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A Multi-Model Approach to Simulate the Storm Surge Due to Hurricane Maria (2017)

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Talk Overview

- DA Storm Surge Modelling
- The Four Models
- The Model Setup
- Basin
- Bathymetry/Friction
- Tides
- Hurricane Wind
- Short Waves

Comparison of Model Results

- Run Time (approx.)
- MEOWs / HWMs
- Time Series

Talk is really from a consultancy perspective

Depth-Averaged Storm Surge Modelling

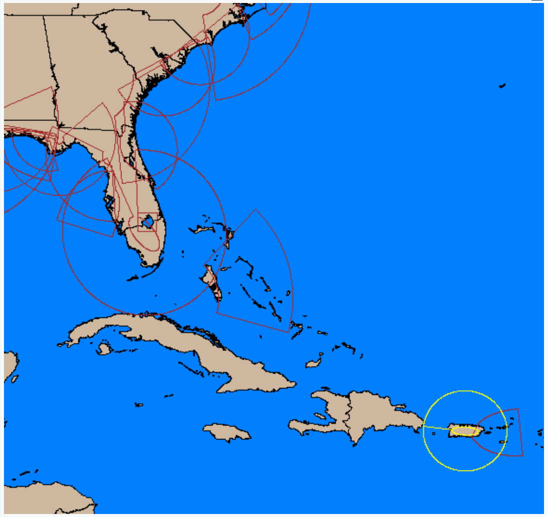
- Form of Governing Eqs PV vs CV (DF)
- Wetting/Drying Fronts – Heuristic, Flux Blocking, RP (WW or WD)
- Solution Technique FD,FE and FVM
- Wind Forcing (forecast or hindcast mode)
- Wind Drag and Bottom Friction
- Mesh Type Structured, Unstructured or (Dynamic) Adaptive
- Model Basin Large or Small?

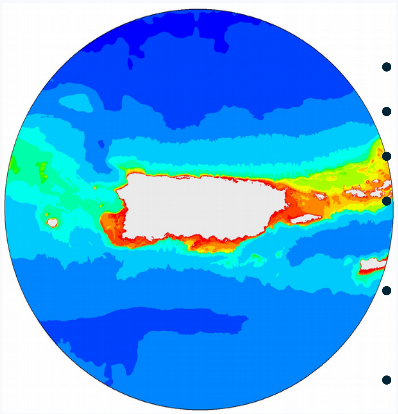
The Surge Models Used

- D-Flow FM – Finite Volume PV form Casulli formulation (Con. Momentum in adv step).
- FIST – Fully Implicit version of the IHRC CEST model developed in-house at Baird employing high-order, montone SL advaction. Casulli's approach for solution of free surface and FD method, CL grid fully implicit. Internally generated wind field.
- MIKE 21FVM – Roe (1981) ARS with linear reconstruction for 2nd order spat. accuracy.
- TELEMAC-SS based model developed in-house at Baird. Whilst TELEMAC has the option of using modern (ARS-based) FVM schemes we use the FE scheme. Internally generated wind field. Model has a number of ADVANTAGES i.e. inclusion of rainfall runoff model.

Numerical Model	Vendor/ Developer	Numerical Approach	Type of Mesh	Time Step	Boundary Condition	Wind Forcing
TELEMAC-SS	EDF/Baird	FE/FVM	Unstructured (Triangular)	Semi-Implicit	Dirichlet	Parametric (**I**) Re-analysis data
MIKE21	DHI	FVM	Unstructured (Triangular)	CFL Explicit	Flather	Parametric (**E**) Re-analysis data
D-Flow FM	Deltares	FVM	Unstructured (Mixed)	Semi-Implicit	Flather	Parametric (**E**) Re-analysis data
FIST	IHRC/Baird	FD	Curvilinear	Implicit	Flather	Parametric(**I**) Re-analysis data

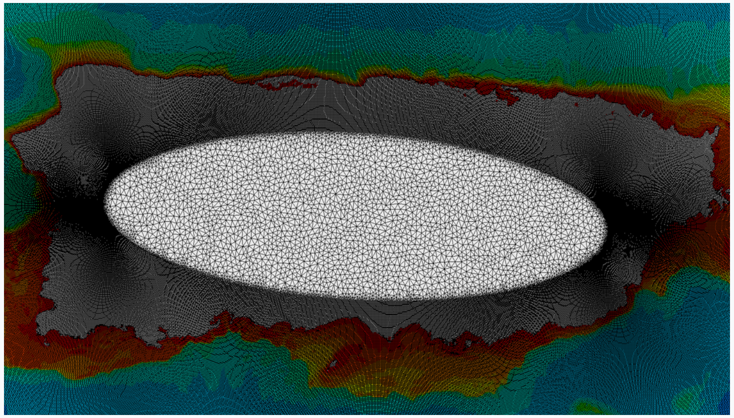
Model Set-Up 1: Mesh and Bathymetry

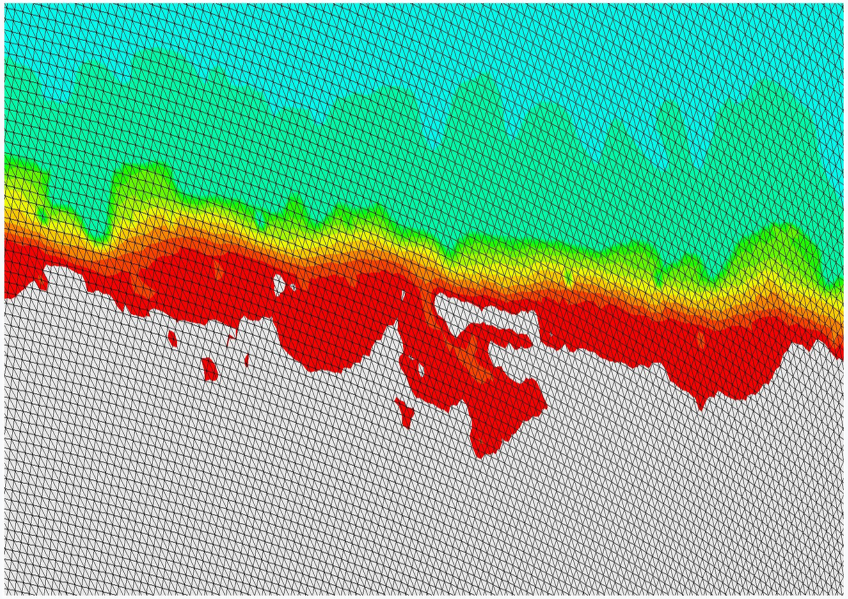




Mesh Details

- NOAA Puerto Rico v6 (op.)
- ~ 450,000 nodes (0.9M elements)
- Min cell size 200m
- TELEMAC, MIKE same mesh – triangulated SLOSH grid
- Delft 2D modified version (due to orthogonality constraints)
- FIST (CEST) uses original SLOSH grid (curvilinear model)





