Hurricane Sandy (2012) Waves, Surge, and Circulation: Validation and Synoptic Analysis Using SWAN+ADCIRC

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13th International Workshop on Wave Hindcasting and Forecasting and
4th Coastal Hazards Symposium

October 29, 2013

Motivation

- Hurricane Sandy (2012)
  - Category 2 while in the Atlantic
  - Largest Atlantic hurricane on record
  - Record inundation in and around New York for a storm with winds that regionally never exceeded 30 m/s
- Evaluate hindcast skill of the SWAN+ADCIRC model
  - Wave and surge validation
- Evaluate driving processes that led to the extra-ordinary levels of storm surge
  - Geostrophic set-up
  - Wave induced set-up
  - Tidal nonlinearities
  - Forward speed

Summary

- SWAN+ADCIRC hindcast with similar skill as Gulf hurricane models
  - Waves and surge validate with high skill
  - When applying ***Oceanweather Inc.*** winds
  - With sufficient grid resolution and accurate topography/bathymetry
- Processes that led to the extra-ordinary storm surge
  - Storm size
  - Geostrophic set-up
  - Wave induced set-up vital behind Long Island barrier islands
  - Tidal add is linear for peak surge but not for resonant resurgence in Long Island Sound
  - Forward speed does not strongly impact surge unlike eastern Louisiana

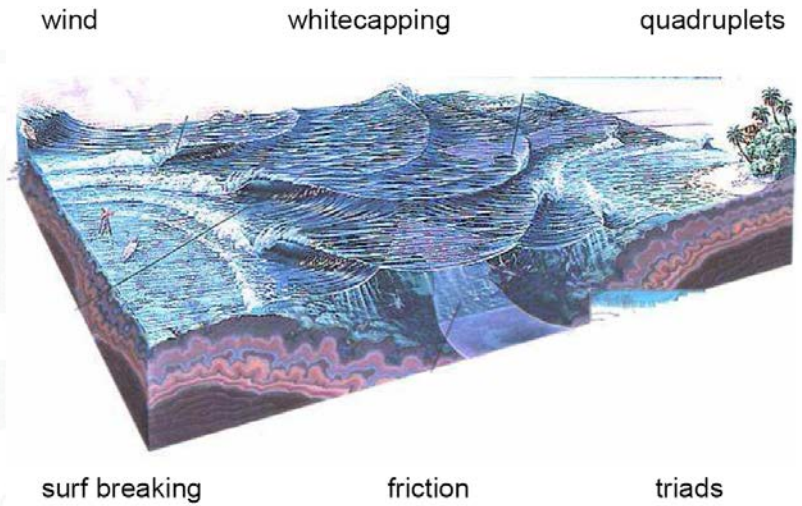
Methods

- SWAN+ADCIRC Wave and Circulation Model Overview
  - Coupling
  - High Performance Computing
  - Air-sea interaction
  - Validation data
  - Ocean, Coast, Floodplain Applications
- SWAN+ADCIRC Model for New York and vicinity

SWAN+ADCIRC Model – Coupled waves and current on identical unstructured grids

- ADCIRC solves for water surface elevations and currents in two and three dimensions

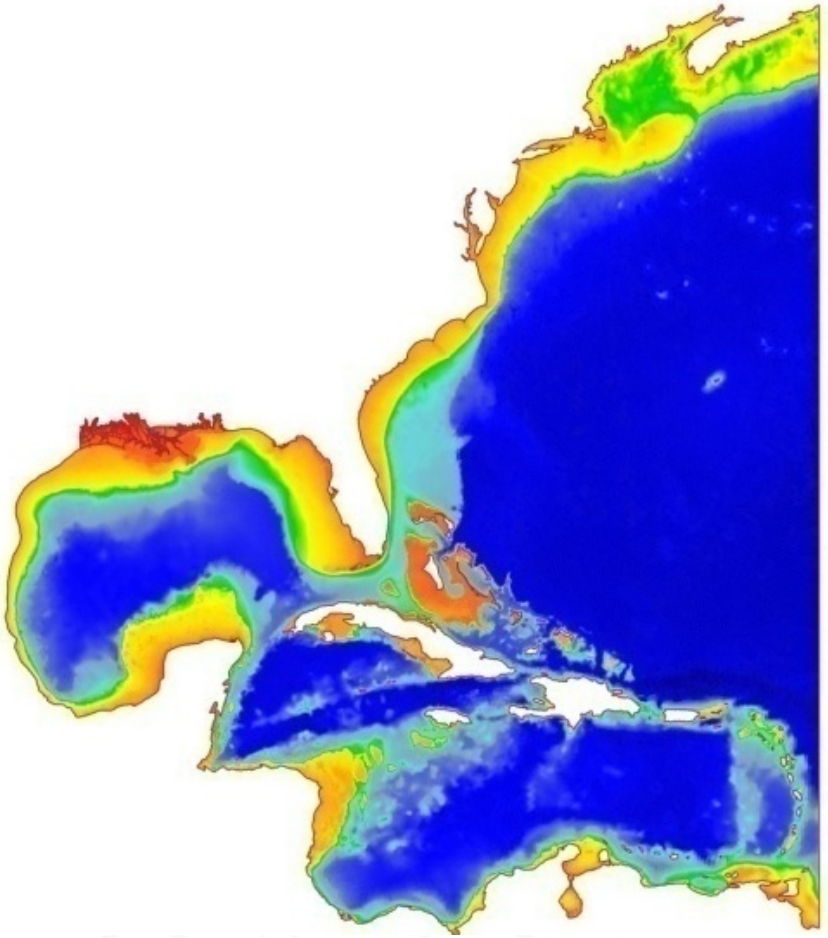
- SWAN solves the wave action density and is a non-phase resolving wave model with wave energy represented by a spectrum

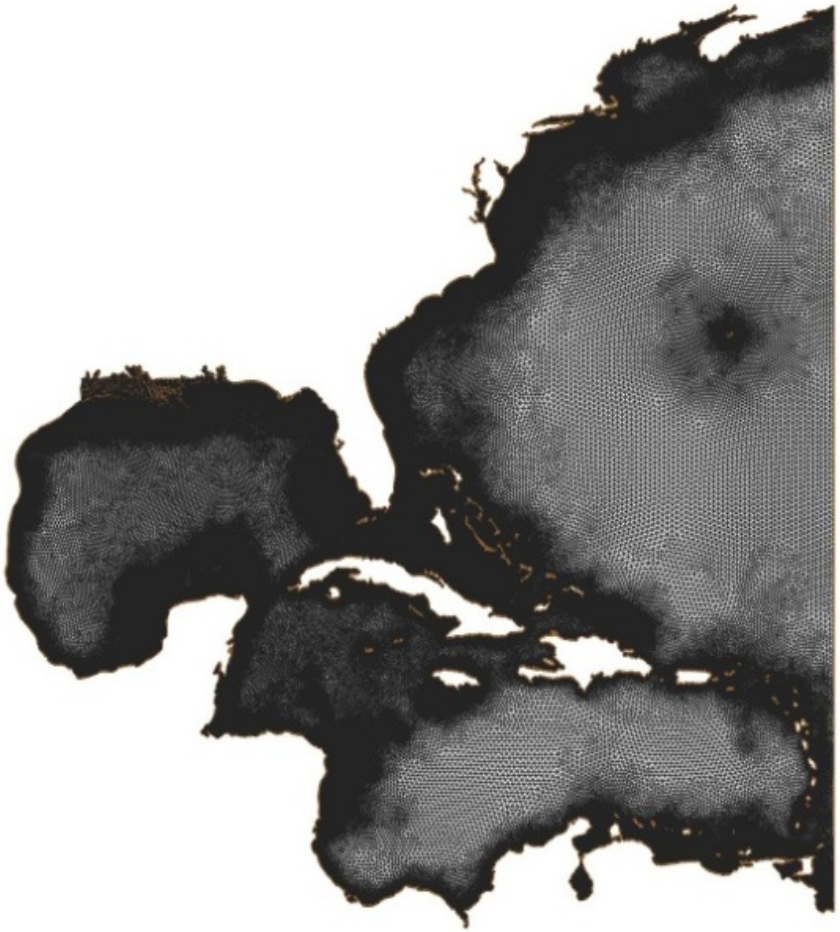


- ADCIRC and SWAN interact
  - Water levels and currents affect waves
  - Wave breaking forces water level setup and currents

Dietrich et al., ***Coastal Engineering***, **58**, 45-65, 2011.

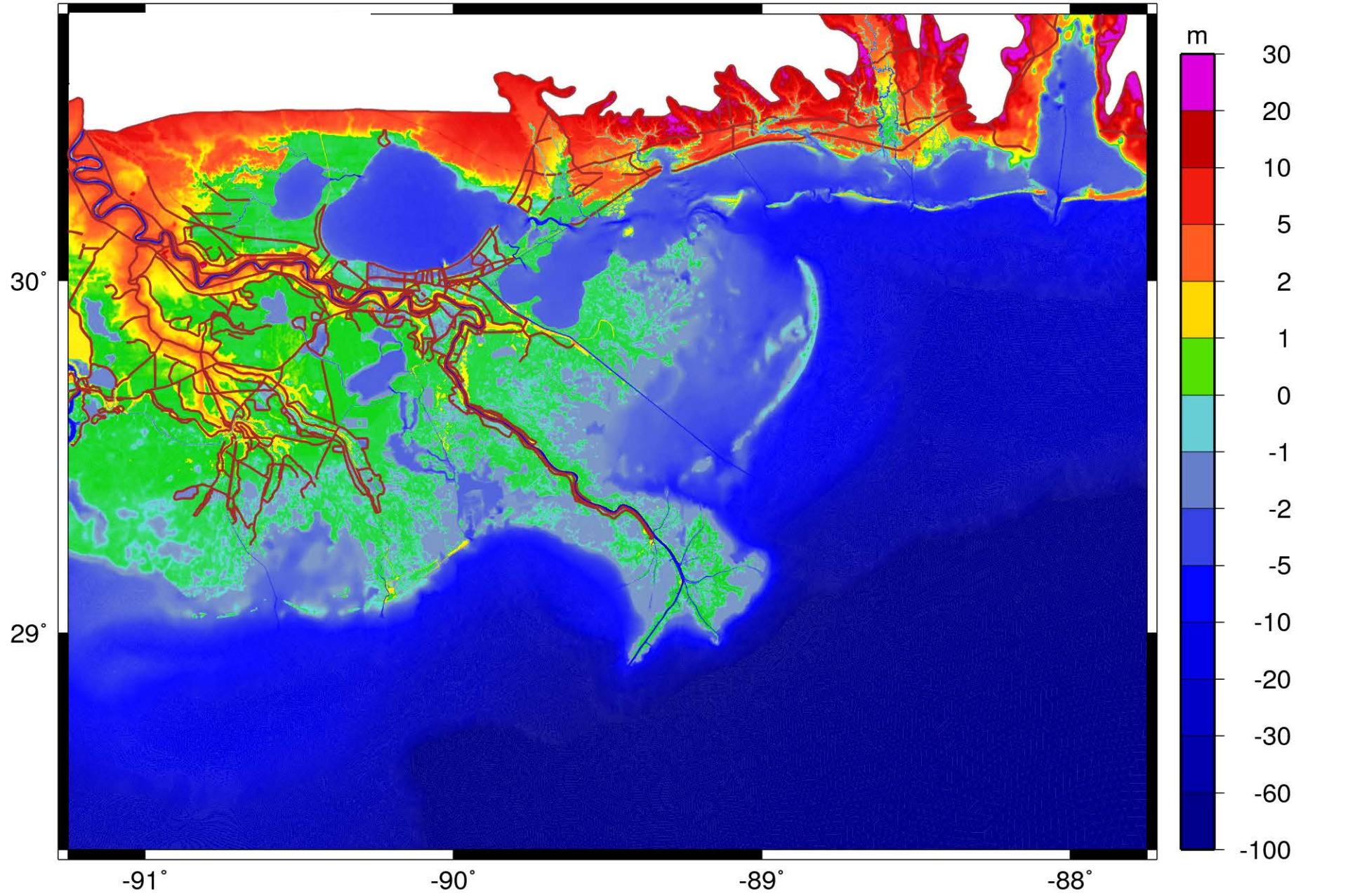
SL16v18 Bathymetry &Topography and unstructured mesh



