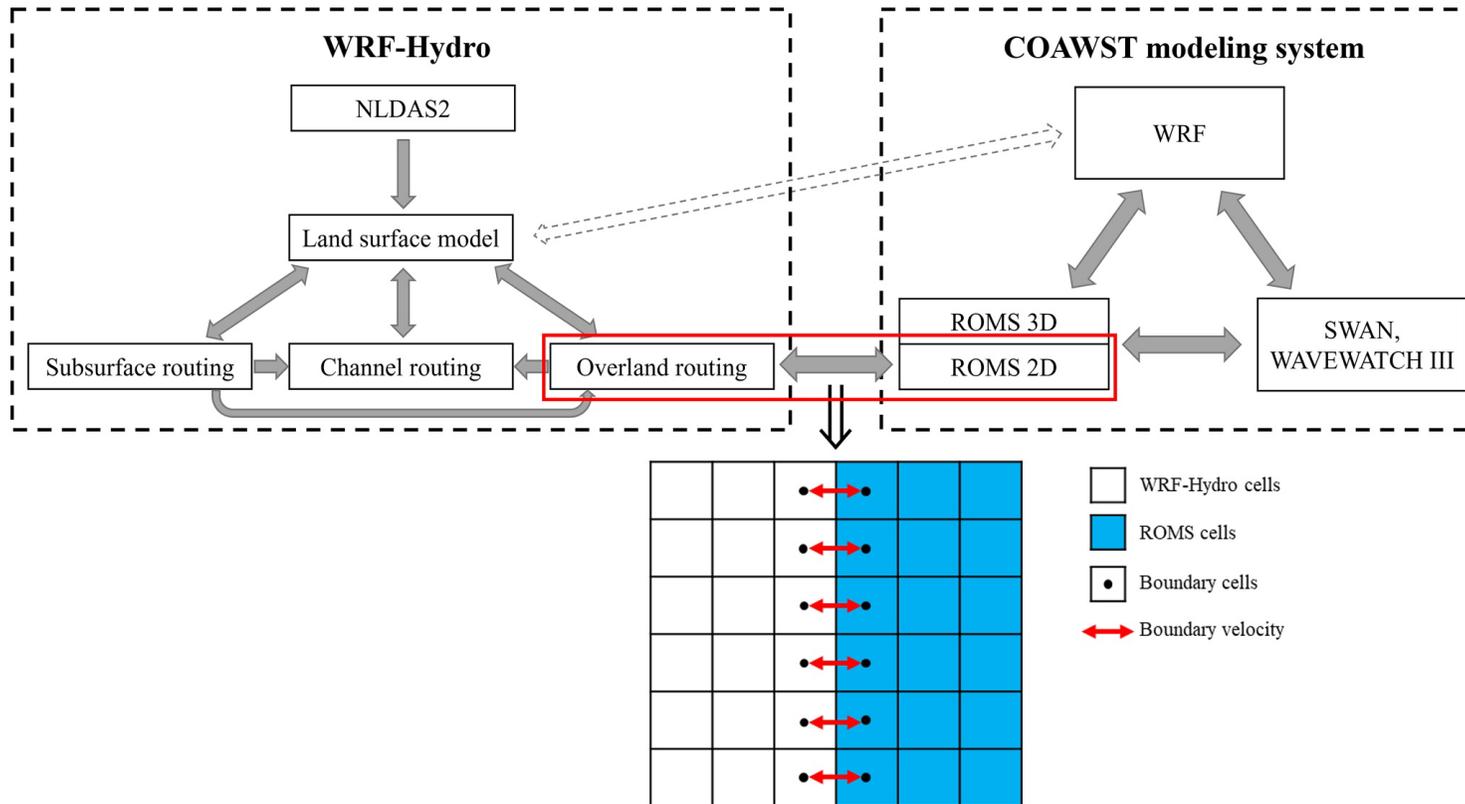


H_{wave} , L_{mwave} , L_{pwave} , D_{wave} ,
 T_{psurf} , T_{mbott} , Q_b ,
Diss_{bot}, Diss_{surf}, Diss_{wcap},
 U_{bot}



Dynamically coupled hydrological-ocean modeling system

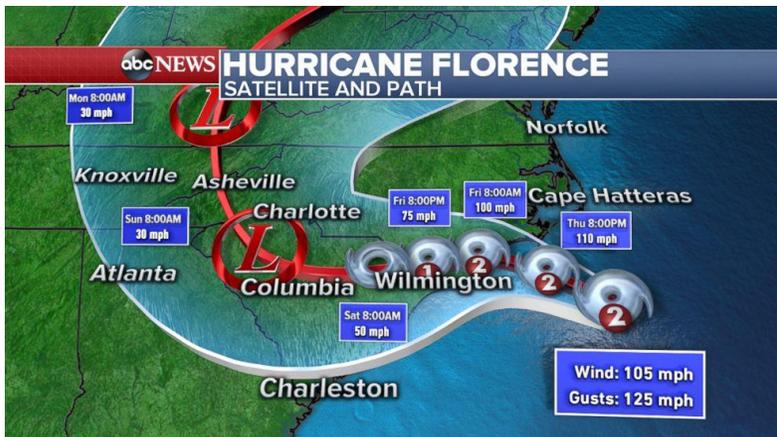
- Computation domain is divided into two subdomains- one for WRF-Hydro and the other for ROMS.
- The two models exchange water level information on every connected cell along the boundary.
- A coupler is applied to assure the two models have the same velocity along the interface boundary.
- The dynamic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



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>



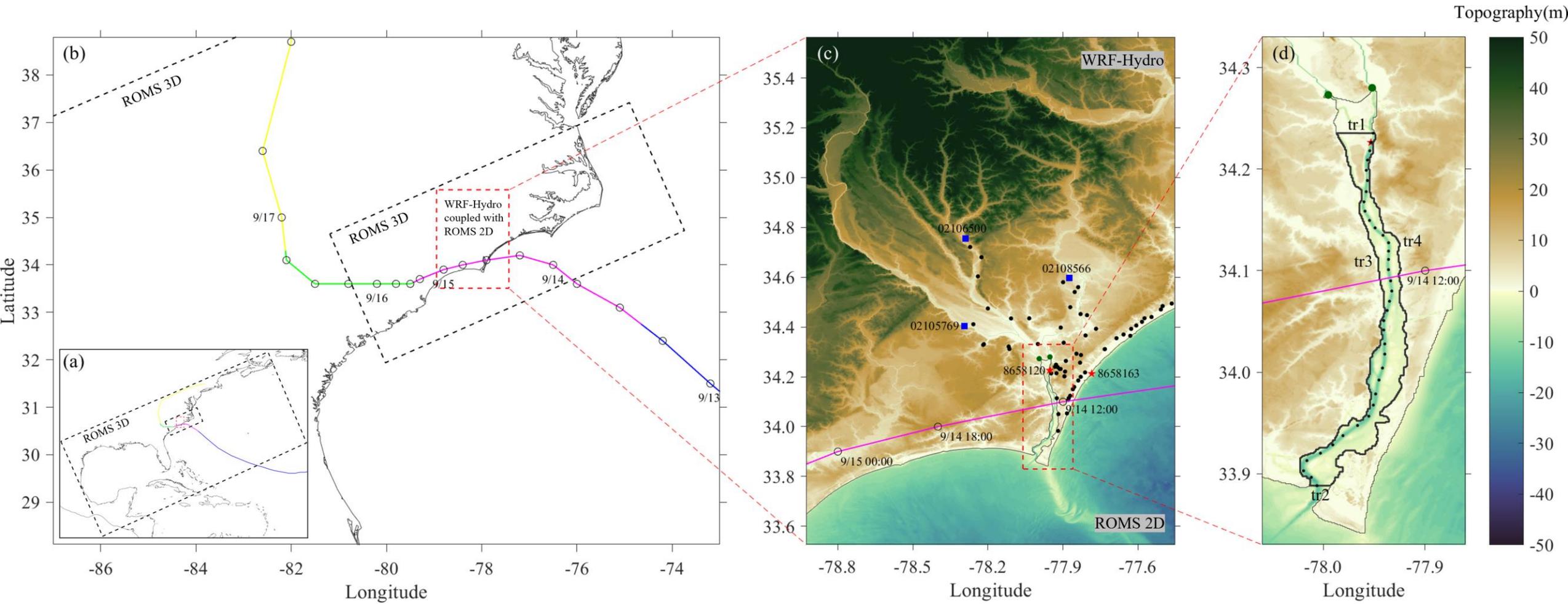
Satellite image of Florence.
<https://www.bbc.com/news/world-us-canada-45511312>