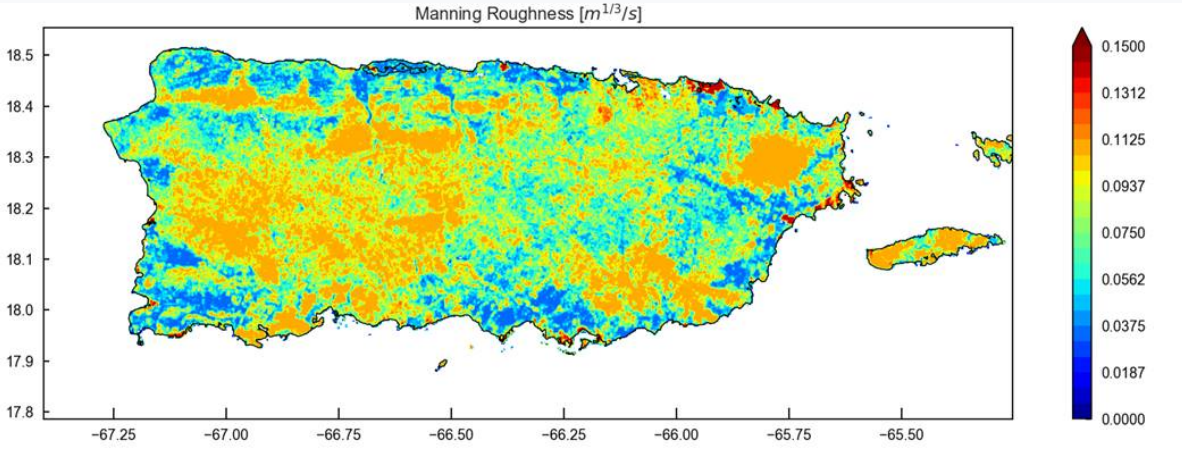
Model Set-Up 1: Mesh and Bathymetry

- **Bathymetry Details – NB: NOAA basin bathy not publicly available**

  1) For Puerto Rico and the U.S. Virgin Islands coastal regions, 1 arc-second and 1/3 arc-second digital elevation models (DEMs) developed by the National Geophysical Data Center (NGDC), and NOAA for the Pacific and Marine Environmental Laboratory (PMEL) and the NOAA Center for Tsunami Research were used.

  2) For the offshore areas the NGDC ETOPO1 1 arc-minute global relief model was used.

- Datasets were combined and transferred to mesh via kernel type interp.
- Island represented through bathy (not reflective BCs)



Bottom Friction Set-up

- Use spatially varying Manning's *n* values
- Determined from USGS landcover based on Mattocks & Forbes (2011)
- *n=0.02* in ocean (missing coral/mangove)
- Simple quadratic friction law used in all models (likely to over predict bed shear stress)

Model Set-Up 2: Tides and Wind

Tide setup

- OSU global TPXO data base employed for linear superposition of 7 components carried out within models.
- Implementation of tidal BCs differed between models (MIKE/DELFT octants, TELEMAC nodes, FIST segments)
- Use Flather Conditions (Riemann Invariants of Linear SWEs)
- Validation performed for each model over month of September 2017.

Wind model set-up

- Parametric – **forecast mode study** using Holland (1980) single vortex model: $S_t = 0.88$, $\beta = 0.79$ and $v = 0.5$
- *Track details:* Track was set up by experts at the IHRC at FIU: RMW, max. wind speed and central pressure.
- Also employed SLOSH (Myers & Malkin [1961]) wind – ***Results reported in proc.***
- *Drag model:* Garratt (1977) linear. Used outside range of validity (extinction coefficient *h=0.4m*)

Model Set-Up 3: Waves

Mesh Set-up

- Ran within the same domain boundaries as the surge model – background waves considered secondary.
- New mesh with shoreline refinment defined

Wave model set-up

- Used the output of the MIKE21 wind model interpolated onto the wave mesh.
- TOMAWAC – Third Generation Spectral wave model from the TELEMAC suite
- Interpolated the radiation stress gradients (wave forces) onto the flow model mesh
- Provide direct, time-varying, forcing terms into the momentum equations – Only TELEMAC could handle this (after source code mods)

- Uncoupled Wave run – waves were run forced by wind with no feedback to the hydro model.

Validation: Tides

Worst Case - Magueyes

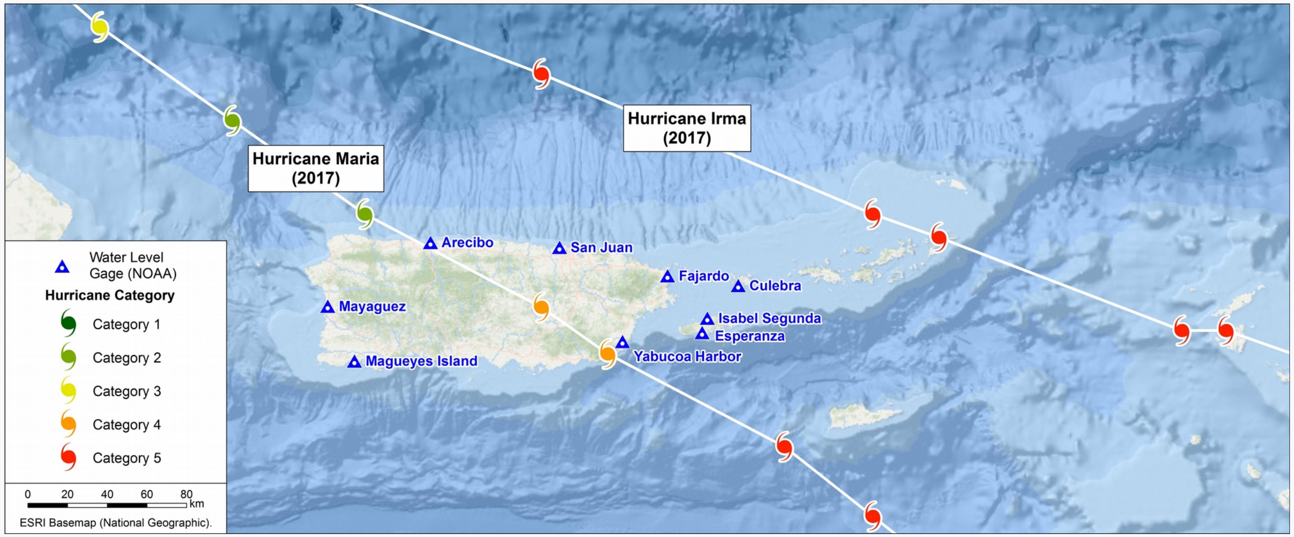
	Amplitude (m)			Phase (deg)		
	Obs	Mod	Diff	Obs	Mod	Diff
O1	0.05	0.07	0.01	224.97	223.90	-1.07
K1	0.06	0.05	0.00	242.93	234.39	-8.54
Q1	0.01	0.01	0.01	219.99	227.09	7.10
M2	0.01	0.05	0.05	23.33	64.28	40.95
S2	0.01	0.01	-0.01	10.49	12.50	2.01
N2	0.00	0.02	0.02	321.97	36.41	74.44