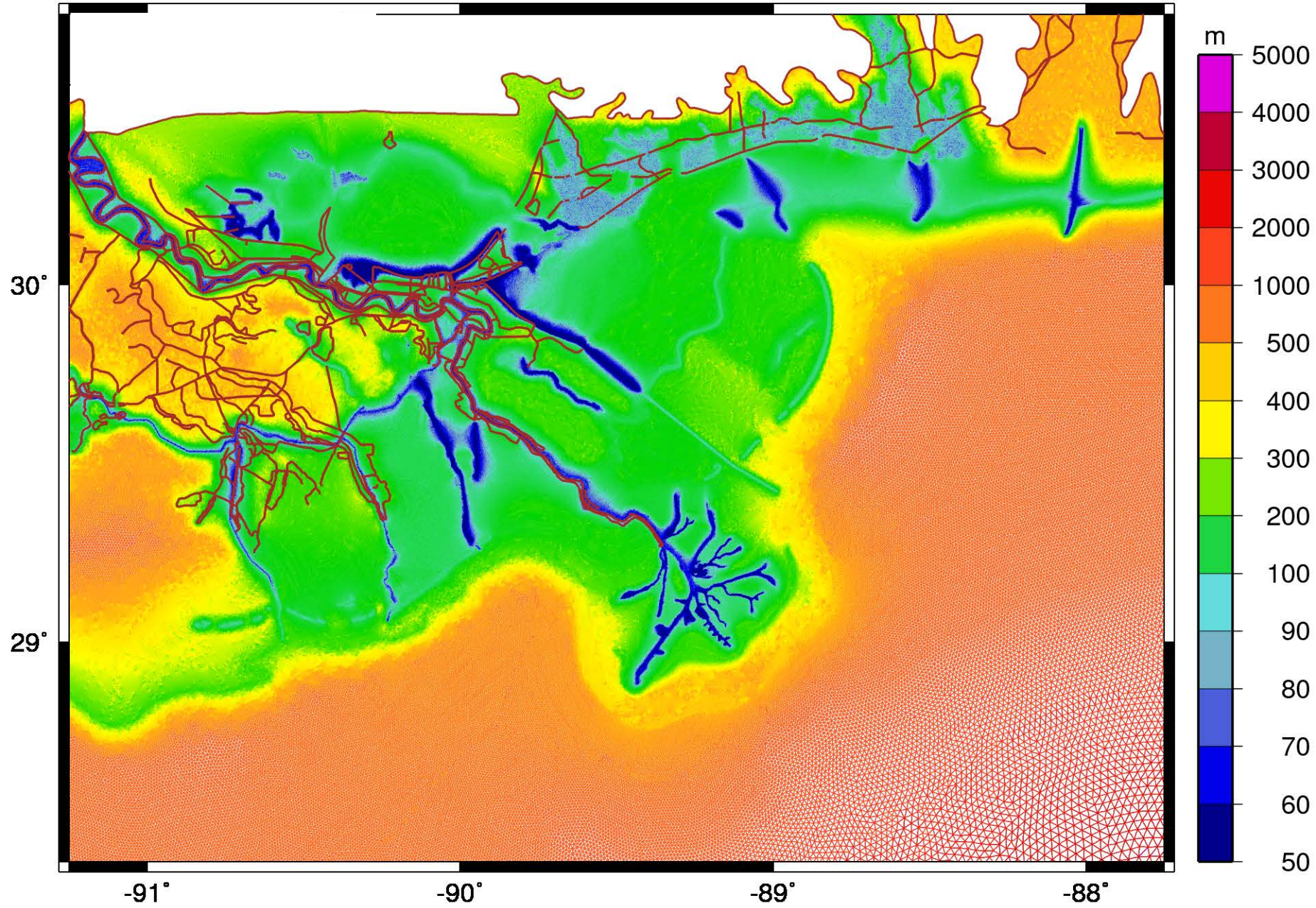


Dietrich et al., ***Monthly Weather Review***, **139**, 2488-2522, 2011.
Kennedy et al., ***Geophysical Research Letters***, **38**, L08608, 2011.
Kerr et al., ***Journal of Waterway, Port, Coastal, and Ocean Engineering***, **139,** 326-335, 2013.
Martyr et al., ***Journal of Hydraulic Engineering***, **139**, 5, 492-501, 2013.
Hope et al., ***Journal of Geophysical Research: Oceans***, DOI 10.1002/jgrc.20314, In Press, 2013.
Kerr et al., ***Journal of Geophysical Research: Oceans***, DOI 10.1002/jgrc.20305, In Press, 2013.