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/>

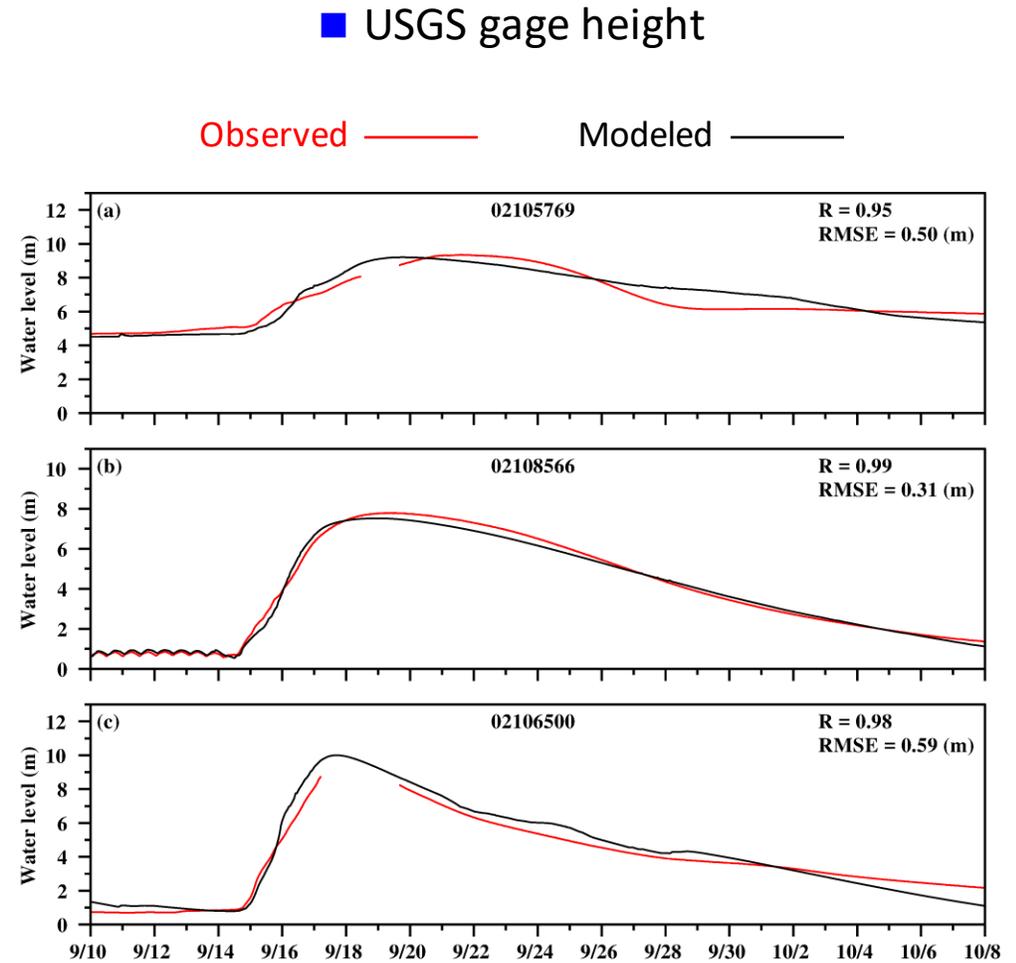
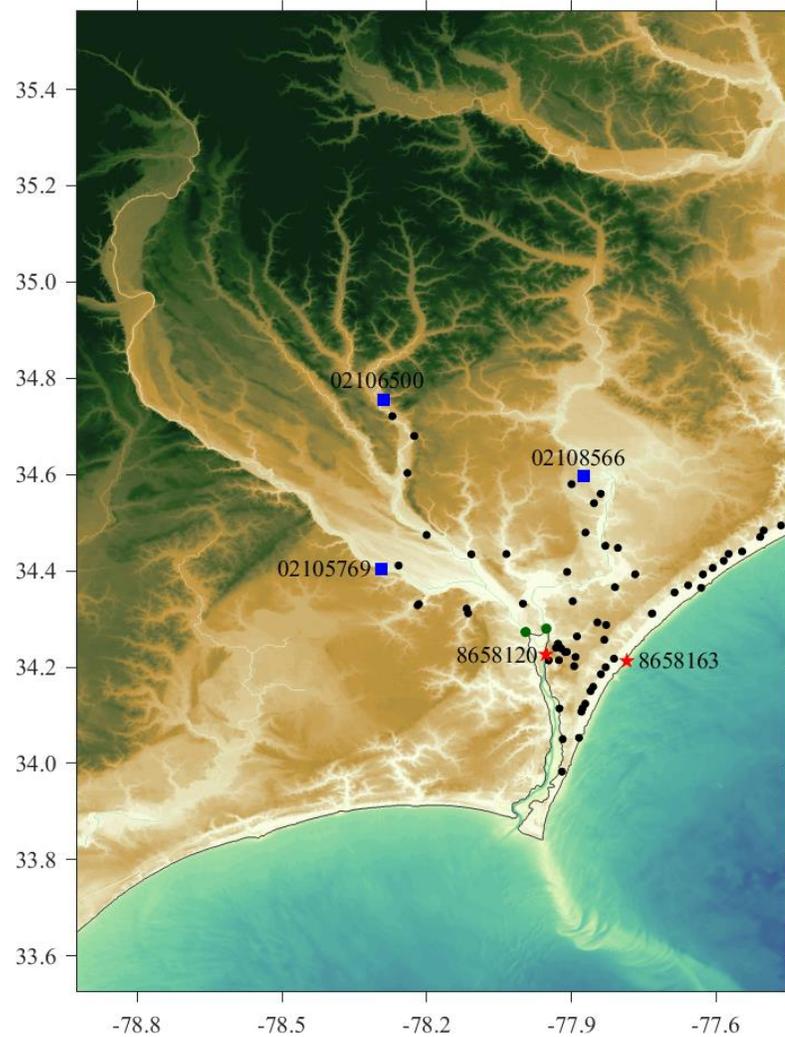
Application: Hurricane Florence

Model set-up



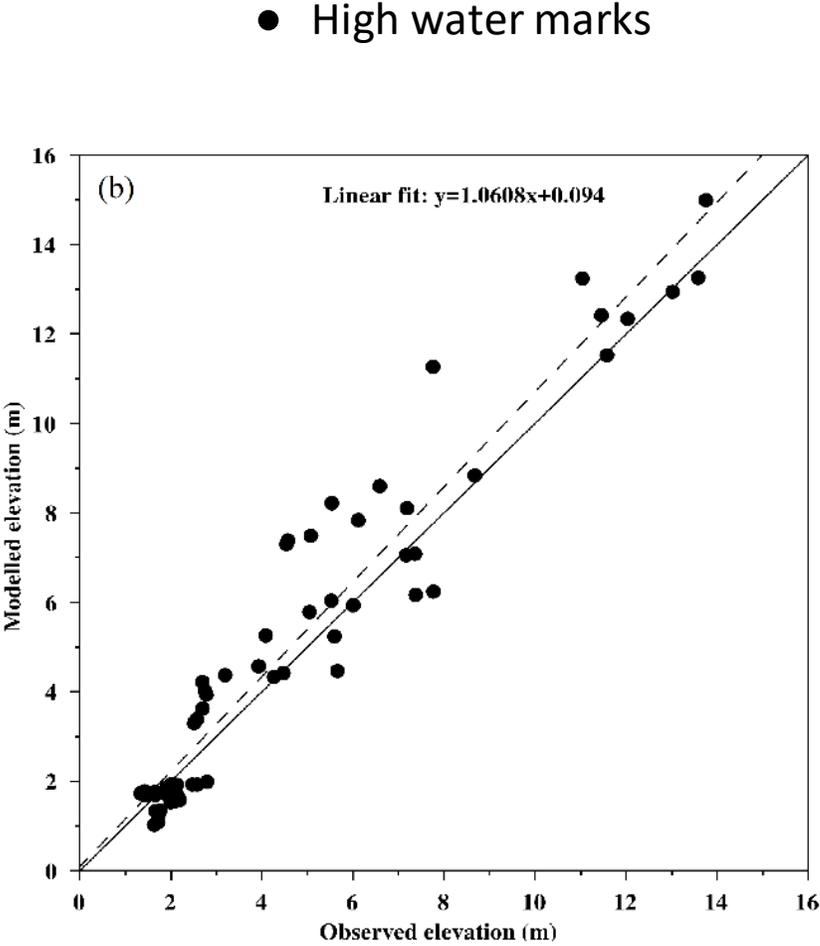
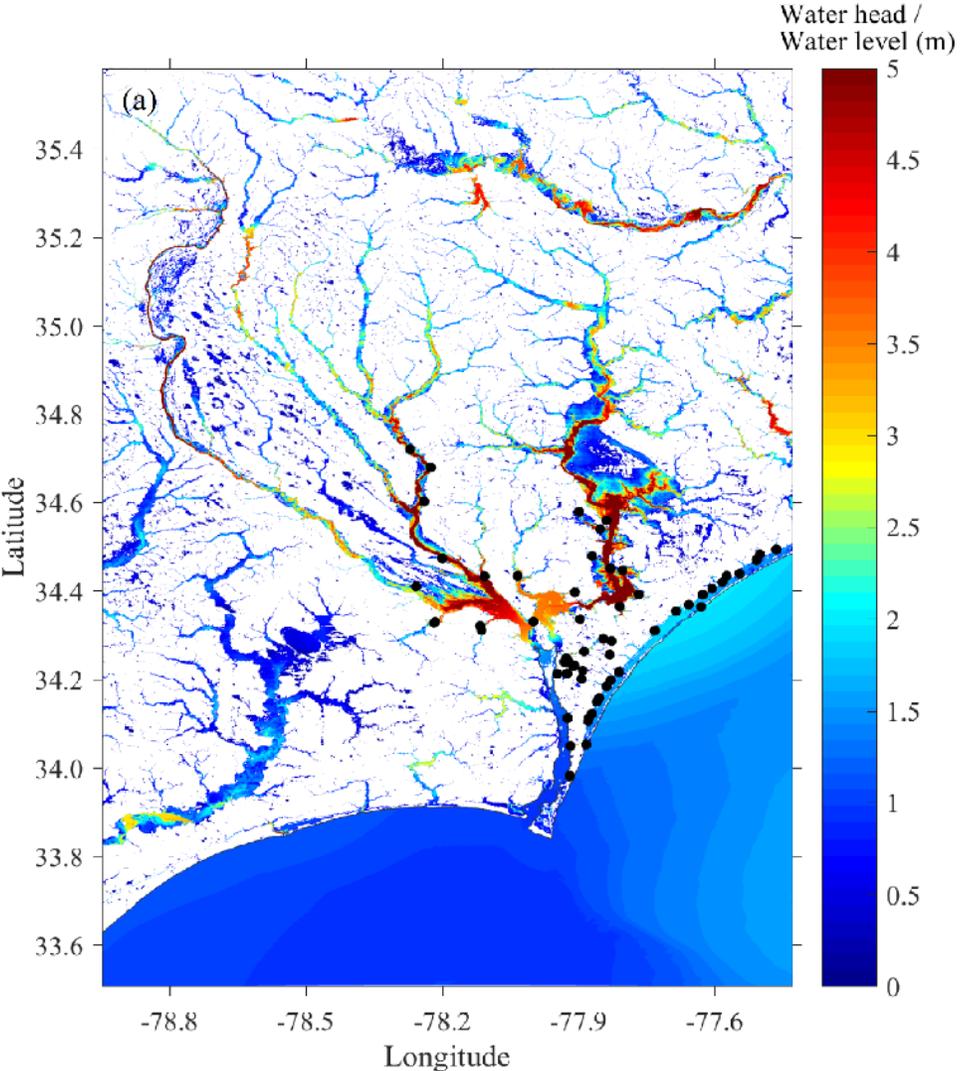
Application: Hurricane Florence