Best Case - Isabel Segunda

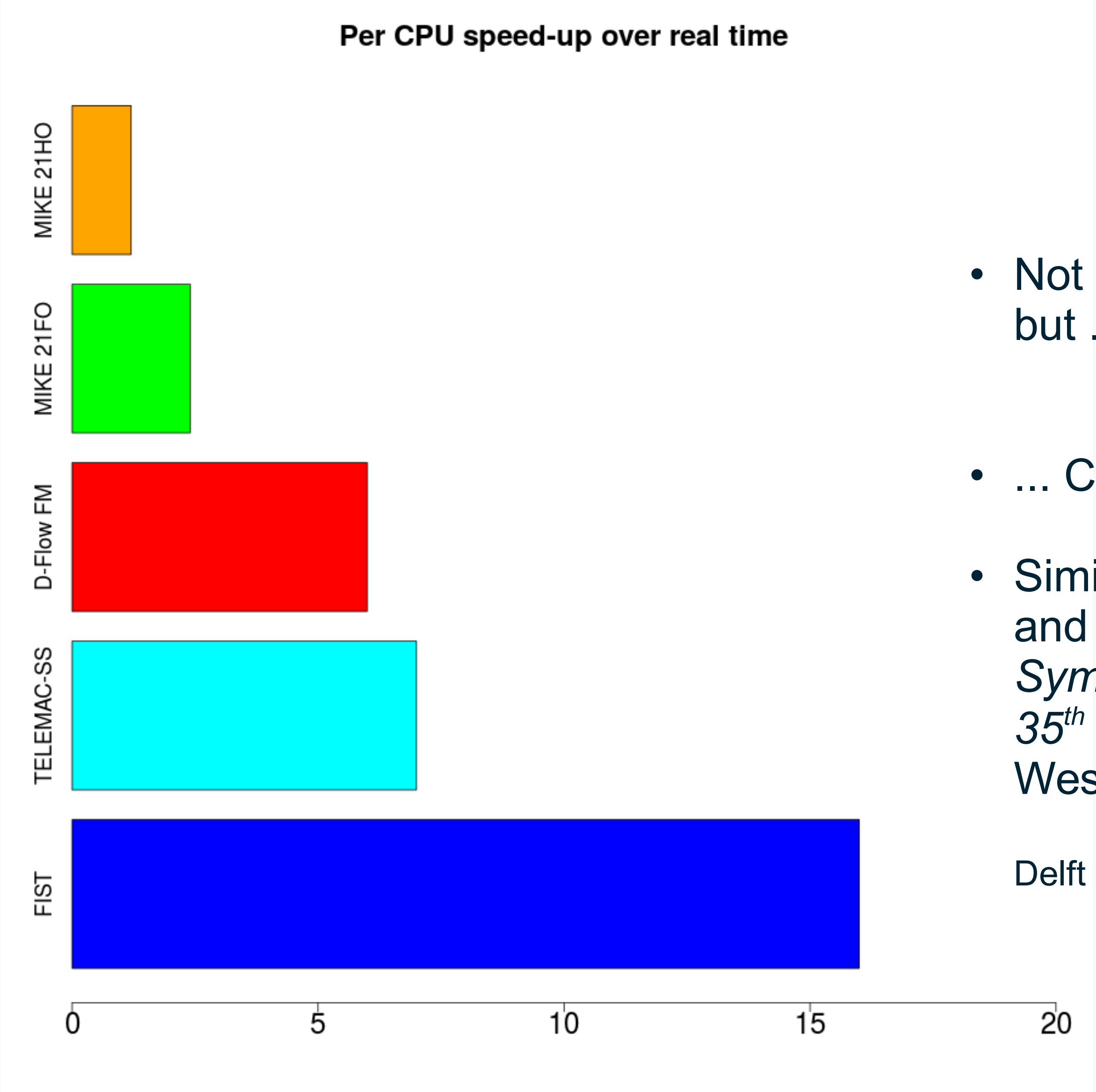
	Amplitude (m)			Phase (deg)		
	Obs	Mod	Diff	Obs	Mod	Diff
O1	0.06	0.06	0.00	221.96	218.12	-3.84
K1	0.05	0.05	0.00	236.72	231.78	-4.94
Q1	0.01	0.01	0.00	214.64	216.60	1.96
M2	0.11	0.11	0.00	17.66	24.62	6.96
S2	0.02	0.02	0.00	37.34	36.09	-1.25
N2	0.02	0.03	0.01	352.55	2.08	9.53