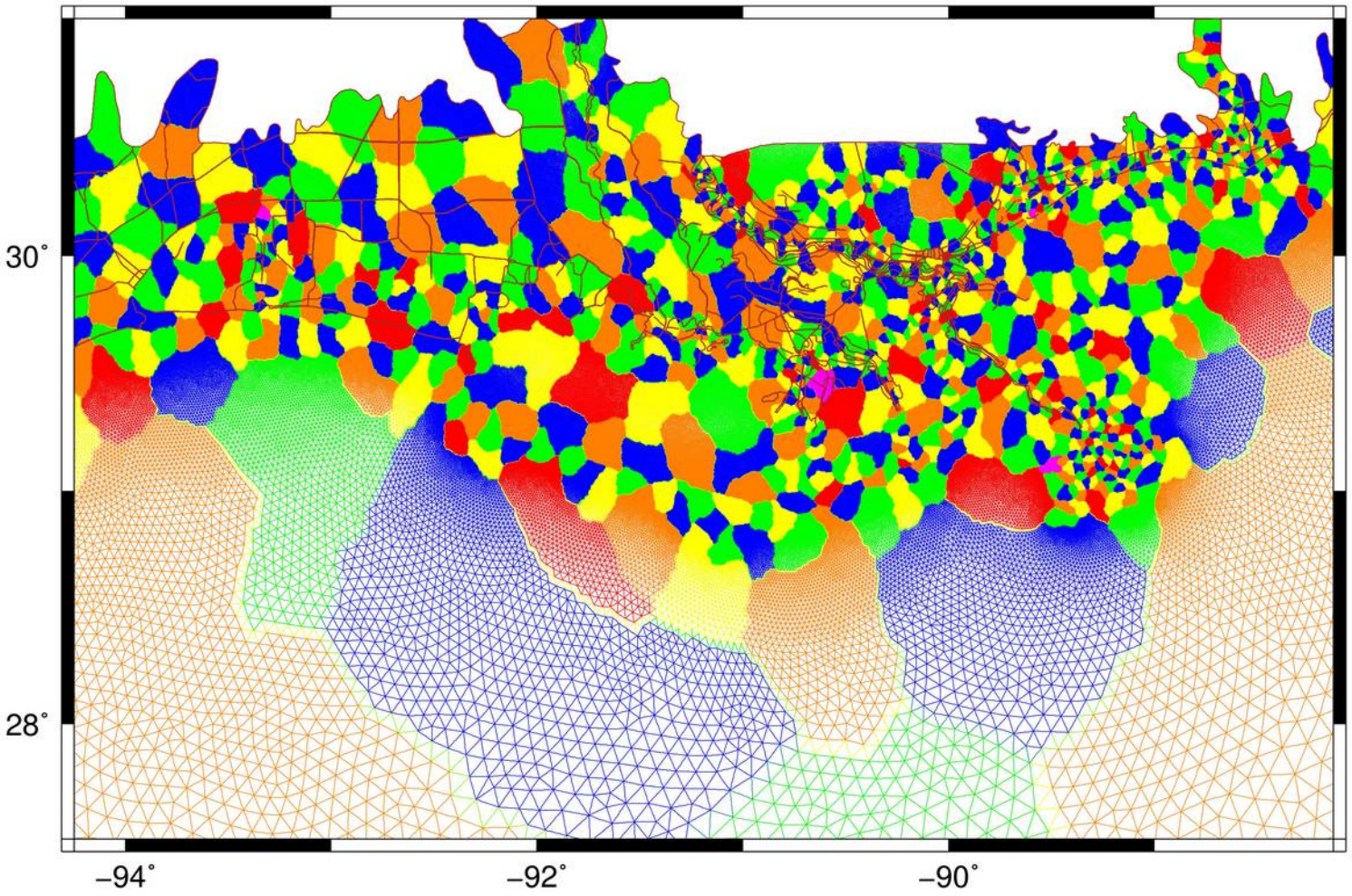
SL16v18 Bathymetry and Topography



SL16v18 Mesh Sizes

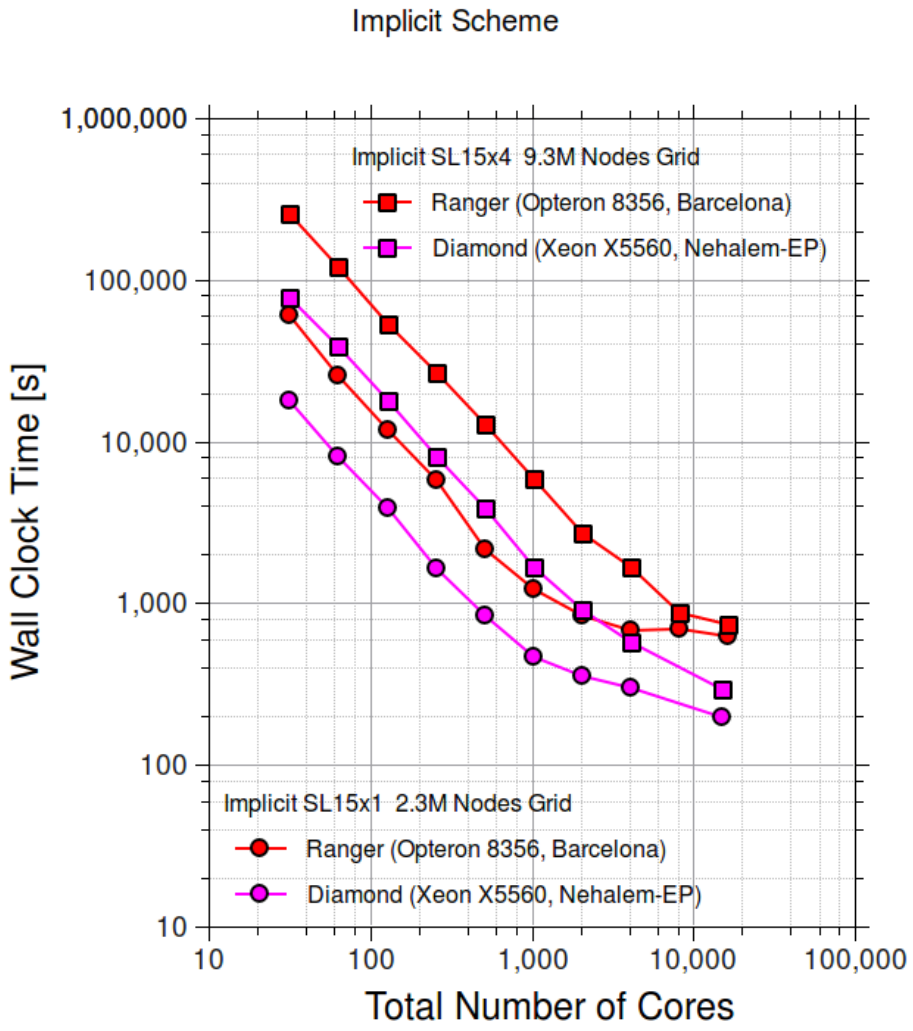


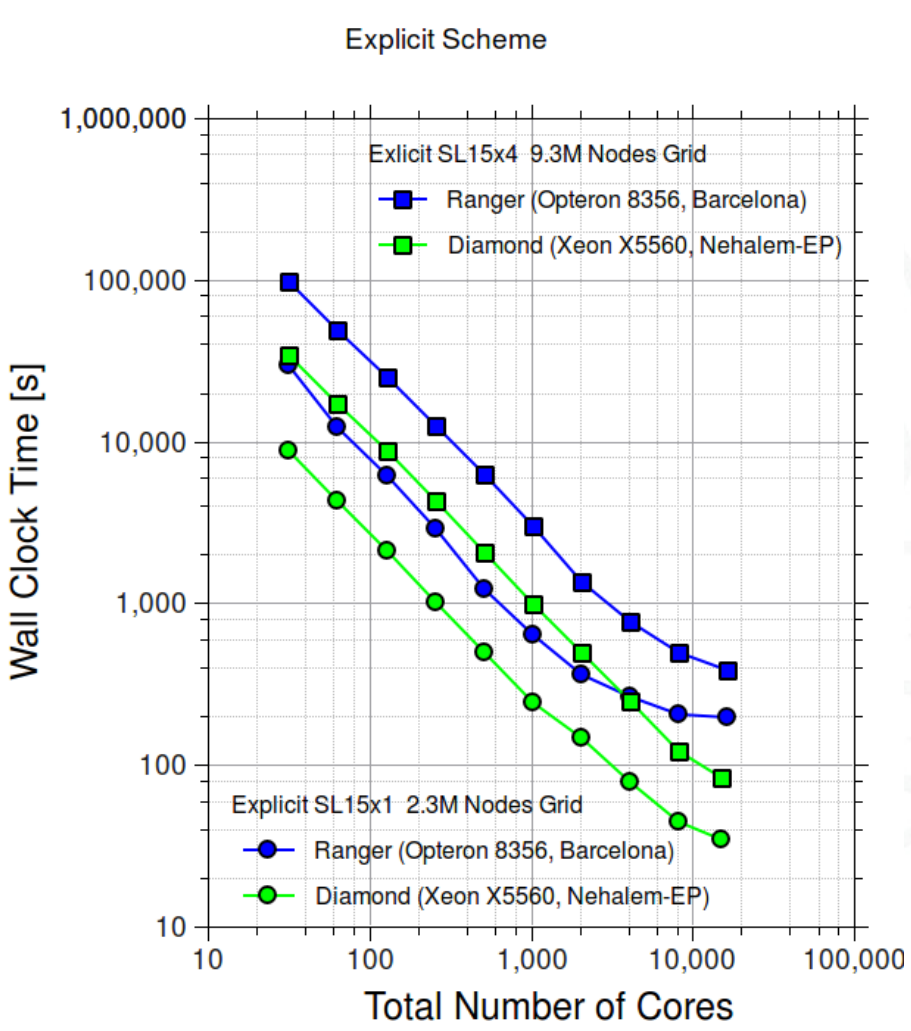
MPI Based Domain Decomposition – Overlapping Element Layer Node to Node Communication



SL15v7l Grid Decomposition on 1024 Cores

Parallel Performance on TACC Ranger and ERDC Diamond





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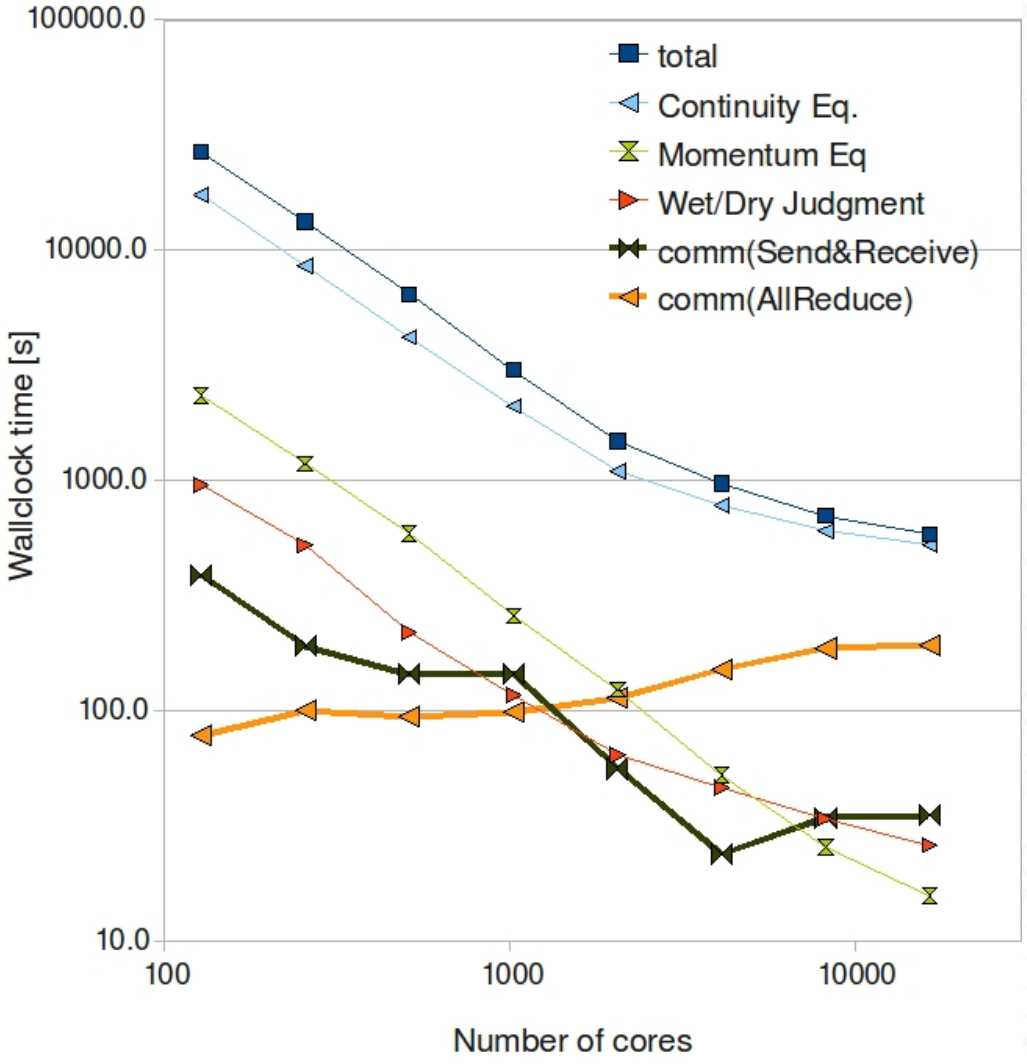
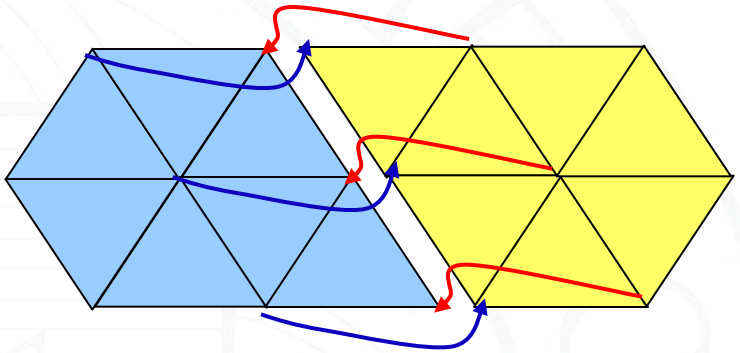
Tanaka et al., ***Journal of Scientific Computing***, **46**, 329-358**,** 2011.

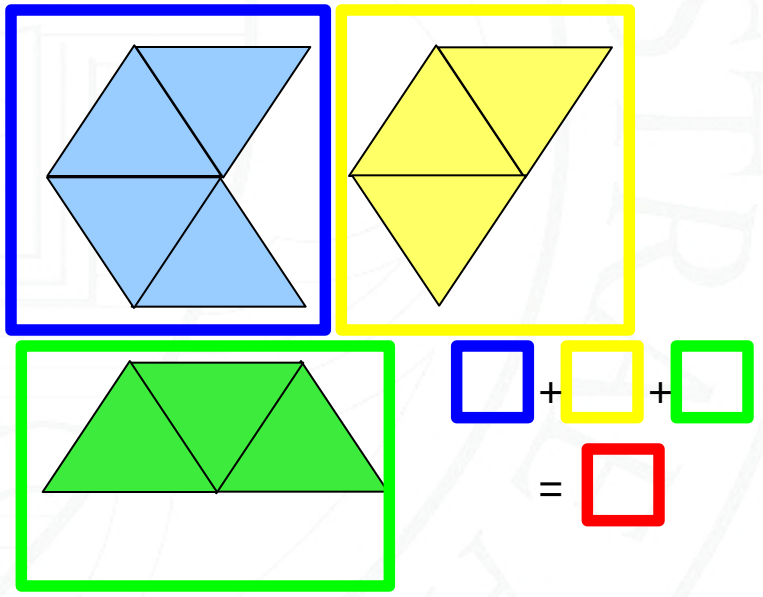
Wall clock versus number of cores for Implicit CG 9.4 million node grid



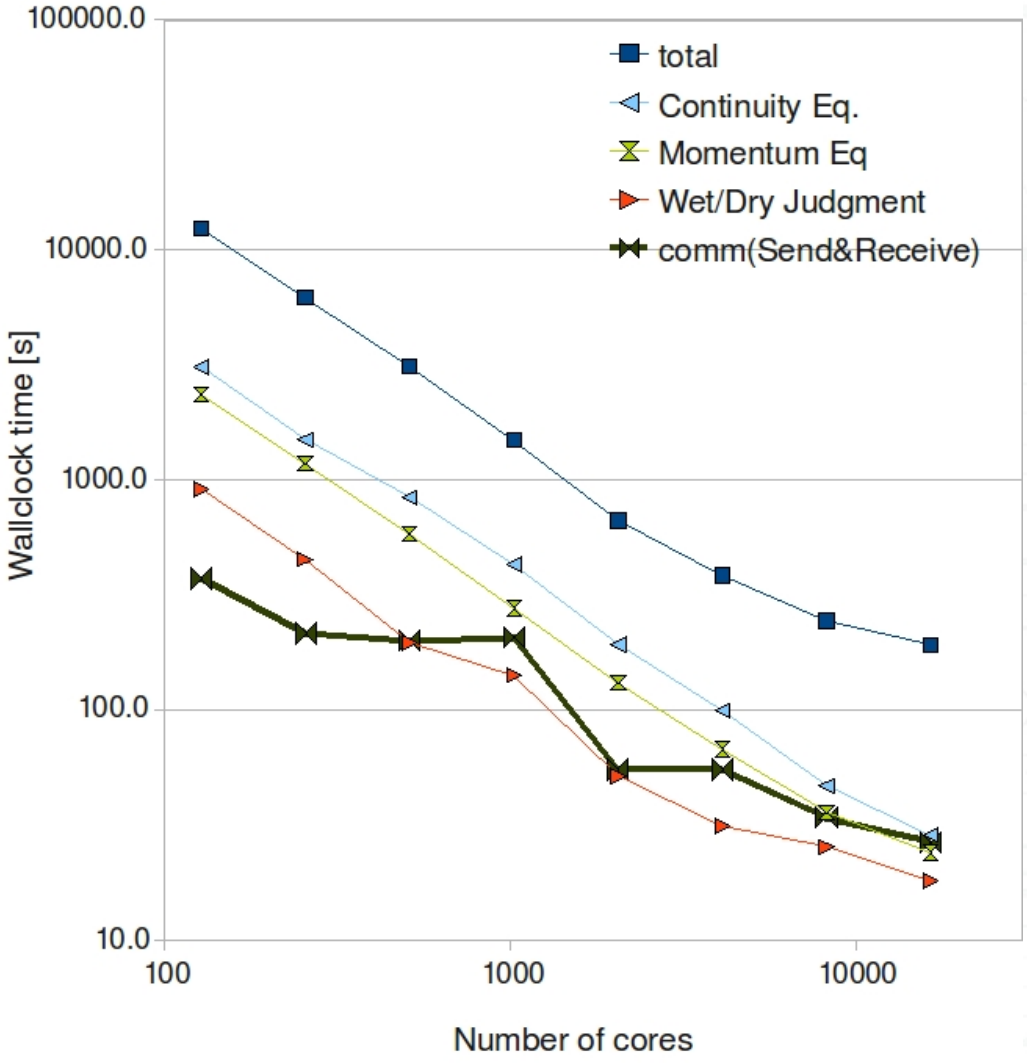
Comm (Send&Receive)