Model validation



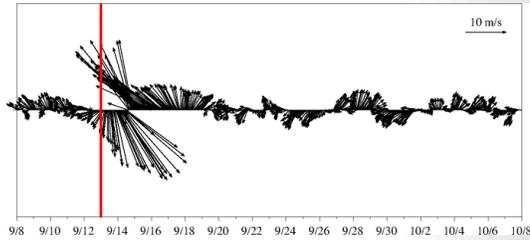
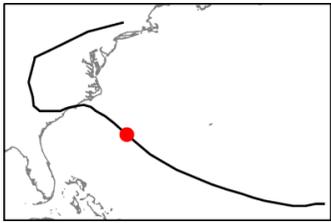
Application: Hurricane Florence

Model validation

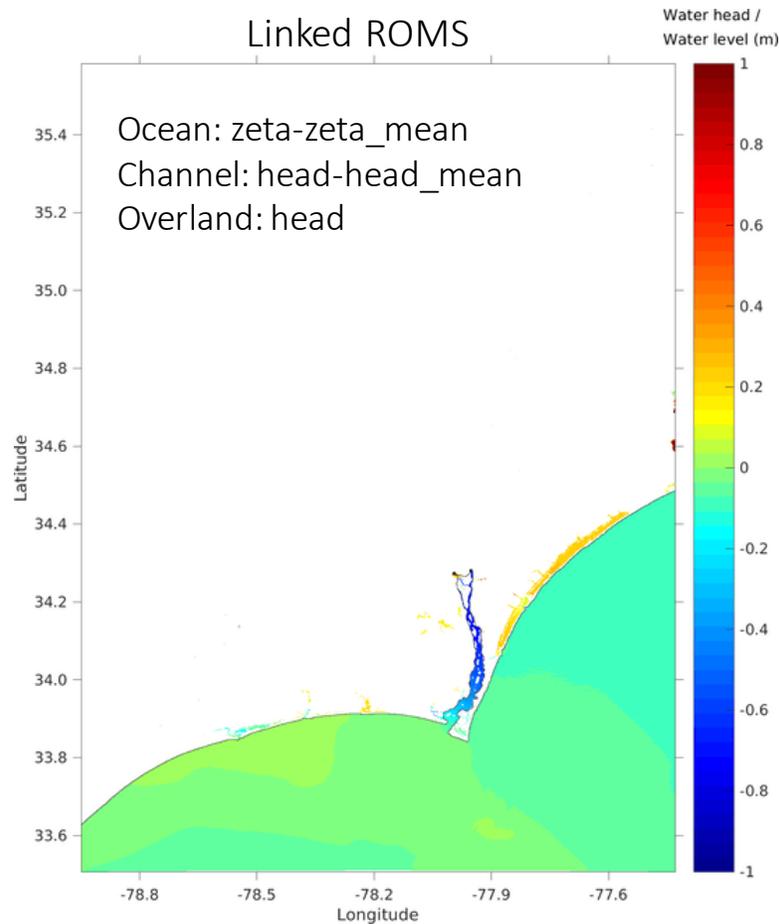


River-Ocean Coupling

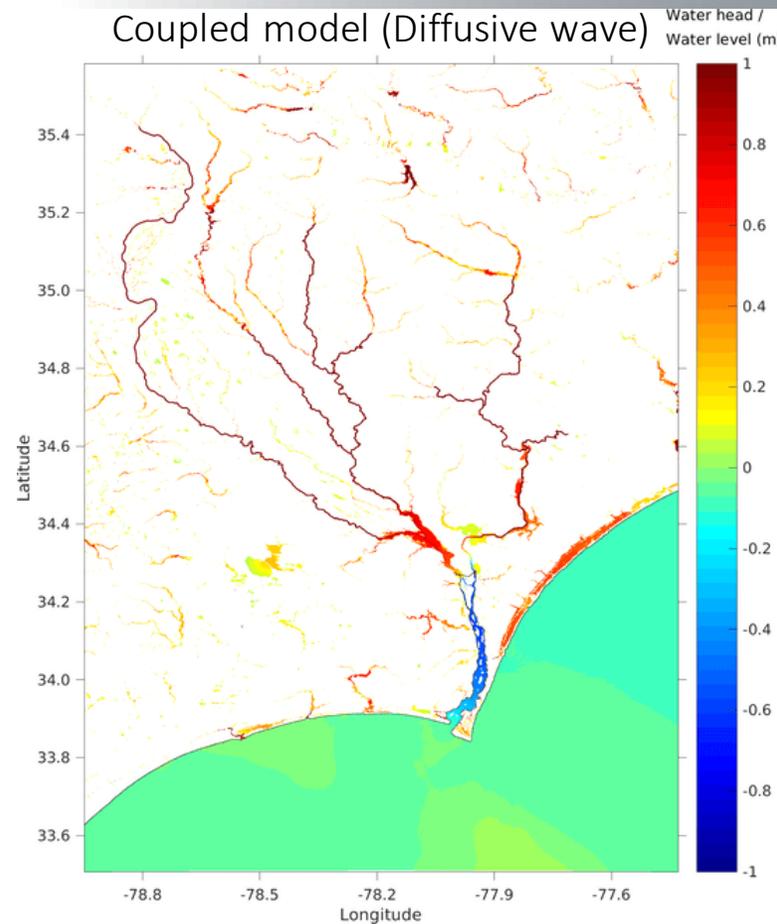
Dynamical (two-way) vs. One-way Coupling



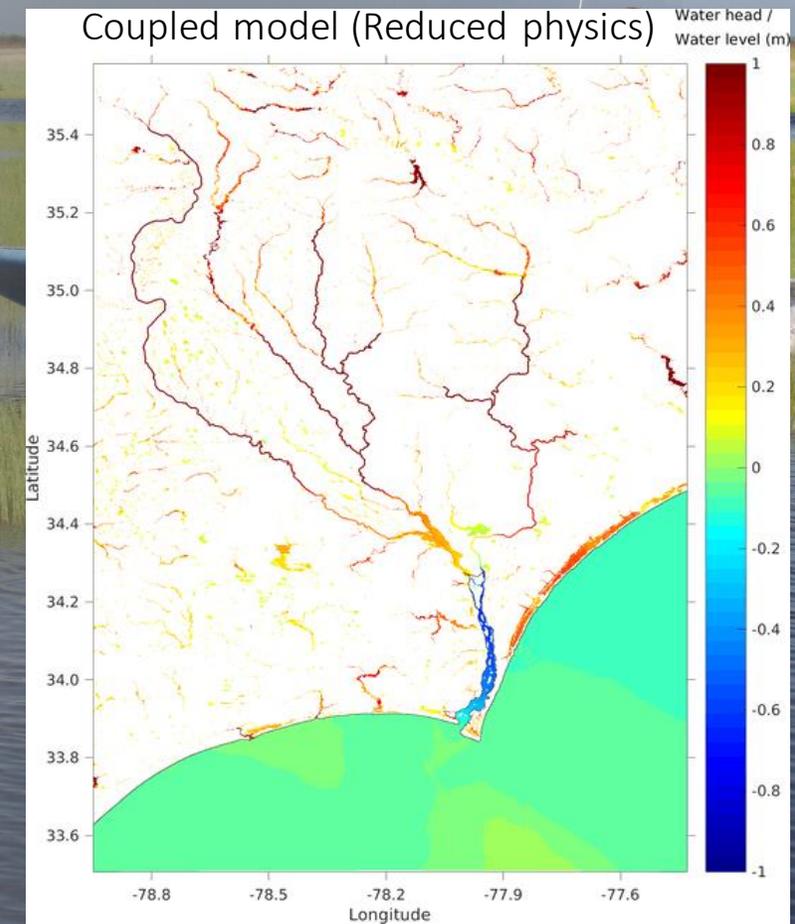
Linked ROMS



Coupled model (Diffusive wave)