Tidal Validation Run for Month of September 2017

All models run – largest error shown



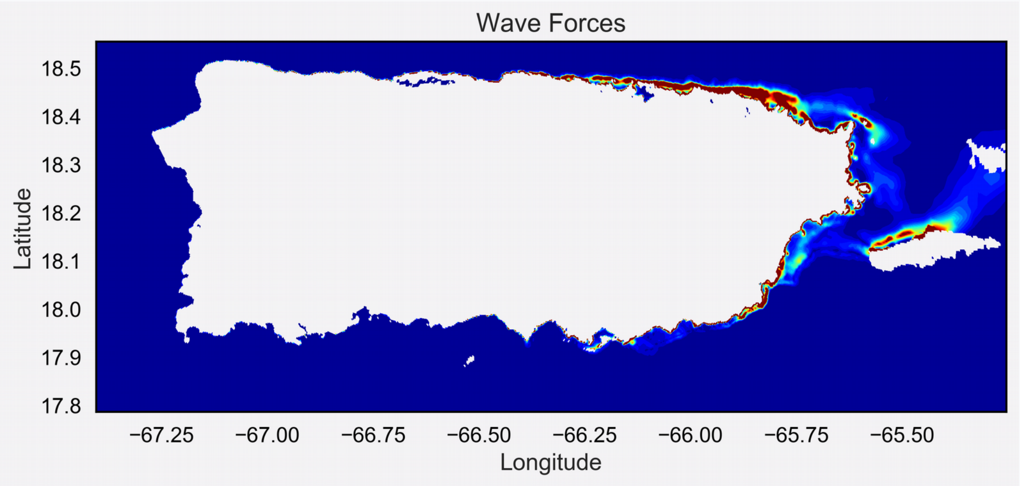
Results: CPU Time

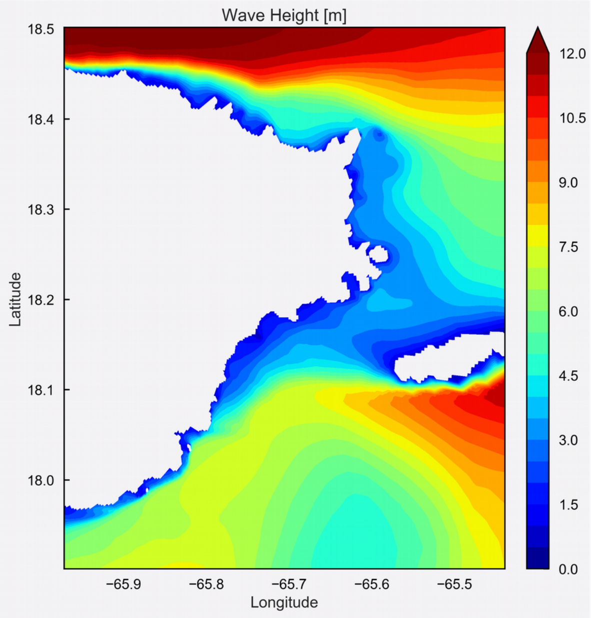


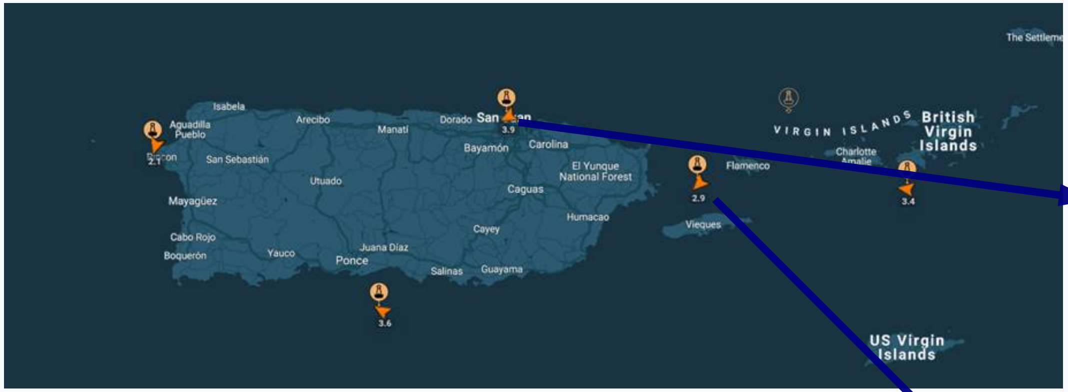
- Not a totally fair comparison but ...
- ... Certainly Representative.
- Similar results for MIKE21 and D-FLOW FM found by *Symonds et al. (2016) Proc. 35th ICCE* in a study of Wester Port Bay Aus.