Comm (AllReduce)



Wall clock versus number of cores for Explicit CG 9.4 million node grid



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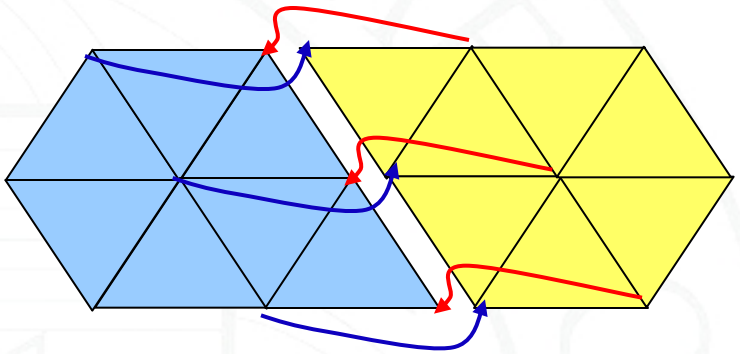
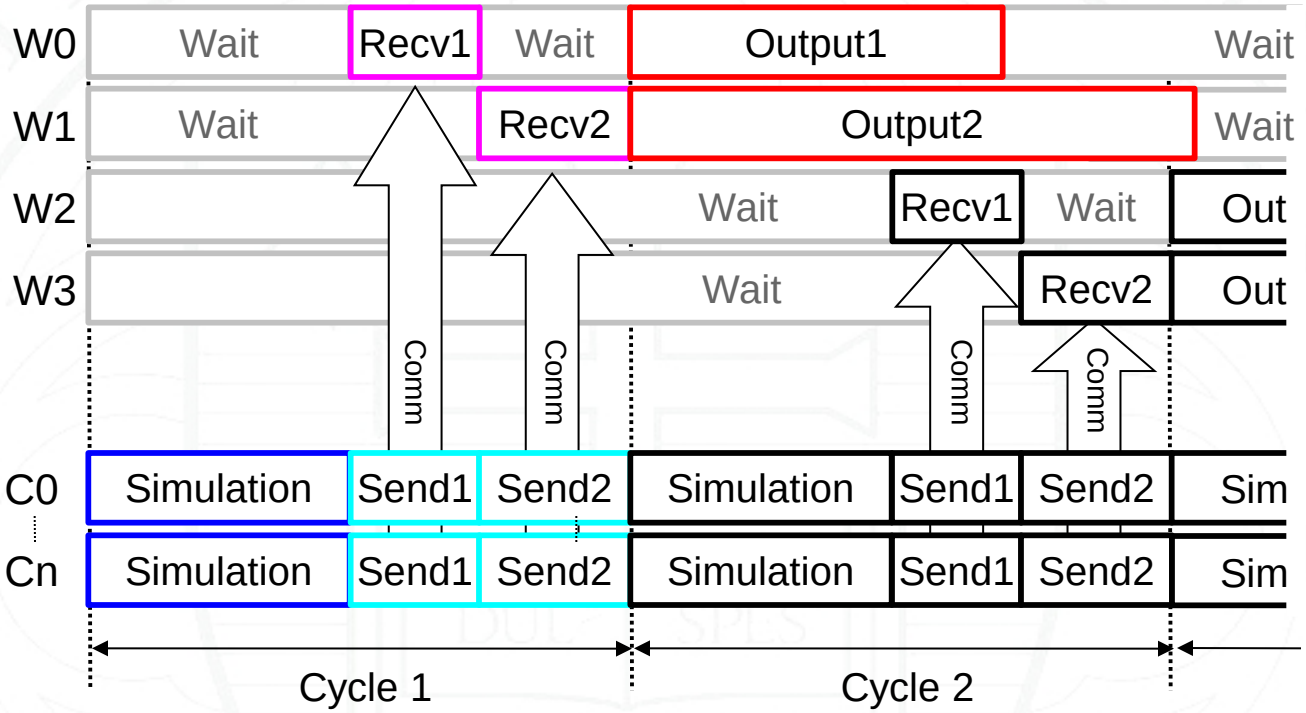
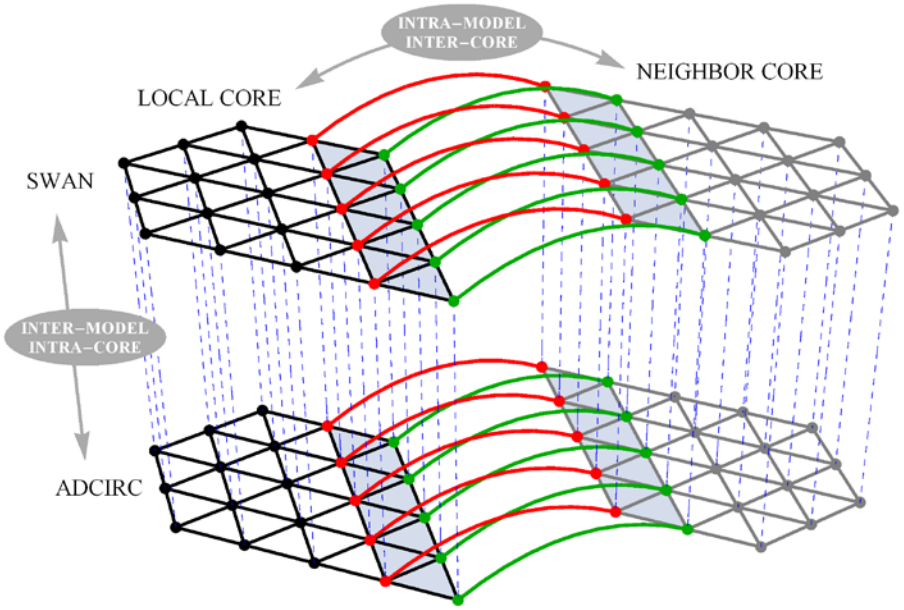


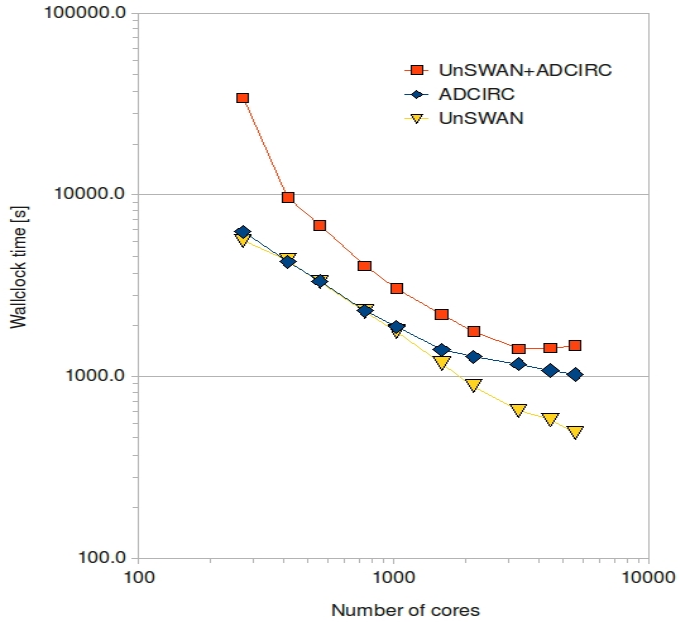
Output options for high performance

Sequential batches of writer cores;



SWAN+ADCIRC Model – Coupled waves and current on identical unstructured grids





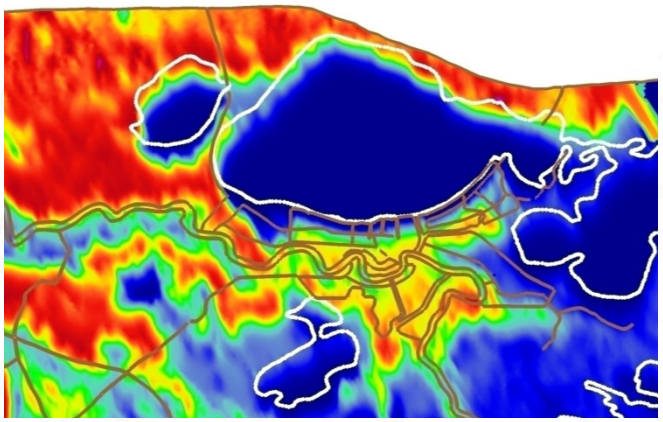
- SWAN+ADCIRC communication is very efficient since
  - Inter-model is intra-node
  - Intra-model in inter-node but only on edges adjacent sub-domains
  - For the TX2008-r09 grid with 3,323,388 nodes
  - Time steps: ADCIRC 1 sec and SWAN 10 min
  - Performance on Diamond

SWAN+ADCIRC-CG: 14 wall clock per day of simulation

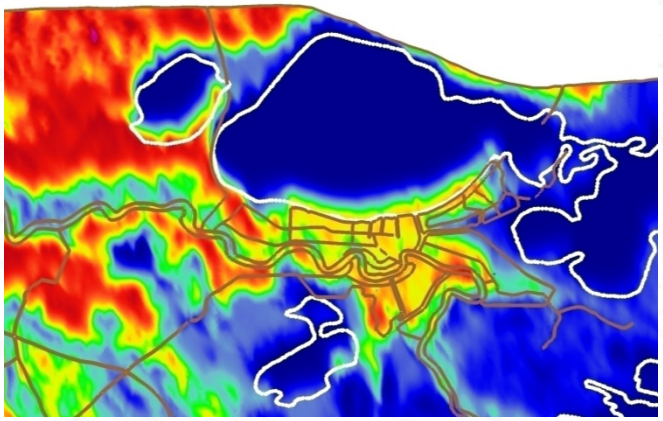
Dietrich et al., ***Journal of Scientific Computing***, **52**, 468-497 2012.

Directional roughness and canopies in determining 10m wind boundary layer adjustment

North Wind

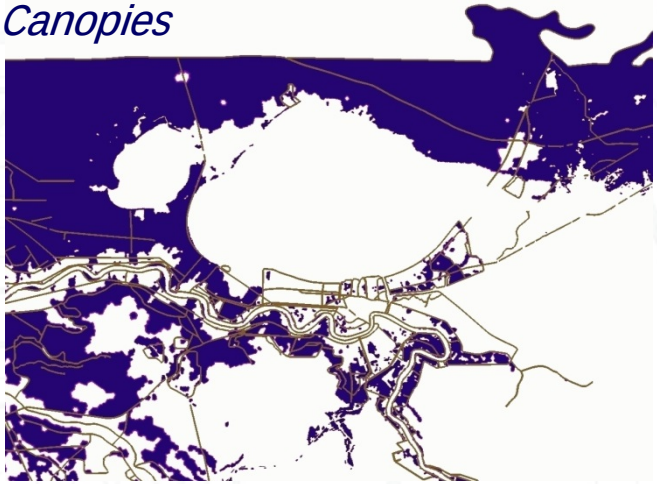


South Wind



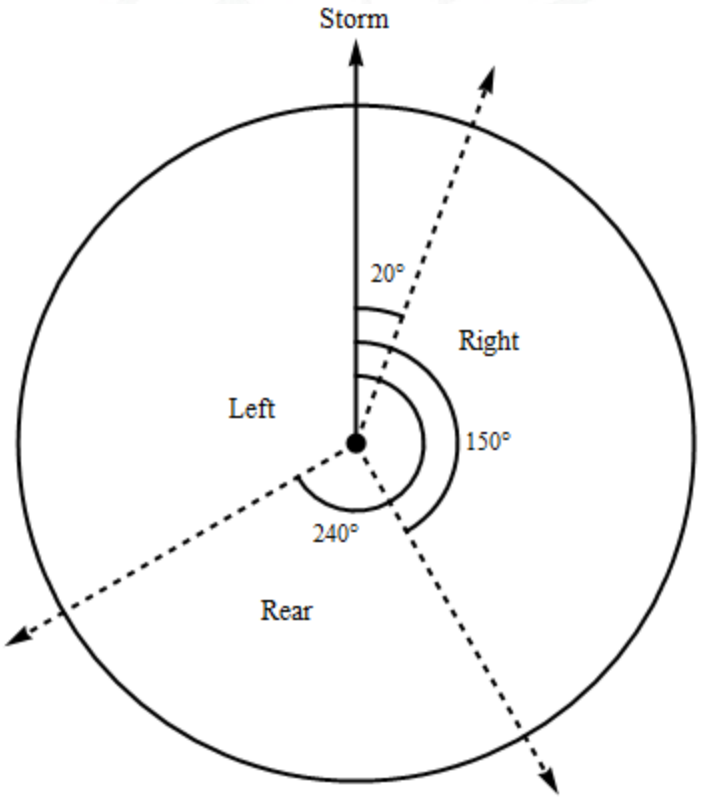
Directional wind reduction is based on upwind roughness as well as the level of inundation