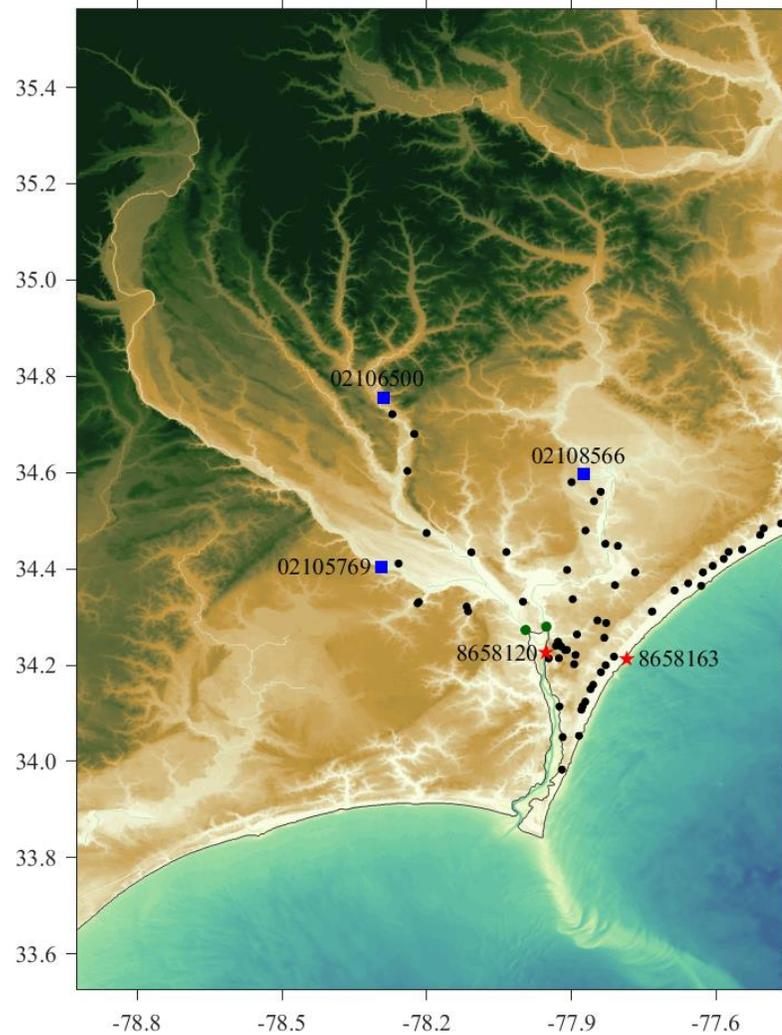


Coupled model (Reduced physics)

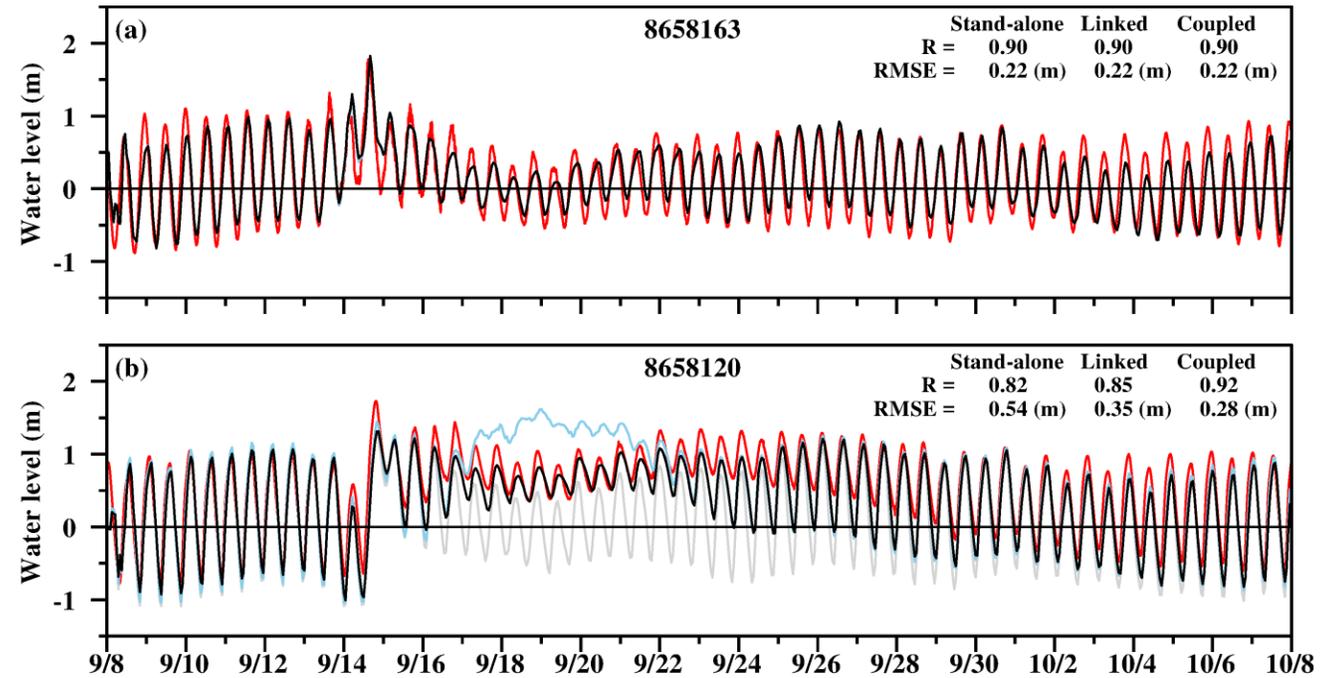


Application: Hurricane Florence

Model validation



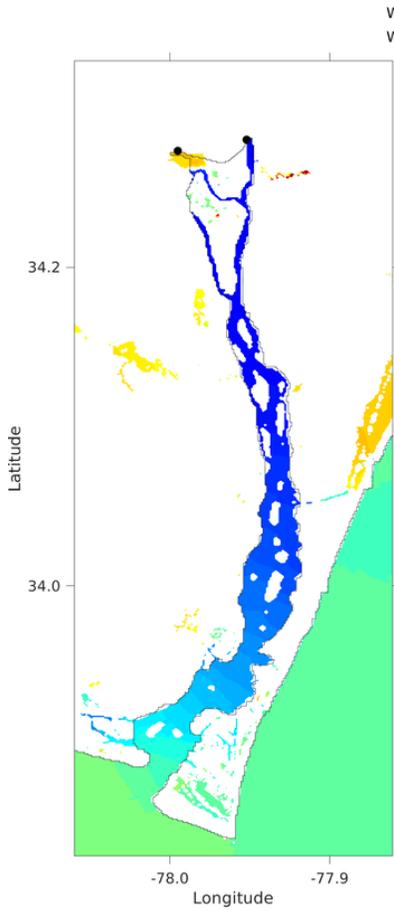
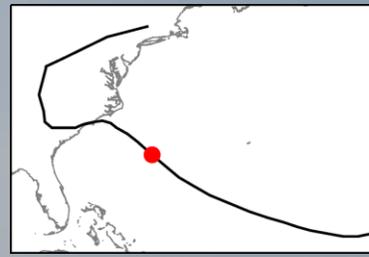
★ NOAA tide station