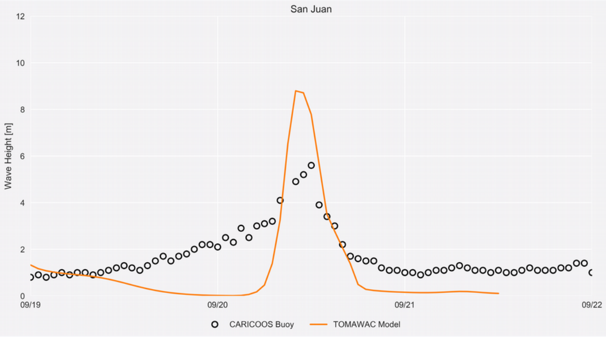
Delft 3.33 x faster than MIKE21

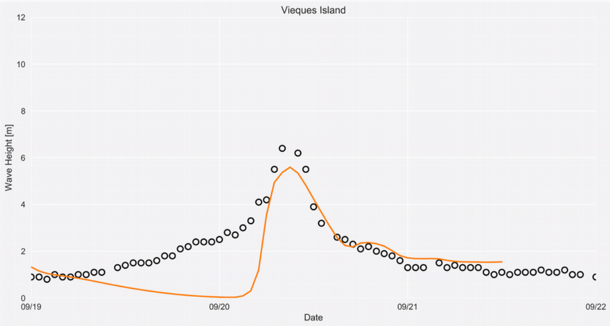
Results: Waves





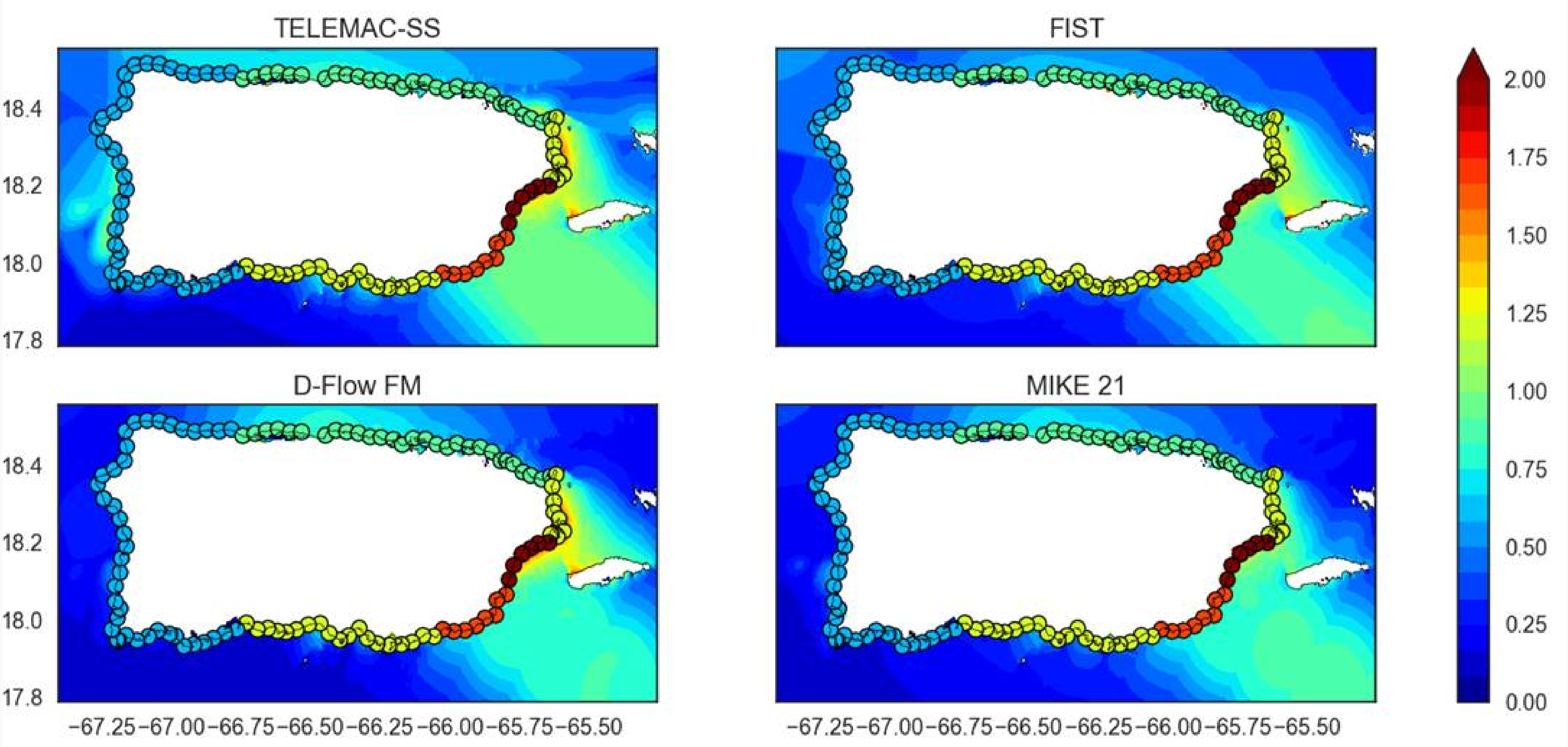






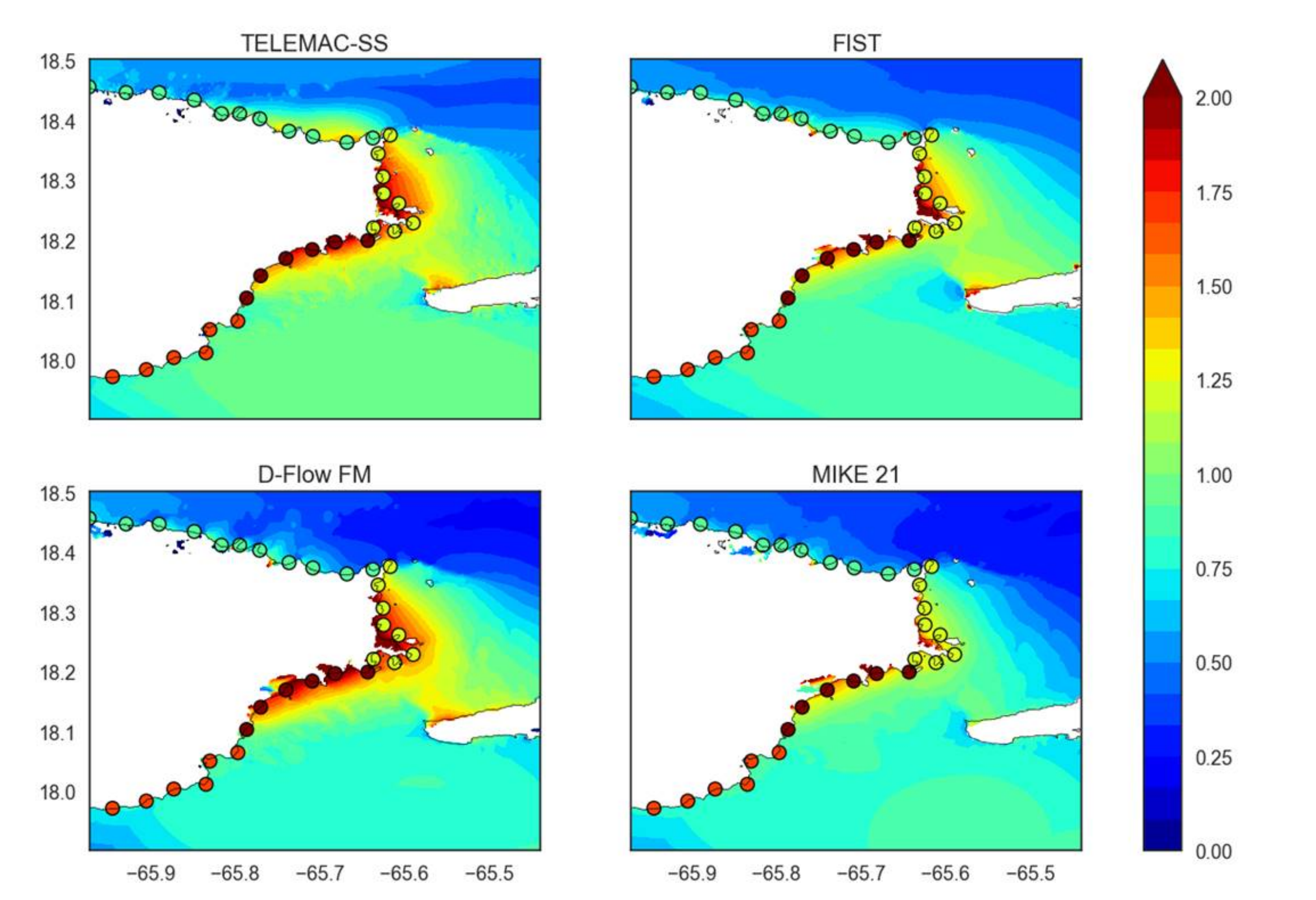
* Effect of static set-up on surge small
* To get waves right better wind field required
* Effect of dynamic set-up likely v. important