Canopies

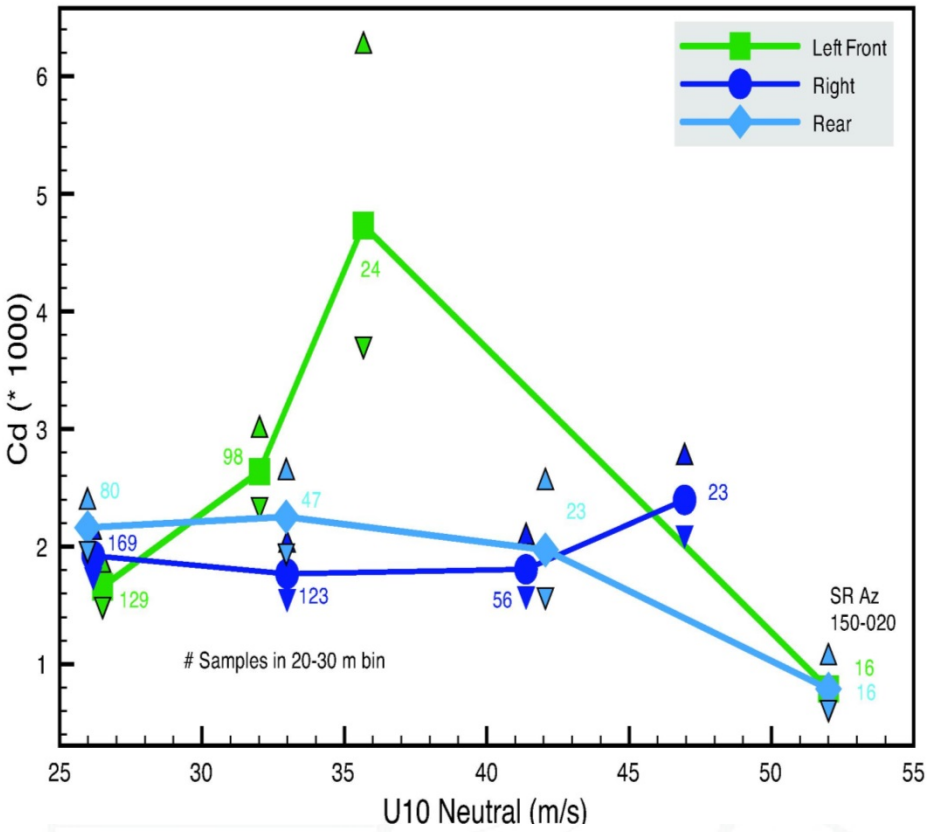


Dense canopies are determined based on land cover and assume negligible penetration of momentum

Sector based drag laws



Extents of sectors in relation to direction of storm movement; Powell (2006)



Wind drag coefficient variability by storm sector; Powell (2006)

Availability of Measured Data *in the Gulf and Louisiana*

	Katrina (2005)		Rita (2005)	
High-Water Marks	**Total:**	*399*	**Total:**	*84*
	URS/FEMA	193	URS/FEMA	84
	USACE/IPET	206		
Time Series	**Water Levels:**	*11*	**Water Levels:**	*23*
	NOAA	3		
	USGS (Permanent)	6		
			USGS (Deploy LA)	23
	USACE	2		
	Wave Parameters:	*17*	**Wave Parameters:**	*12*
	NDBC	14	NDBC	11
	CSI (LSU)	3	CSI	1

Availability of Measured Data *in the Gulf and Louisiana*

	Gustav (2008)		Ike (2008)	
High-Water Marks	**Total:**	*82*	**Total:**	*181*
	URS/FEMA	82	URS/FEMA (LA)	181
Time Series	**Water Levels:**	*438*	**Water Levels:**	*366*
	NOAA	26	NOAA	26
	USGS (Permanent)	48	USGS (Permanent)	20
	USGS (Deploy LA)	43	USGS (Deploy LA)	16
	USACE (LA)	51	USACE (LA)	50
	CSI (LSU)	5	CSI (LSU)	5
	ND (Kennedy)	16	ND (Kennedy)	
	USACE (Smith)	6	USACE (Smith)	6
	CRIMS	243	CRIMS	243
	Wave Parameters:	*39*	**Wave Parameters:**	*23*
	NDBC	12	NDBC	12
	CSI (LSU)	5	CSI	5
	ND (Kennedy)	16	ND (Kennedy)	
	USACE (Smith)	6	USACE (Smith)	6

Methods

- SWAN+ADCIRC Wave and Circulation Model Overview
  - Coupling
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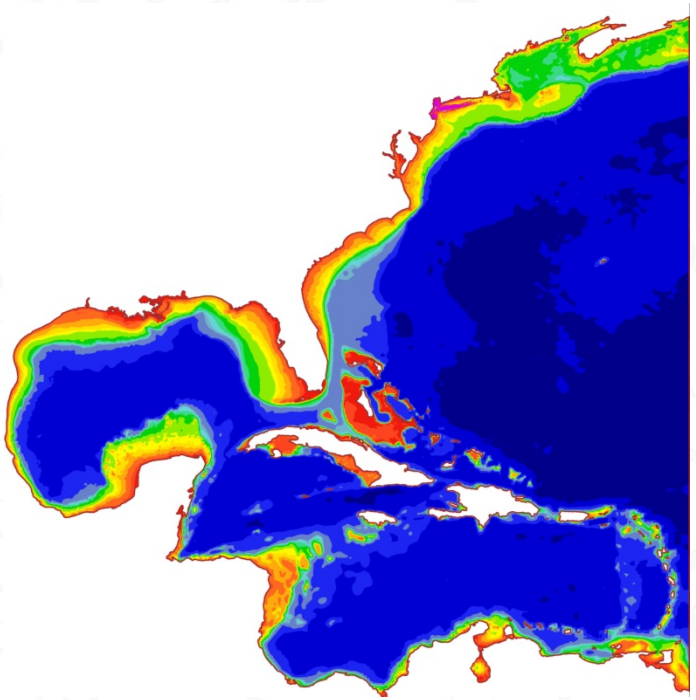
  - Ocean, Coast, Floodplain Applications

- SWAN+ADCIRC Model for New York and vicinity

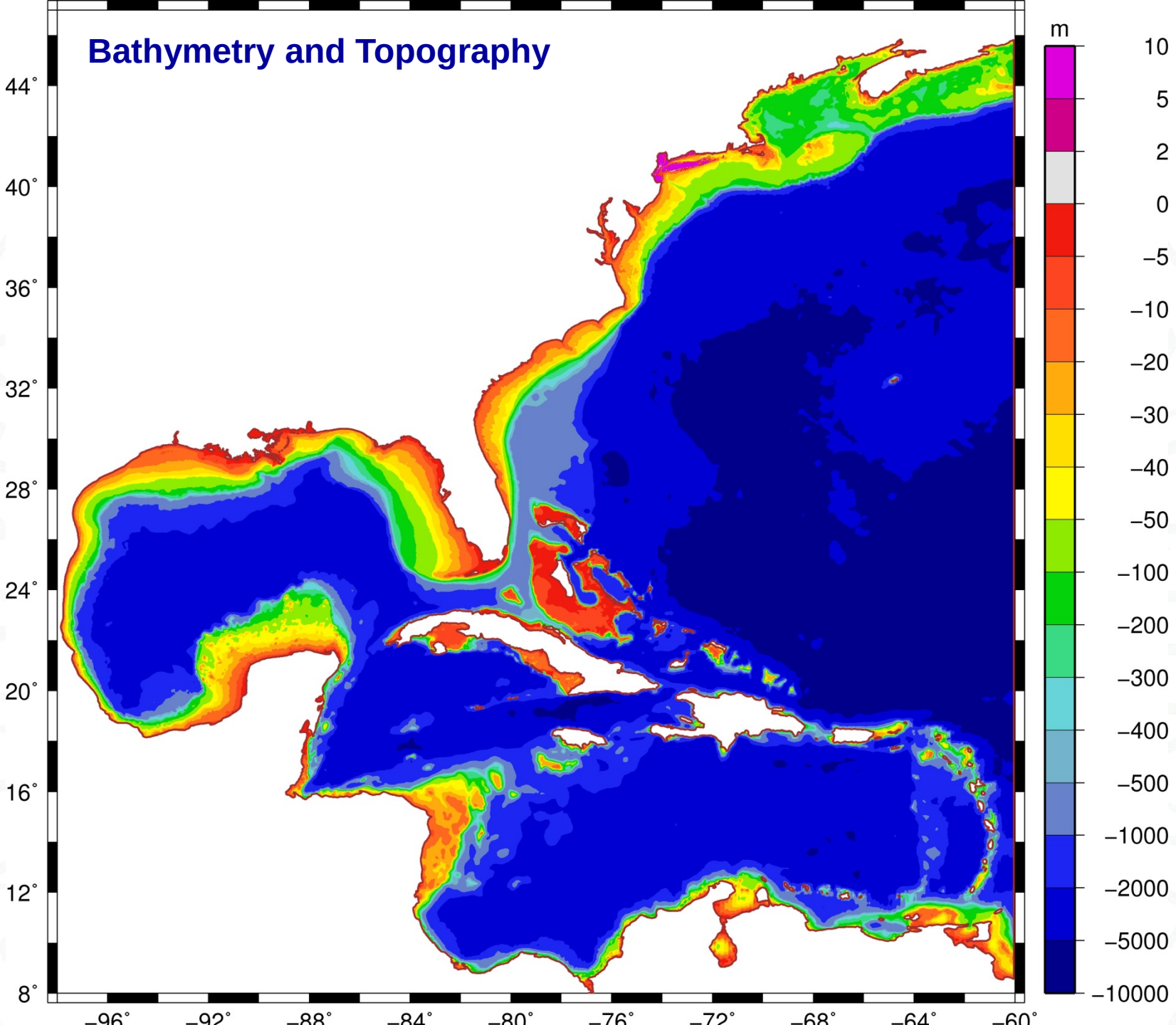
Model for New York and Vicinity

- Western North Atlantic – Gulf of Mexico
- New York and Connecticut bays and estuaries, Hudson River
- Low lying floodplains
- Resolution nearshore and inland 200-400m down to 30m
- Fully incorporates high resolution features, channels, barrier islands and wave breaking zones