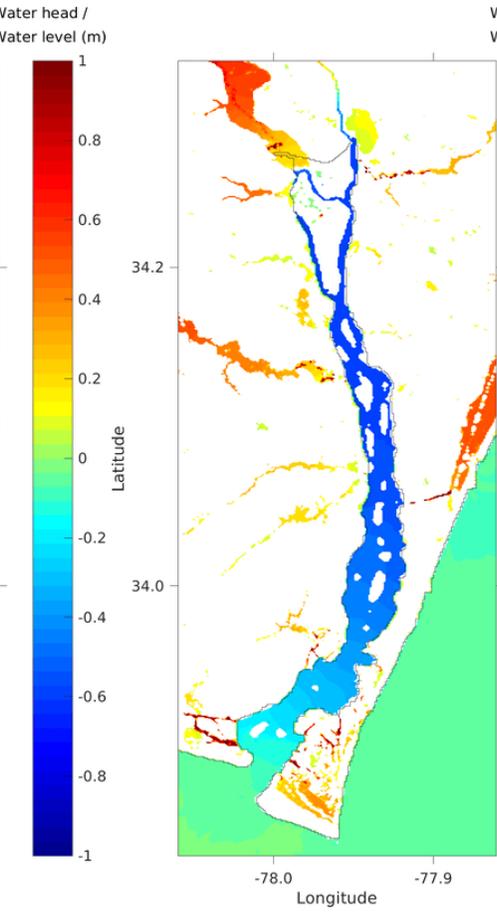
Name	Coupling Method
OBS	
Exp1	Stand-alone ROMS
Exp2	Linked ROMS
Exp3	Dynamic Coupling

River-Ocean Coupling

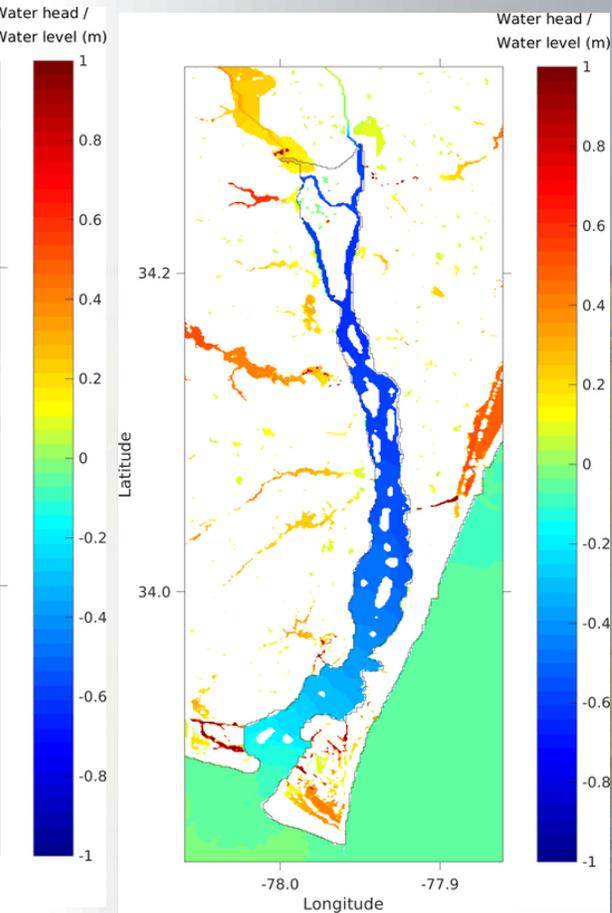
Dynamical (two-way) vs. One-way Coupling



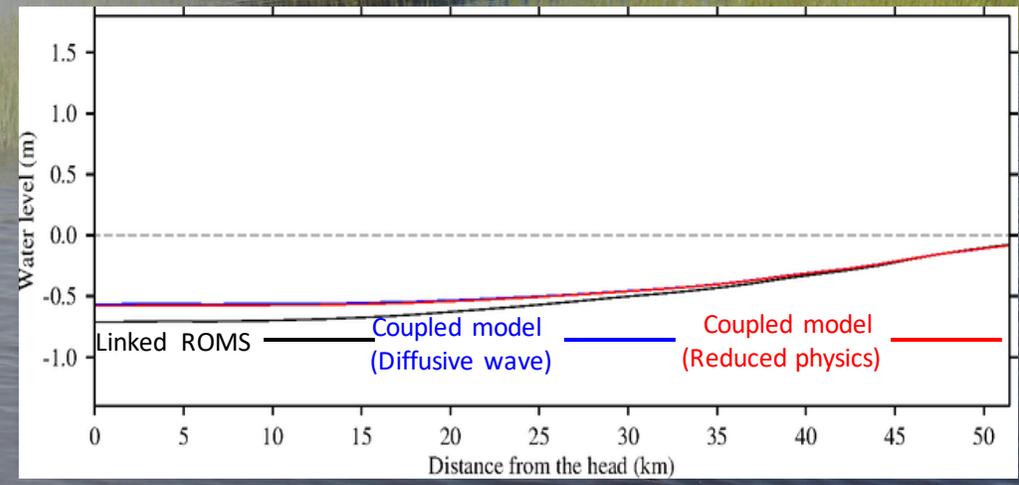
Linked ROMS



Coupled model
(Diffusive wave)



Coupled model
(Reduced physics)