Results - MEOWs



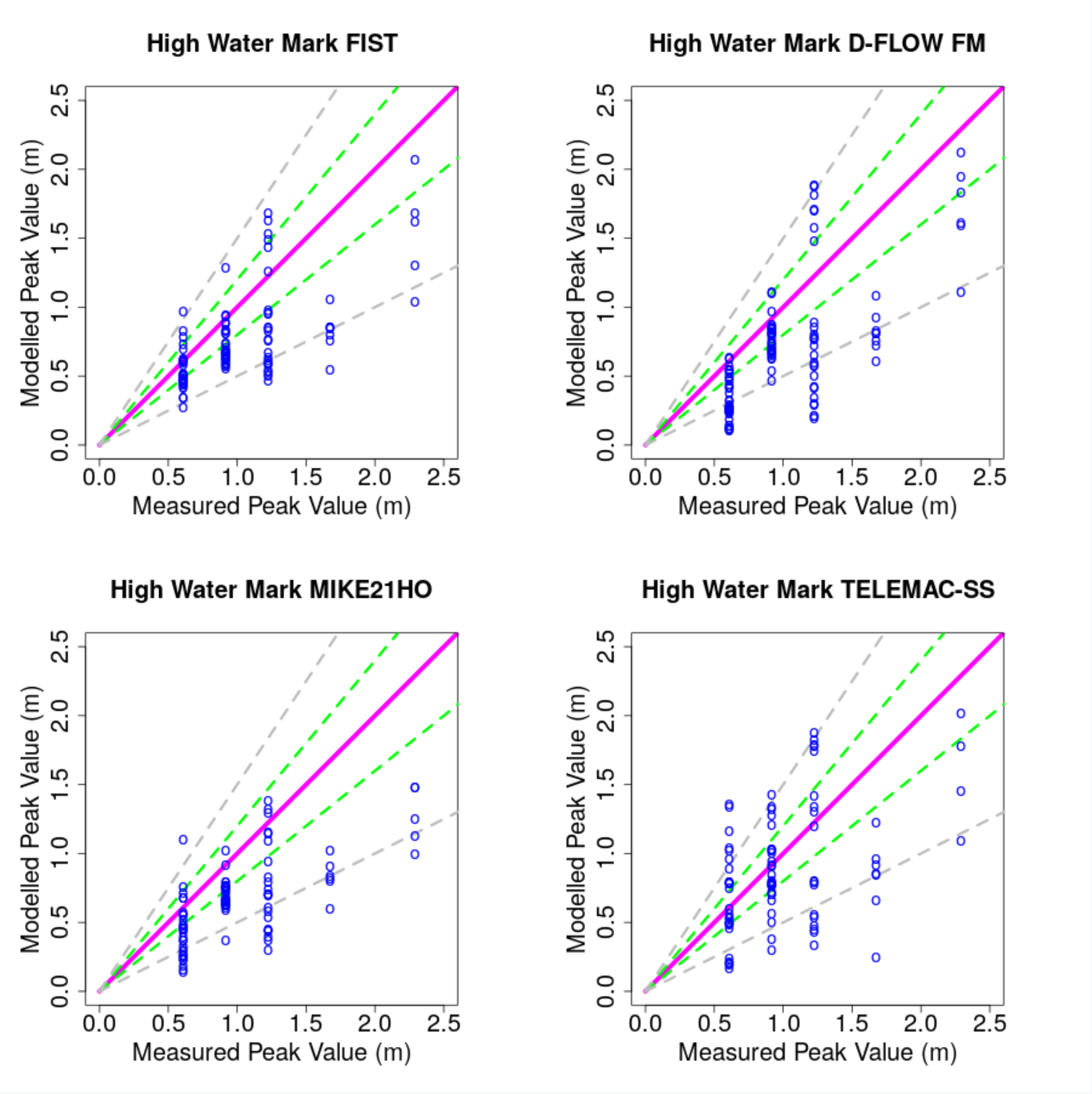
Comparison of model predictions against **mean** NOAA Estimated storm surge inundation (metres above ground level) based on an analysis of water level observations along the coast of Puerto Rico for hurricane Maria (2017) **NOTE: Up to 33% range in NOAA obs.**

Results - MEOWs

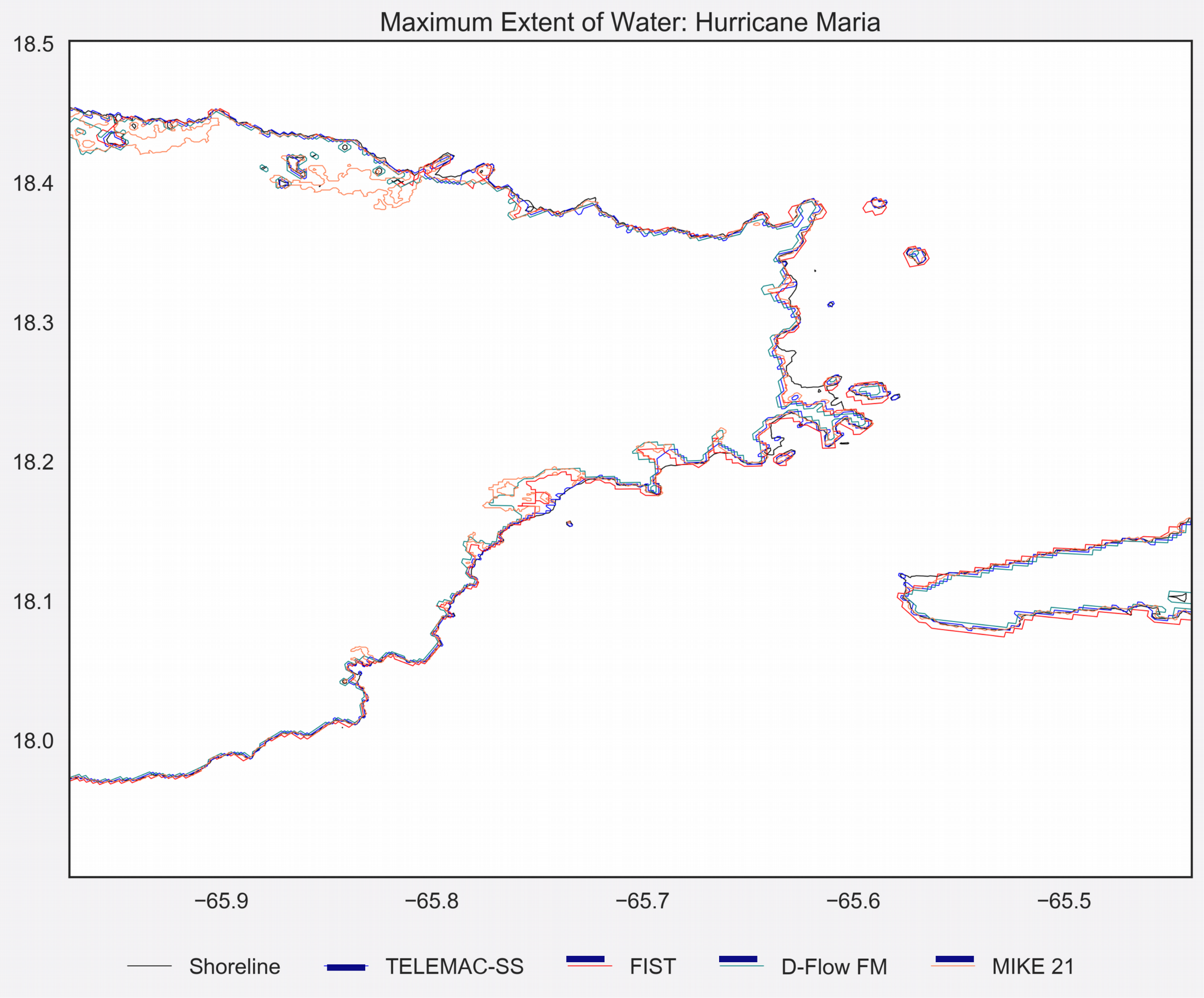


Inter-model comparison of MEOW around the landfall site hurricane Maria (2017). **NOTE: Up to 33% range in NOAA obs.**