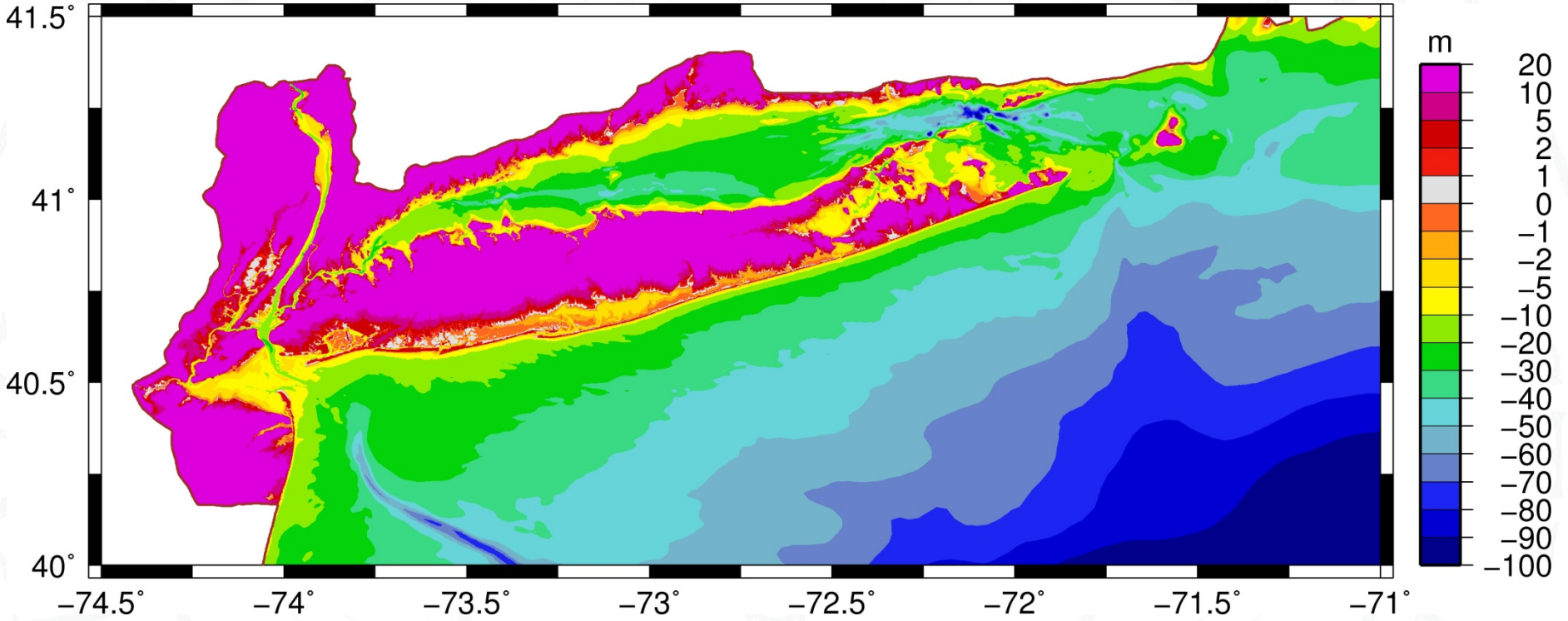


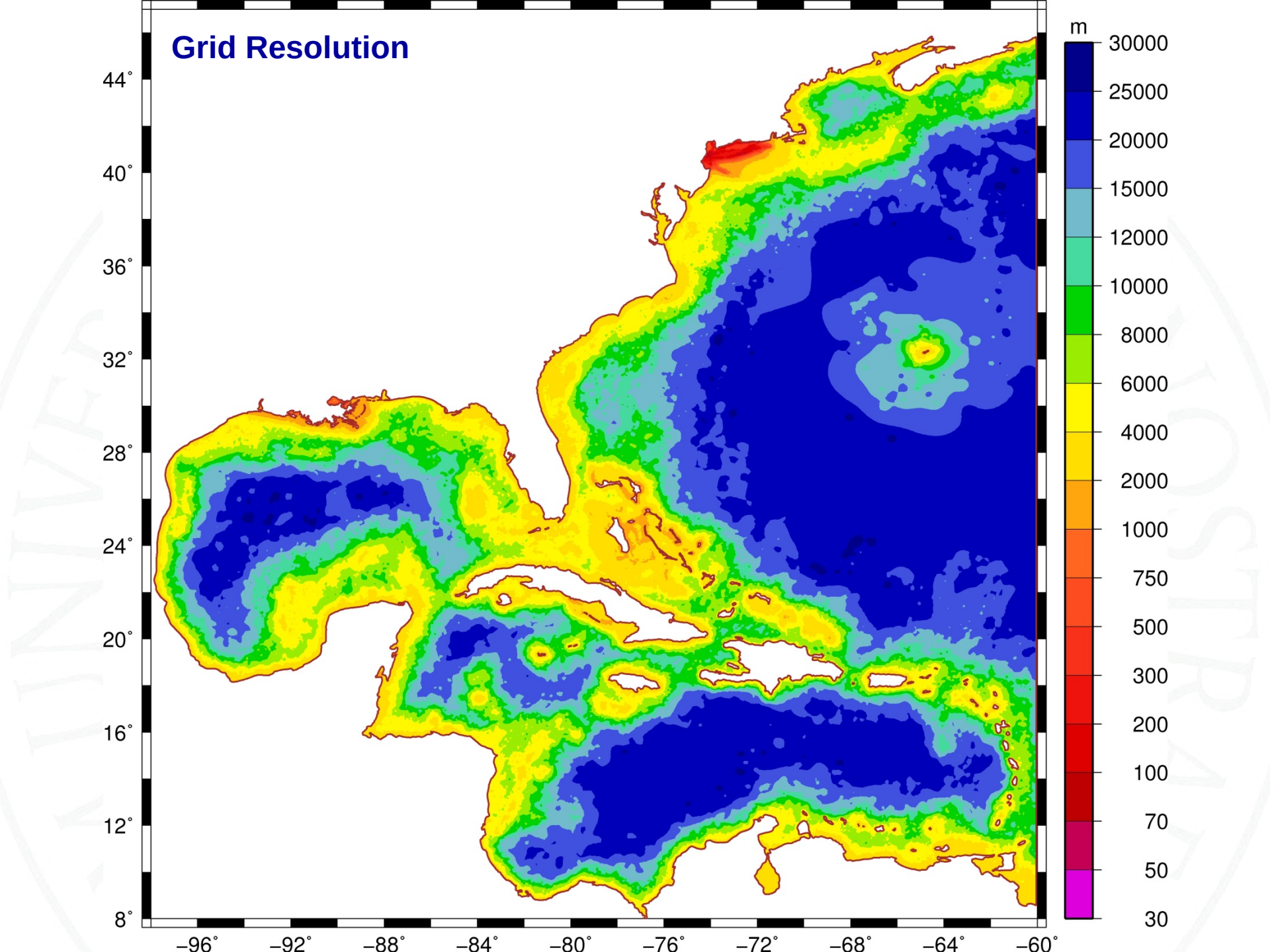
- 931,357 nodes
- Time steps: ADCIRC 0.25 sec; SWAN 10 min

Bathymetry and Topography

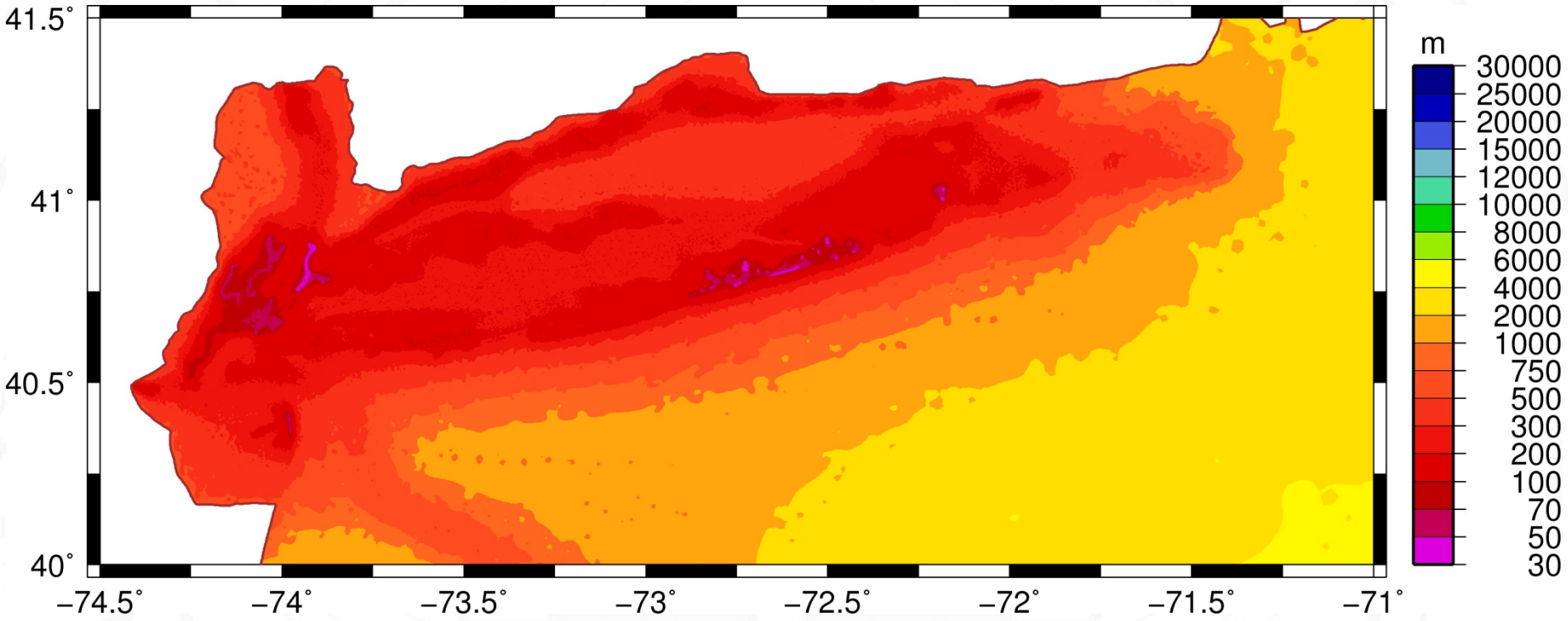


Bathymetry and Topography

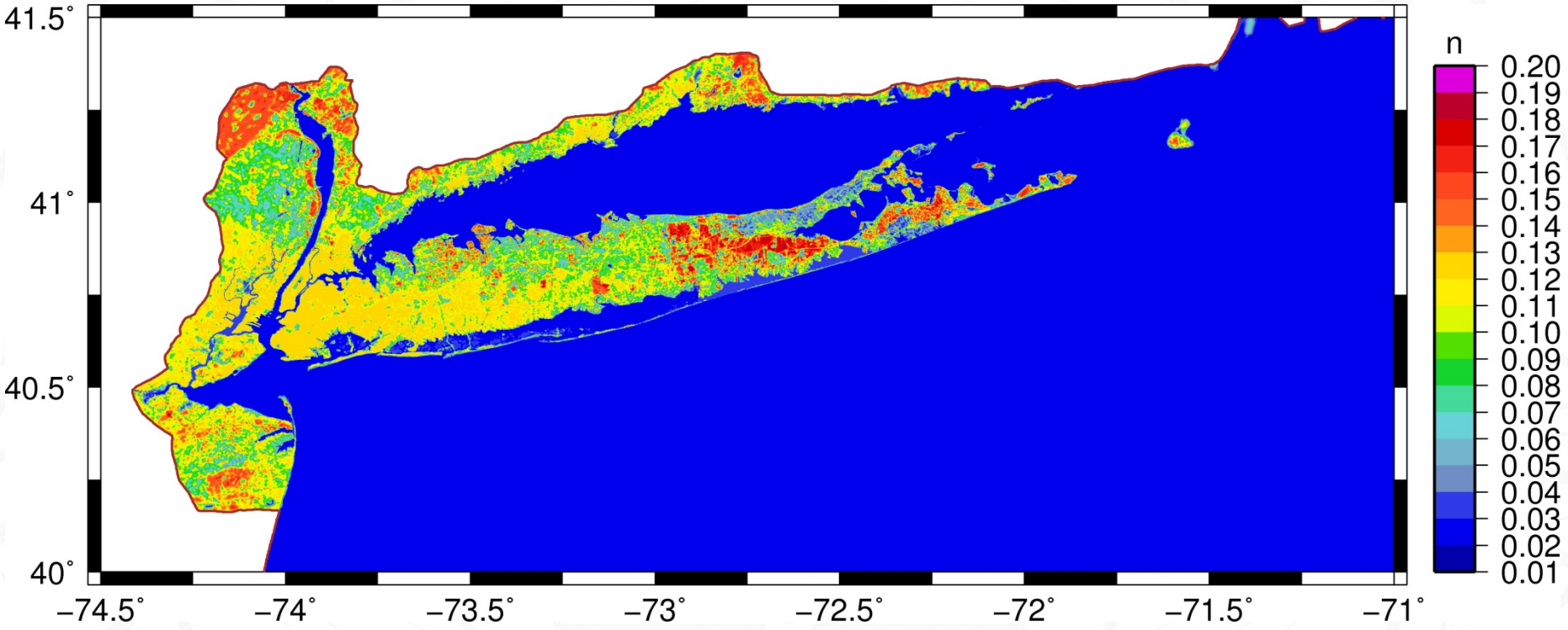



Grid Resolution
m
30000
25000
20000
15000
12000
10000
8000
6000
4000
2000
1000
750
500
300
200
100
70
50
30
44˚
40˚
36˚
32˚
28˚
24˚
20˚
16˚
12˚
8˚
−96˚
−92˚
−88˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