River vs. Surge

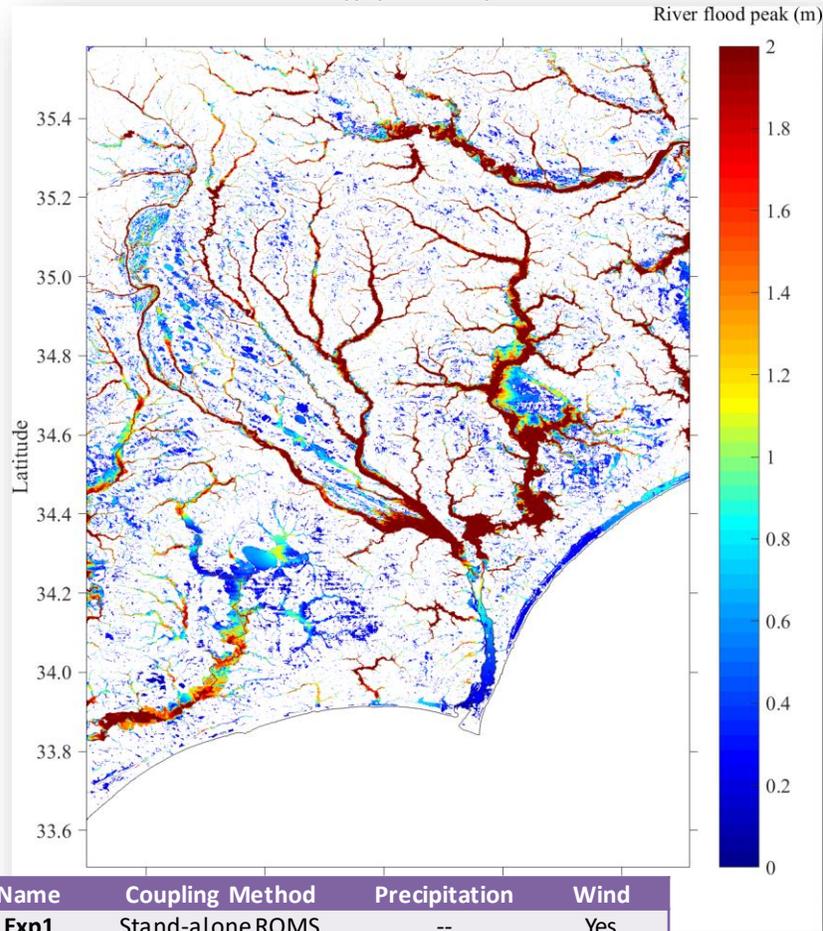
R = river
W = wind
T = tide

River flood peak

Exp4 - Exp6

R+T

T

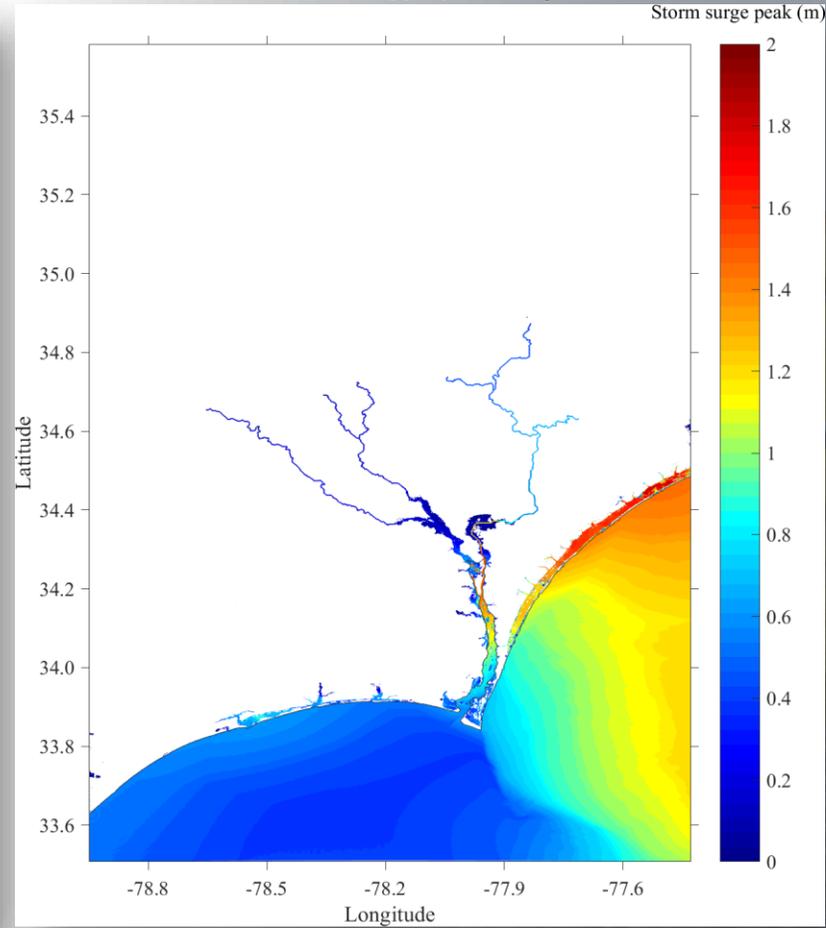


Storm surge peak

Exp5 - Exp6

W+T

T



Nonlinear effect

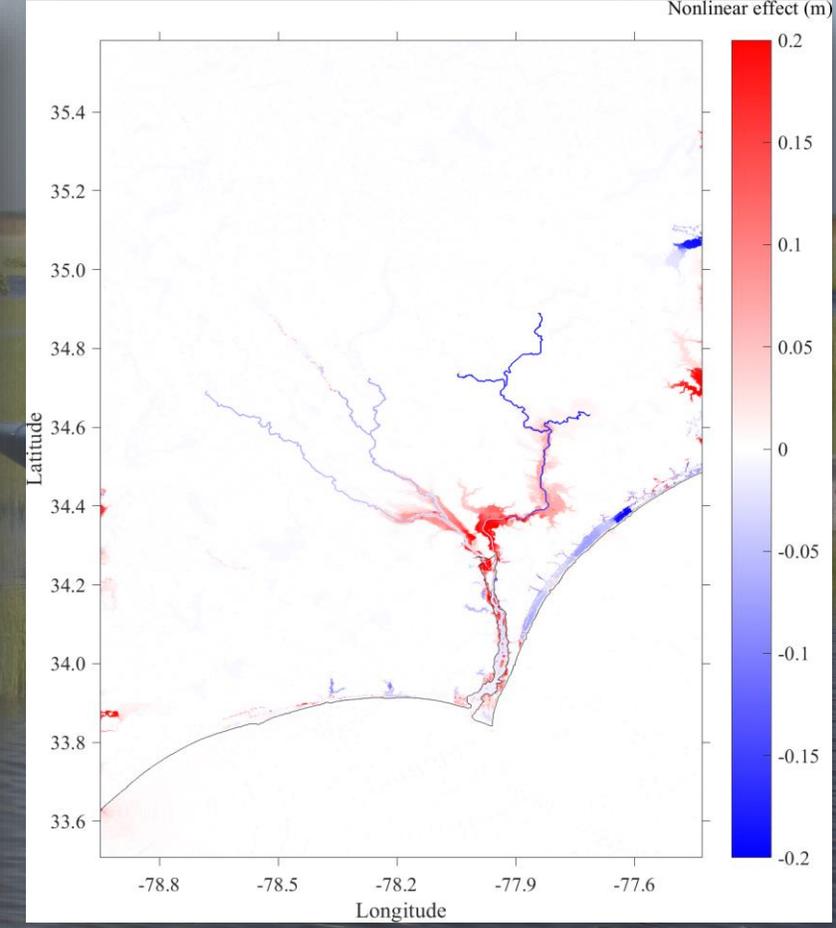
Exp3 - (Exp4+Exp5-Exp6)

R+W+T

R+T

W+T

T

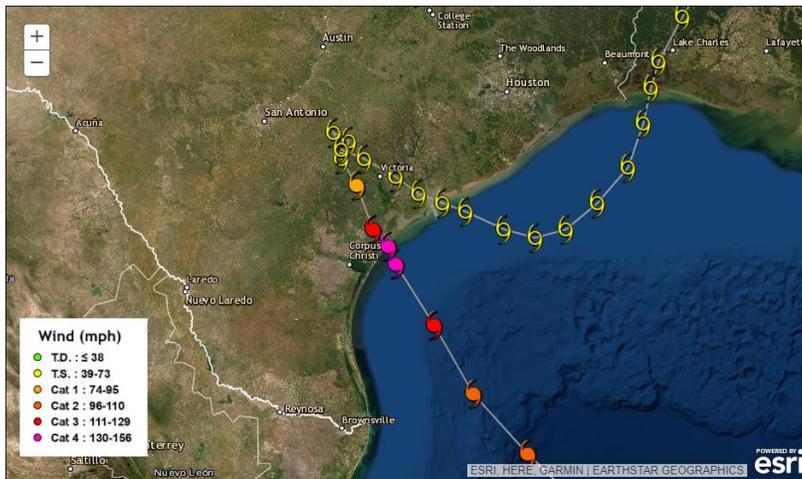


Name	Coupling Method	Precipitation	Wind
Exp1	Stand-alone ROMS	--	Yes
Exp2	Linked ROMS	Yes	Yes
Exp3	Dynamic Coupling	Yes	Yes
Exp4	Dynamic Coupling	Yes	No
Exp5	Dynamic Coupling	No	Yes
Exp6	Dynamic Coupling	No	No

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.

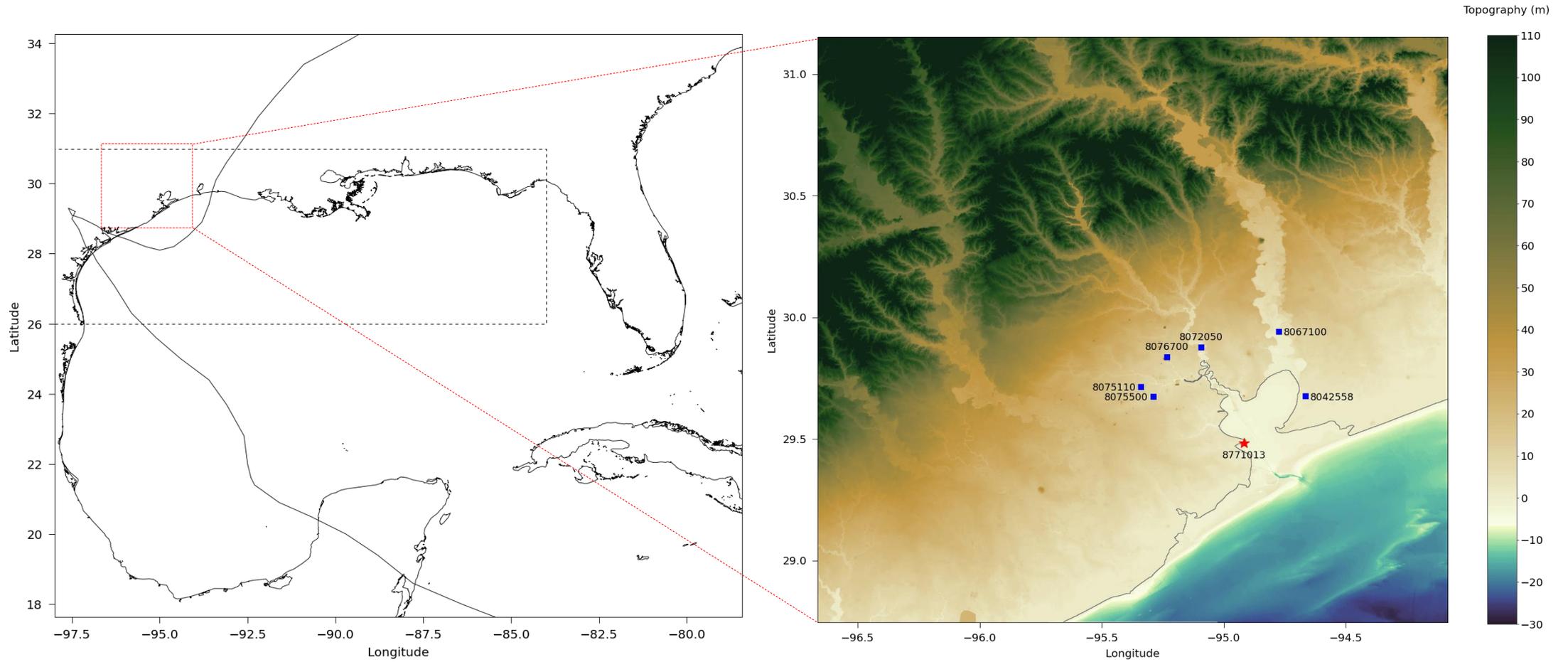
Van Oldenborgh, G. J., Van Der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G., & Cullen, H. (2017). Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, 12(12), 124009.