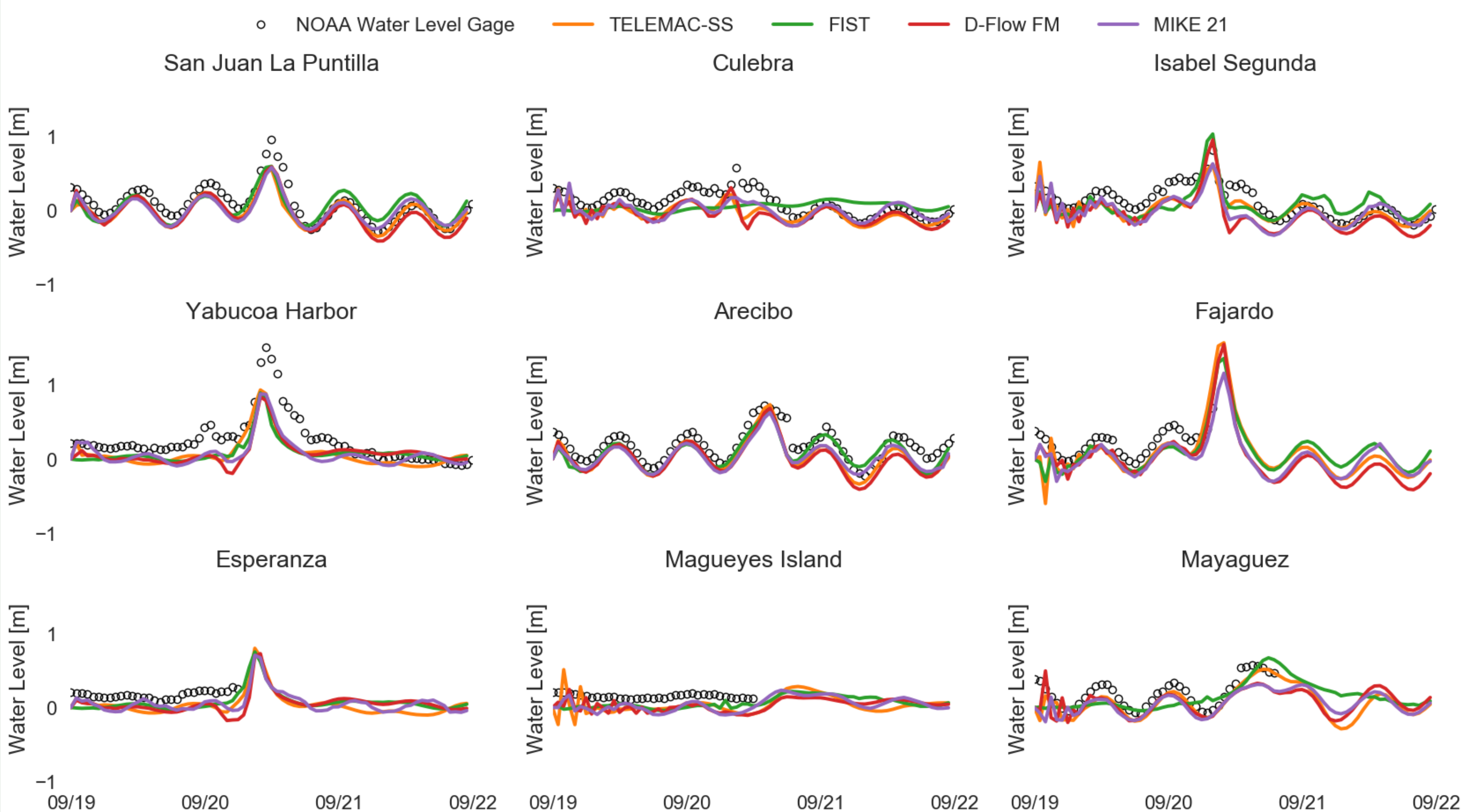
Results: Approx. HWMs



Results – Inundation extents

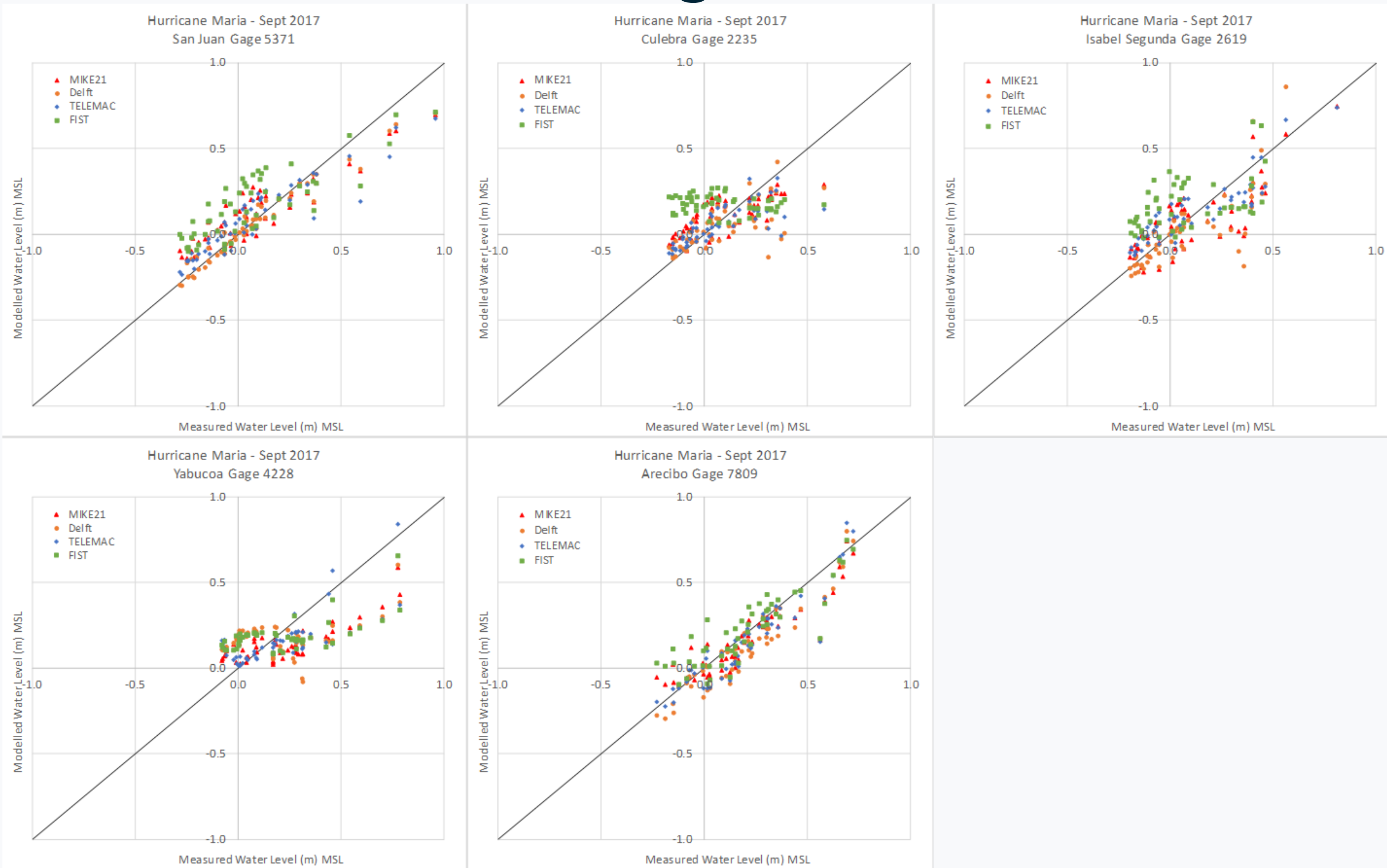


Results – NOAA Gauge Time Series



Time series comparisons between the 4 models predictions and NOAA gauge data (no shift)