Grid Resolution

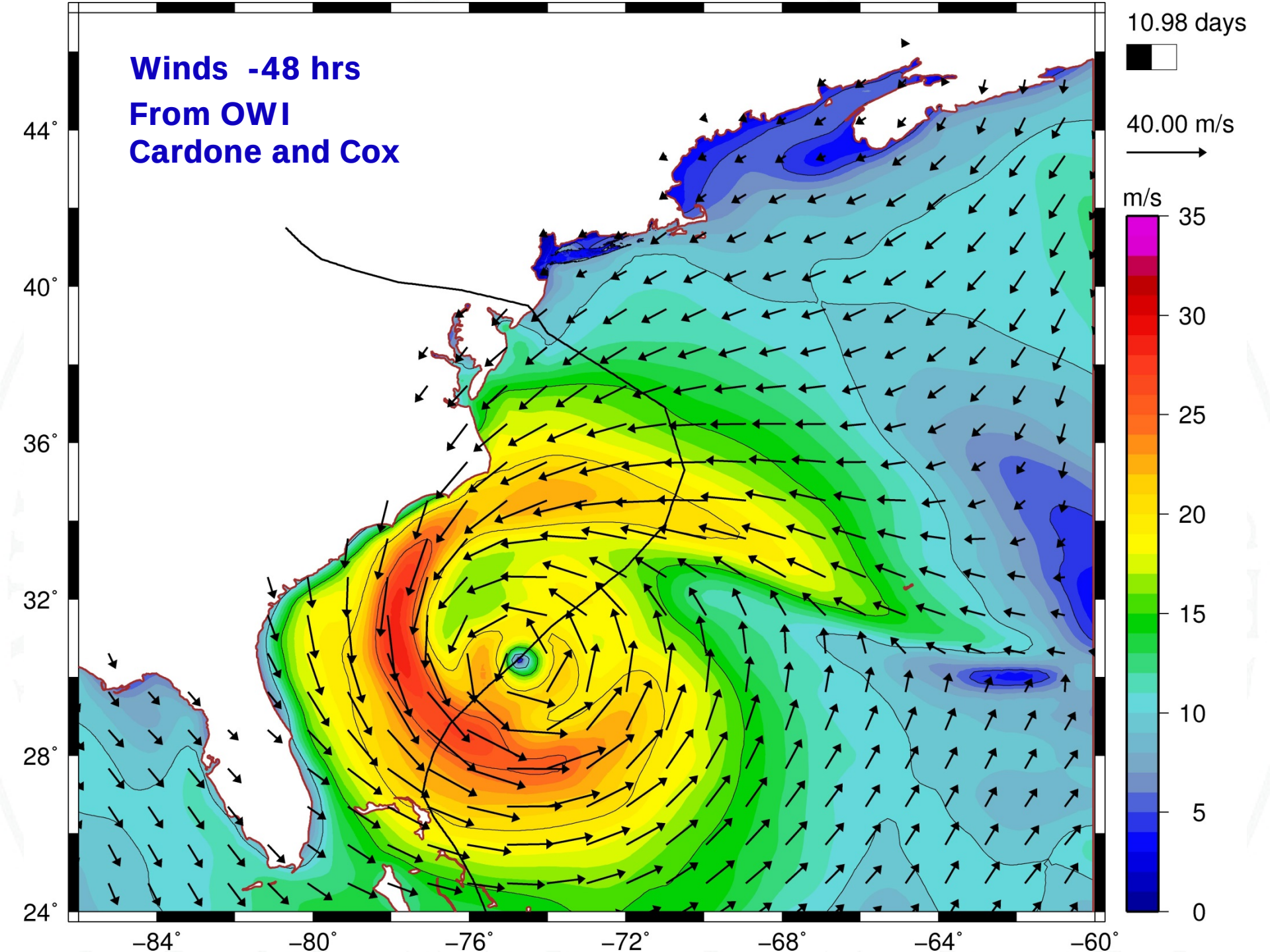


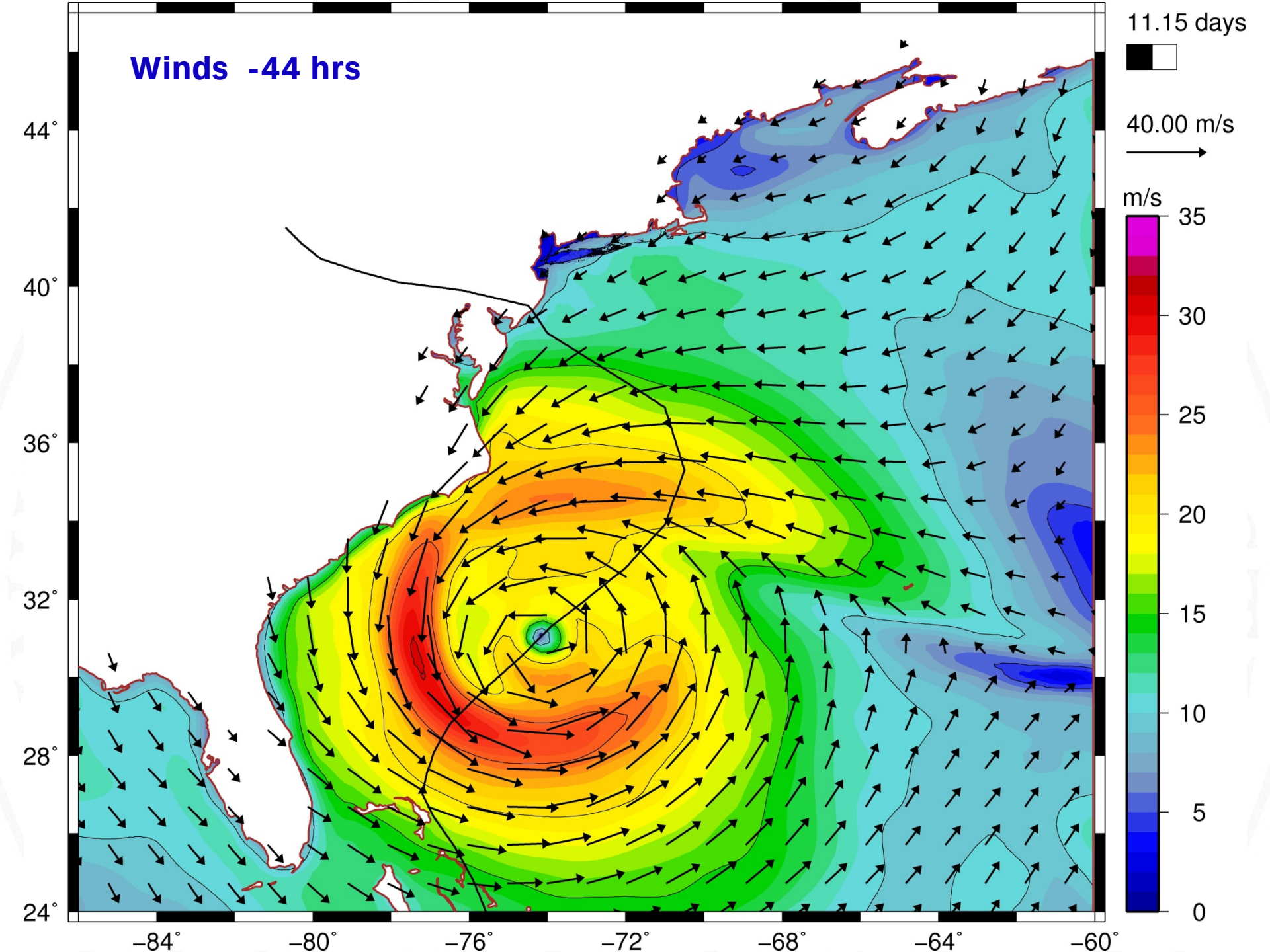
Manning n

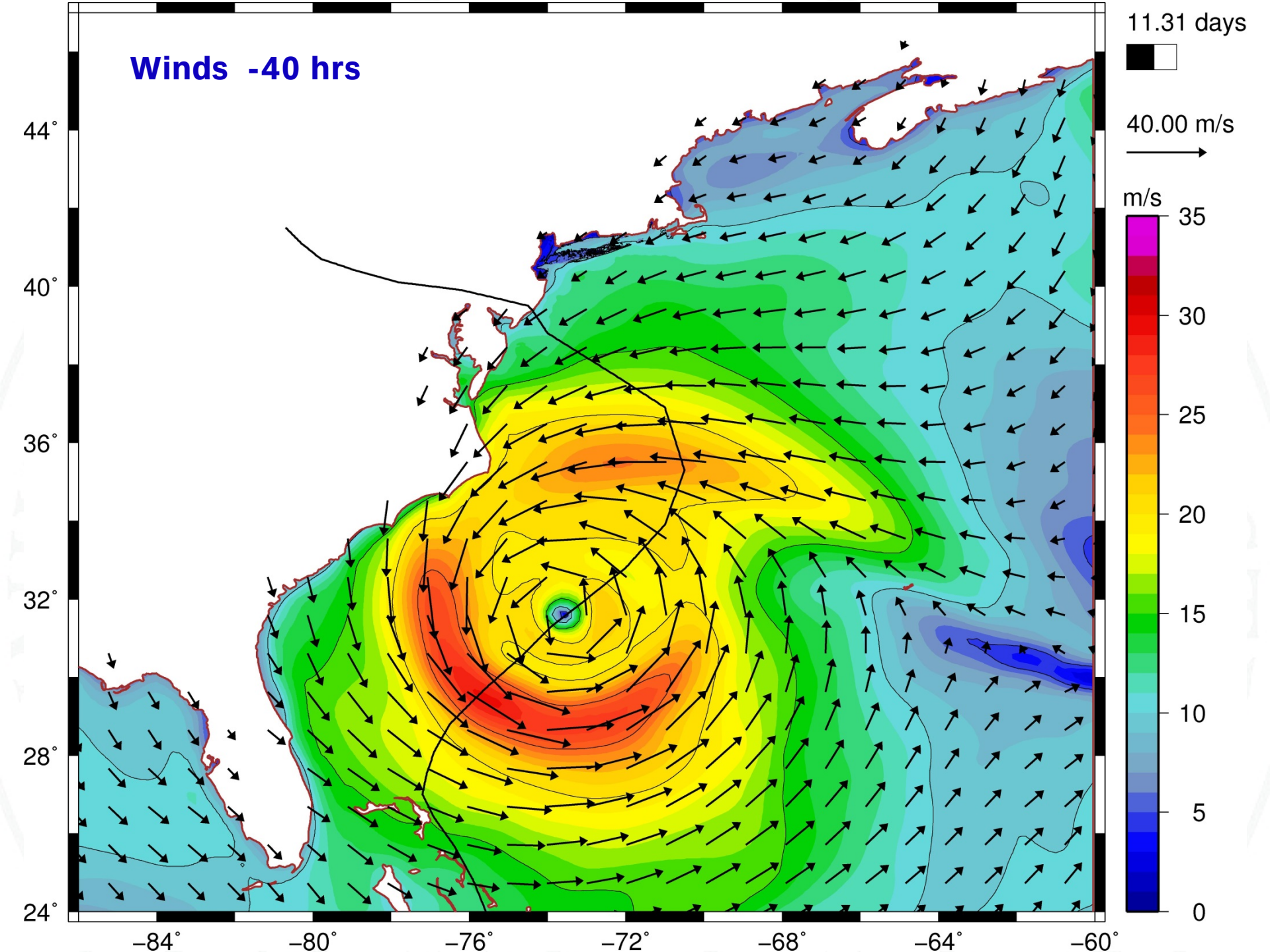

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
n
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01