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

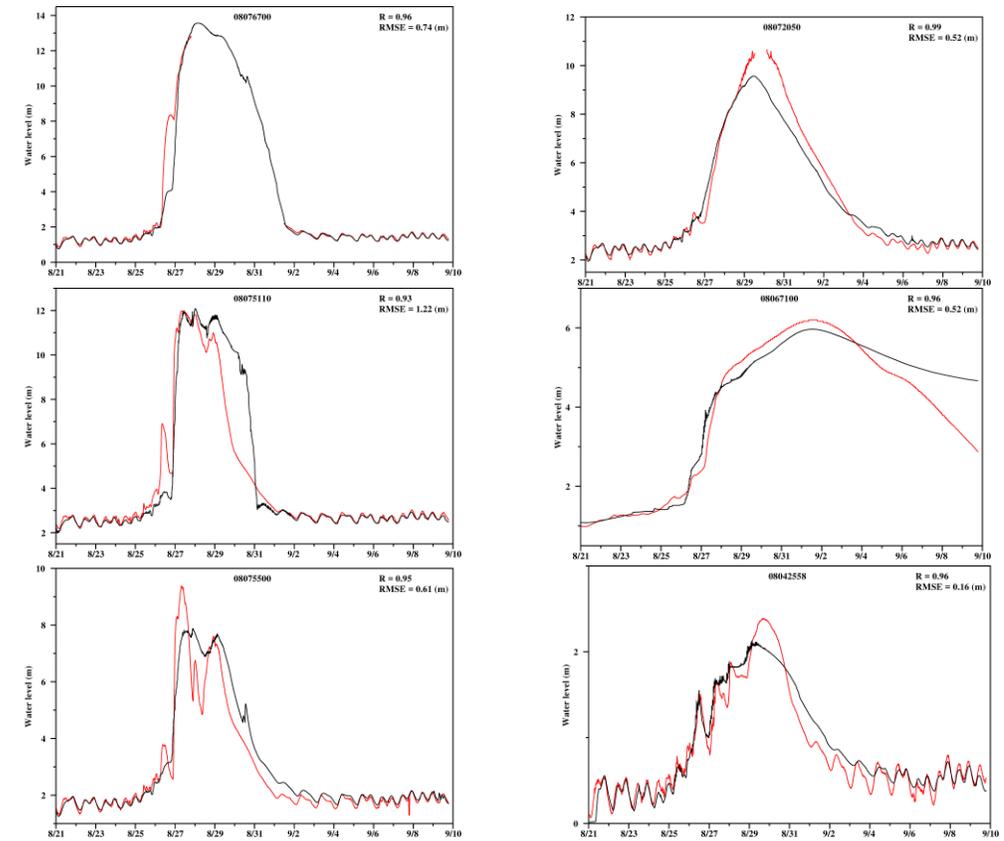
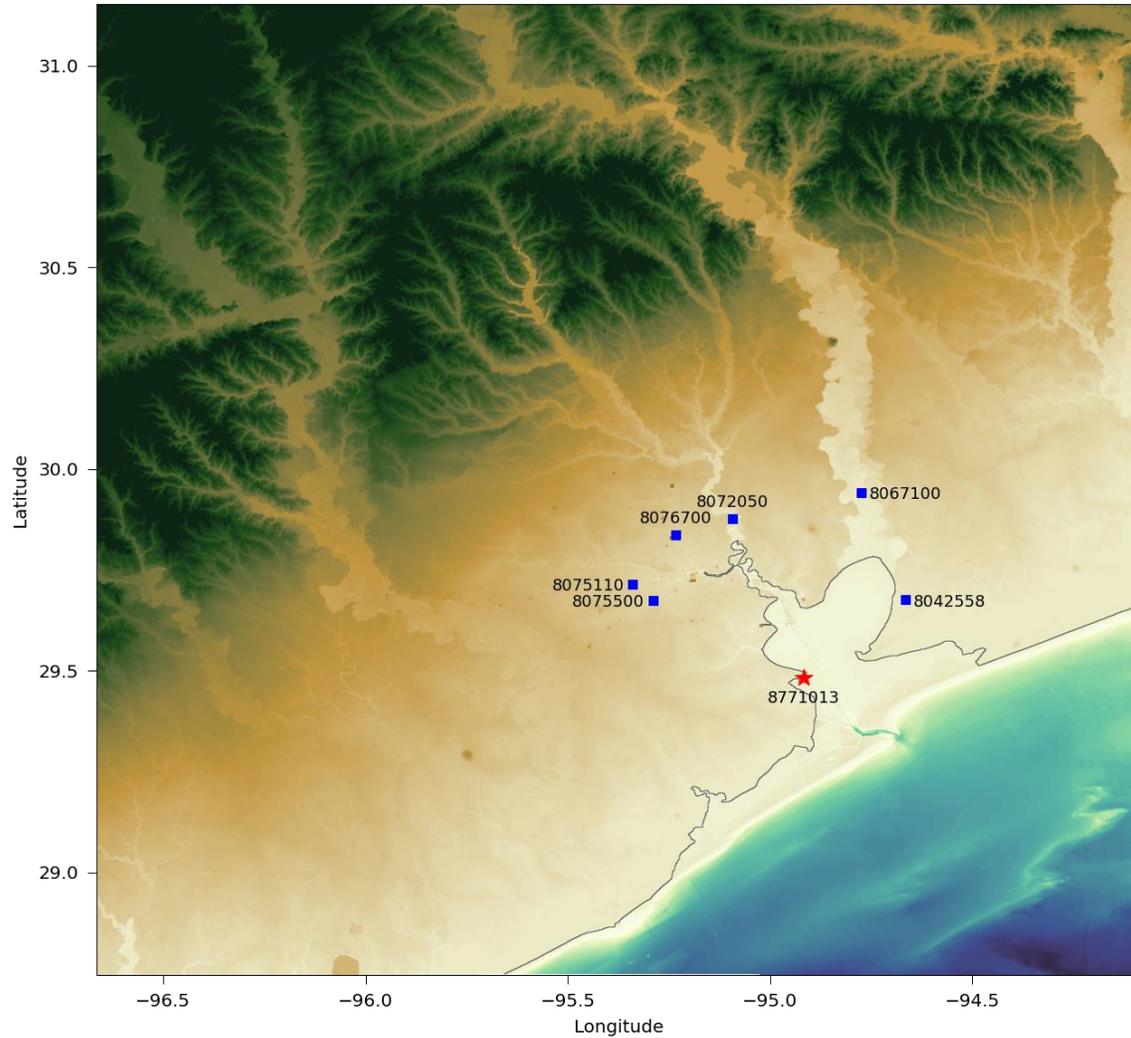
Model set-up