Results – NOAA Gauge Time Series



Measured vs simulated gauge data for all four models (0.1m shift)

Results – Analysis New

Models	Hurricane MARIA: Peak Water Level (m)								
	San Juan	Culebra	Isabel Segunda	Yabucoa	Arecibo	Fajardo	Esperanza	Magueyes	Mayaguez*
Measured Data	0.959	0.580	0.812	1.515	0.722	ND	ND	ND	0.58
MIKE21	0.697	0.289	0.747	0.995	0.743	1.276	0.822	0.349	0.427
DELFT3D	0.706	0.424	1.071	0.952	0.801	1.664	0.843	0.260	0.443
TELEMAC	0.675	0.328	0.738	1.049	0.850	1.687	0.916	0.399	0.632
FIST	0.713	0.27	1.15	1.008	0.747	1.475	0.867	0.332	0.787

* The gage stopped working just after the peak water level

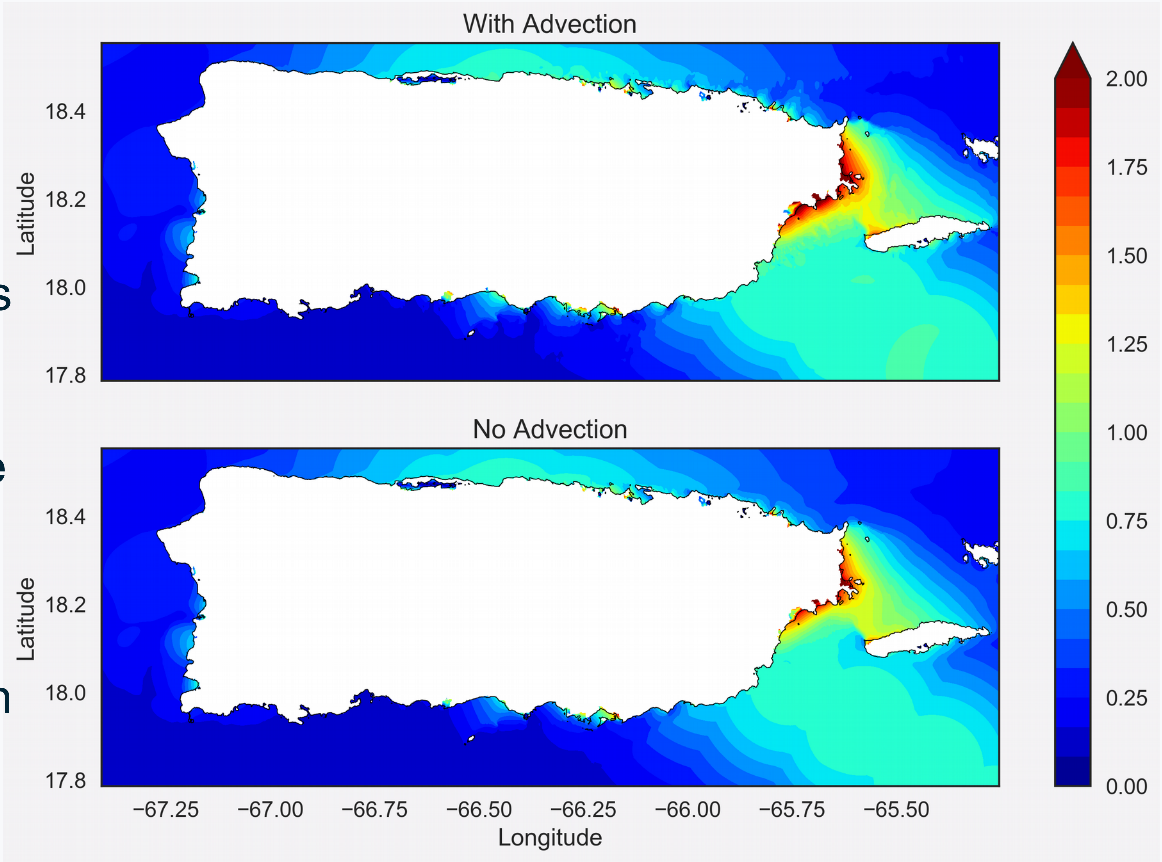
Models	Hurricane MARIA: RMSE (m)*								
	San Juan	Culebra	Isabel Segunda	Yabucoa	Arecibo	Fajardo	Esperanza	Magueyes	Mayaguez
MIKE21	0.13	0.12	0.14	0.21	0.10	ND	ND	ND	ND
DELFT3D	0.07	0.14	0.16	0.25	0.12	ND	ND	ND	ND
TELEMAC	0.11	0.12	0.11	0.21	0.10	ND	ND	ND	ND
FIST	0.19	0.21	0.22	0.25	0.12	ND	ND	ND	ND

* Analysis completed between Sept 19, 2017 09:00 and Sept 21, 2017 23:00

Error on peaks and NOAA Co-ops gauge time series

The Importance of Advection

- In the three PV models FIST, D-FLOW and TELEMAC (also ADCIRC) it is possible to turn off the non-linear terms
- In this case advection does not have a pronounced effect on results (rapid bathy changes at shoreline or maybe not?)
- Advection is expensive – SLOSH doesn't bother with it.
- Important for fast moving shallow shocked flows – PV not suitable anyway!



Conclusions

- Results for all models tested are broadly similar
- TELEMAC and D-FLOW FM are both very promising models for strom surge
- Run Time varies *dramatically* between models
- In the case of Puerto Rico a relatively small model domain appears to be sufficient for both the tide and surge and (maybe) wave modelling.
- Unsurprisngly, the wind field is *all important* – and hard to get right in forecast mode modelling
- Drag not investigated - Powell (2006) sector-based drag now in TELEMAC
- The proceedings will include results for Irma and more in-depth model analysis

Thank you for listening.
(Questions)

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