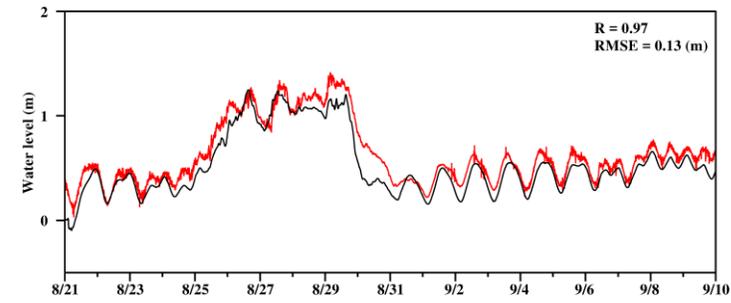
Application: Hurricane Harvey

Observed ——— Modeled ———
■ USGS gage height

Model validation

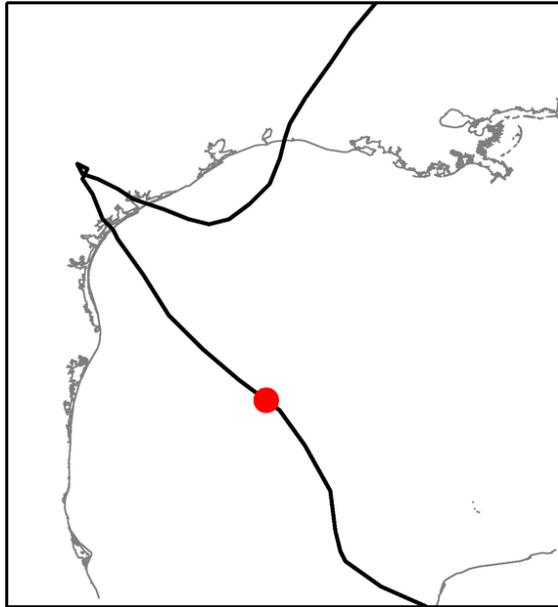


★ NOAA tide station

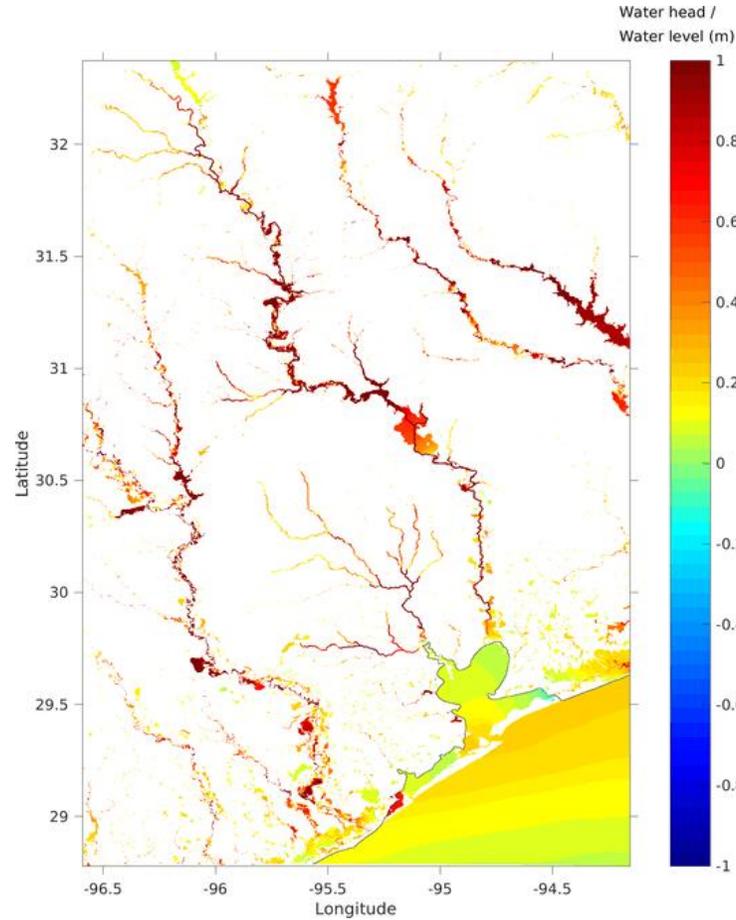


Application: Hurricane Harvey

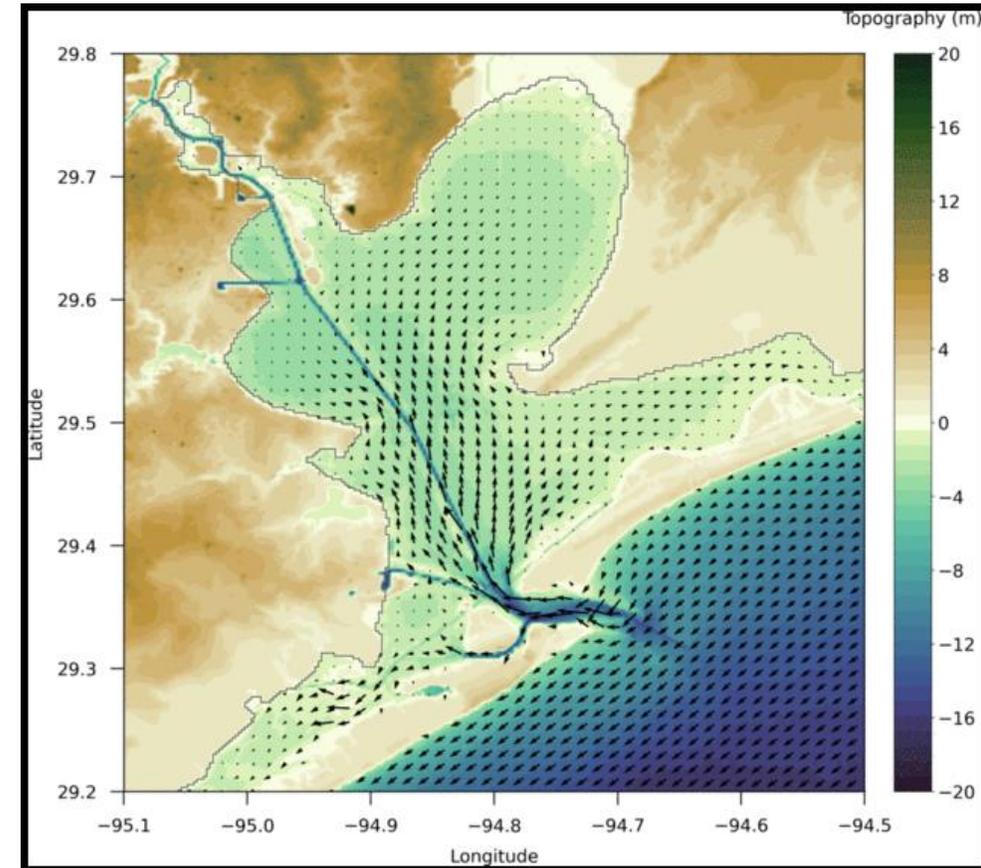
Model results



Hurricane Harvey track



Simulated flooding



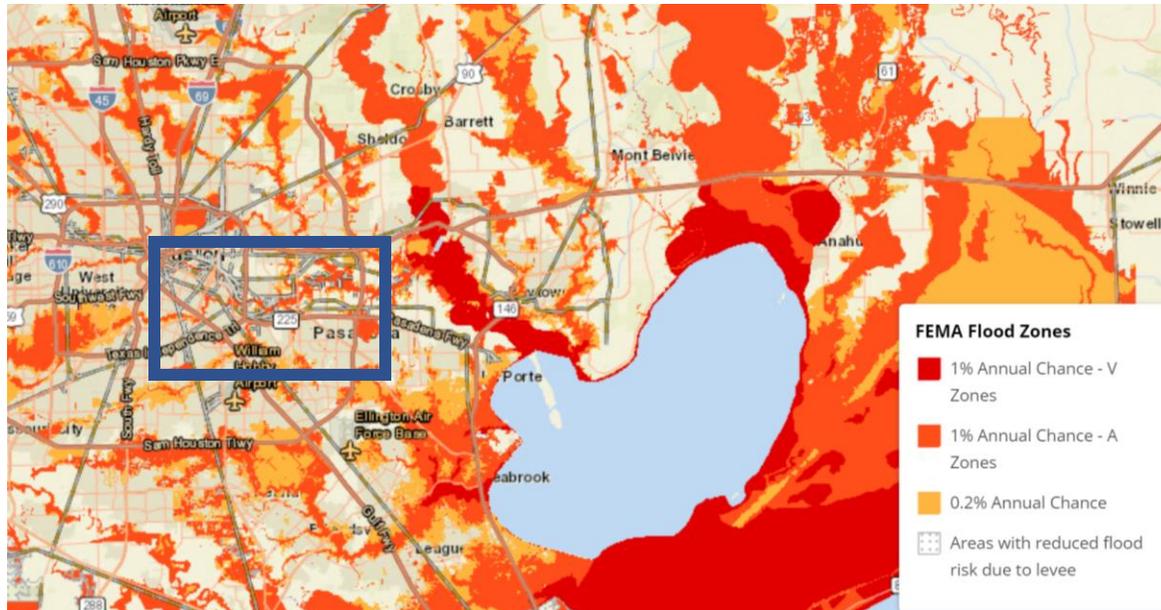
Simulated velocity in the Bay

Flood Zone vs Real-time Model

Flood Zone:

Input: historical data

Output: flooding probability

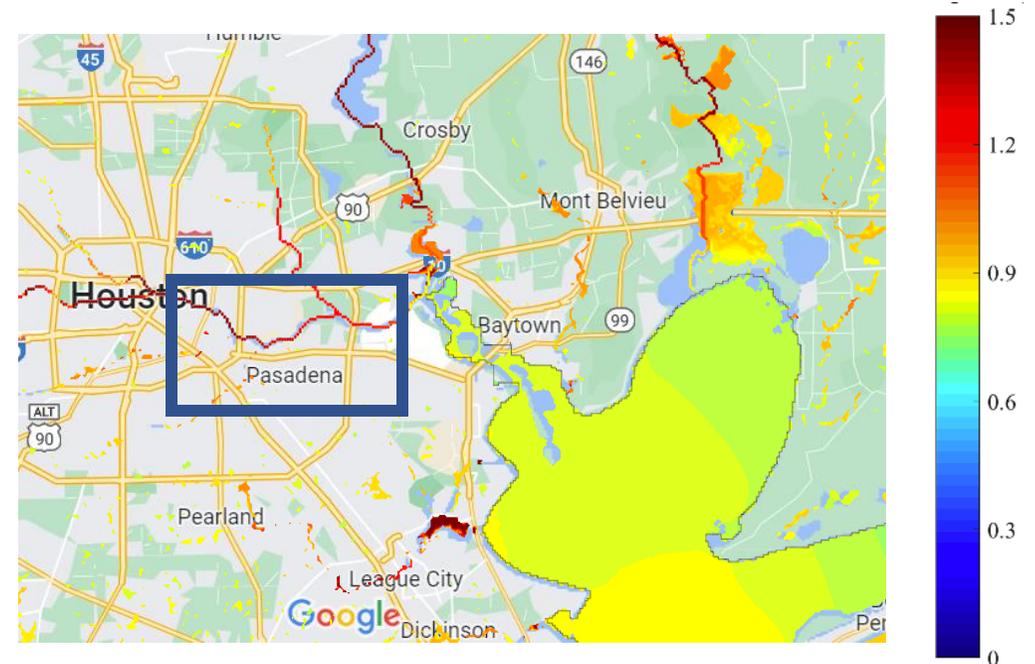


FEMA Flood Zone Map from <https://coast.noaa.gov/floodexposure/>

Real-time Model:

Input: real-time data

Output: real-time water level



Simulated flooding peak during Harvey

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

What if Hurricane Harvey happens in Louisiana?