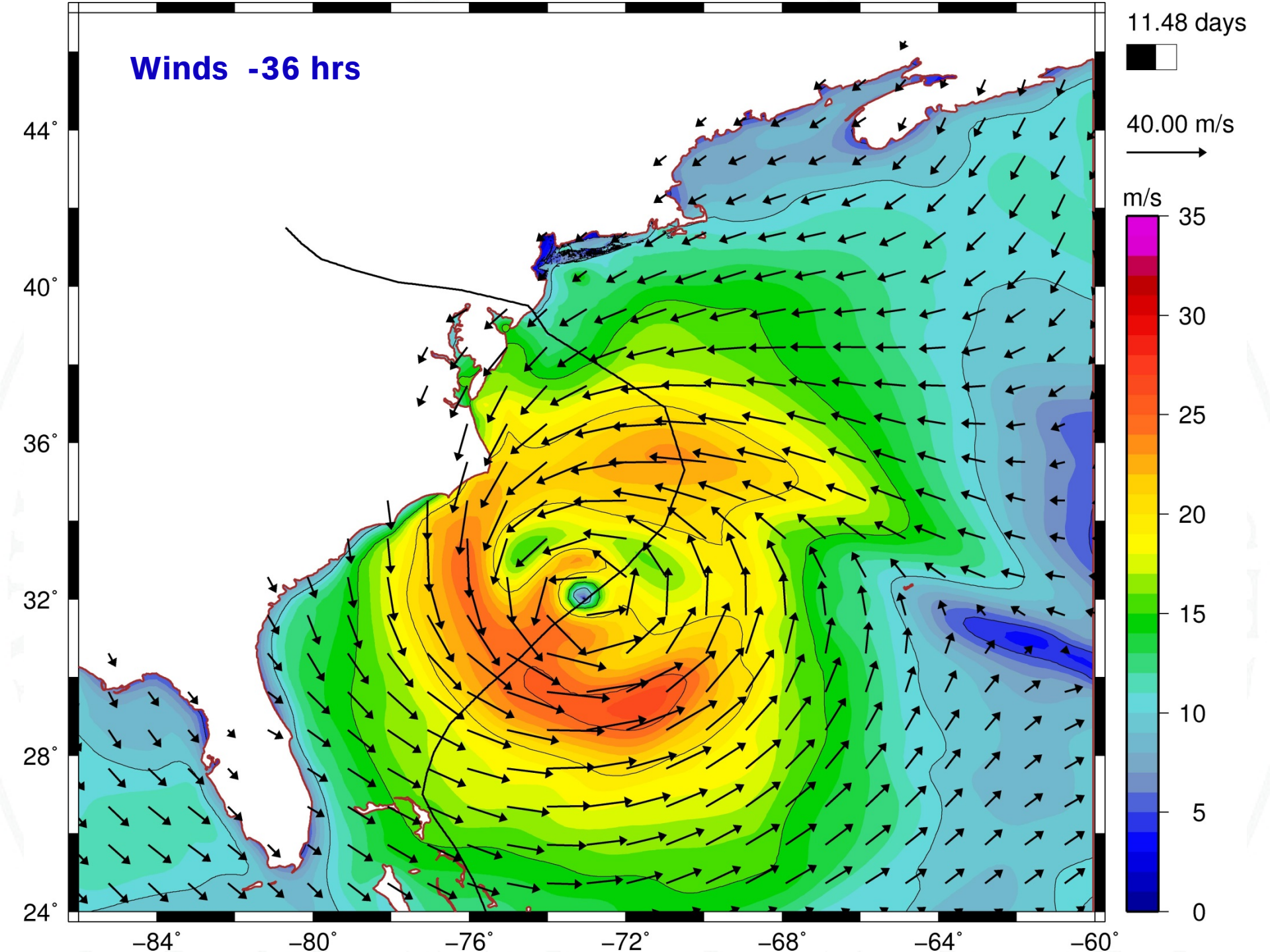
Analysis

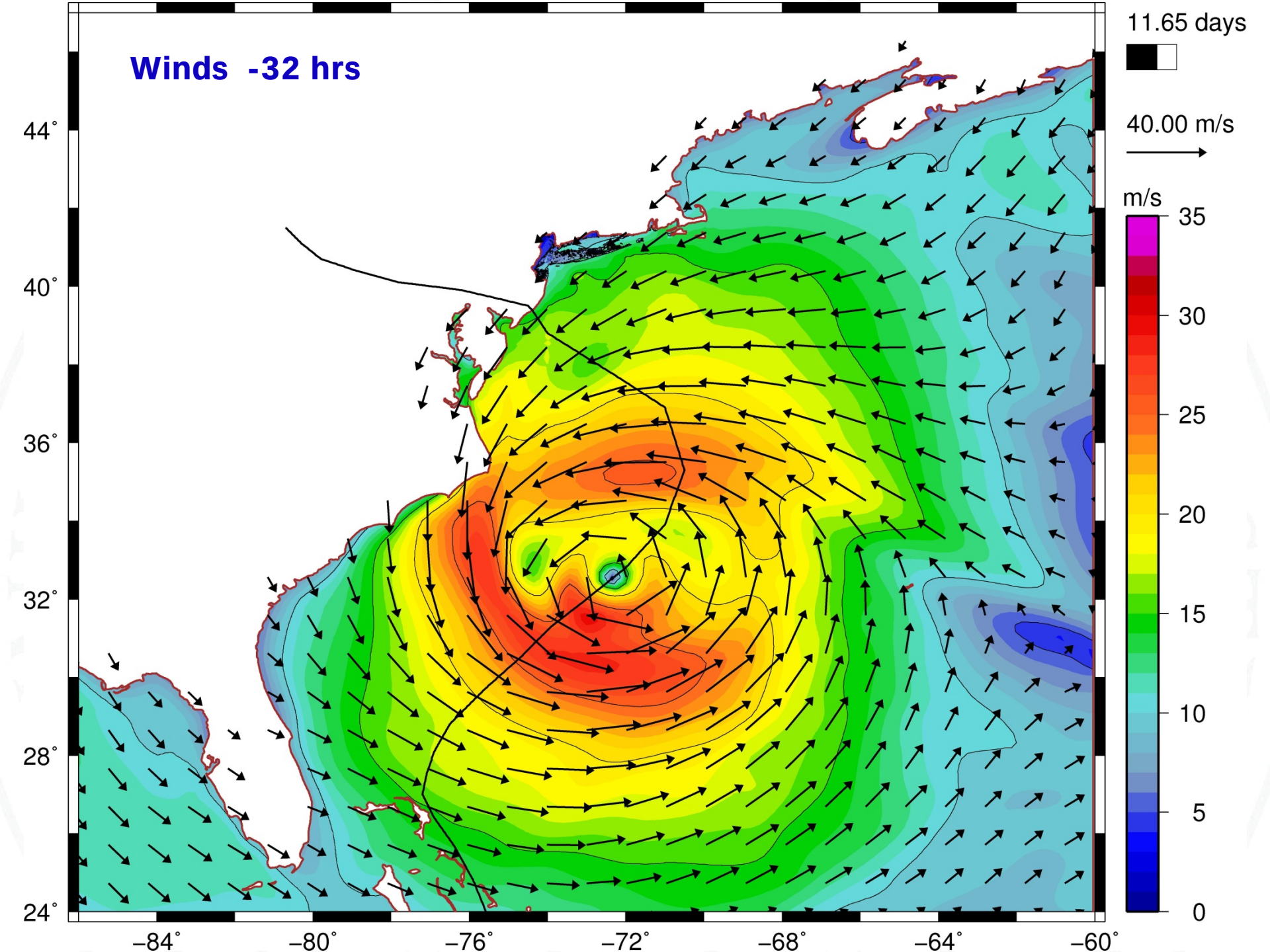
- Sandy Hindcast, Validation and Analysis
  - Winds, Waves, Surge, Shelf velocities
  - Validation
  - Geostrophic setup
  - Long Island Sound resonance
  - Wave effects
  - Tidal nonlinearities
  - Effect of storm speed and abrupt wind ending

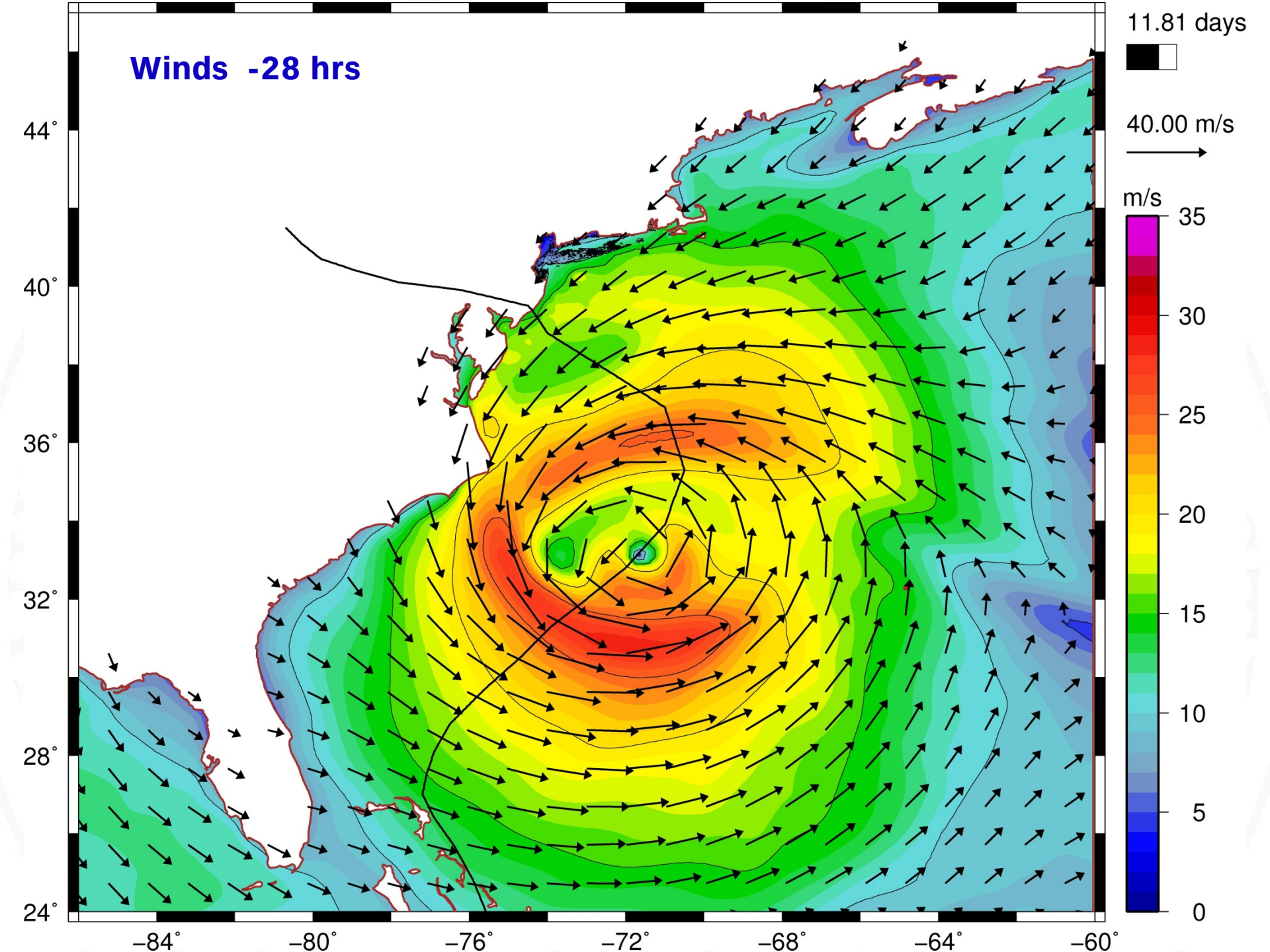

Winds -48 hrs
From OWI
Cardone and Cox
10.98 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

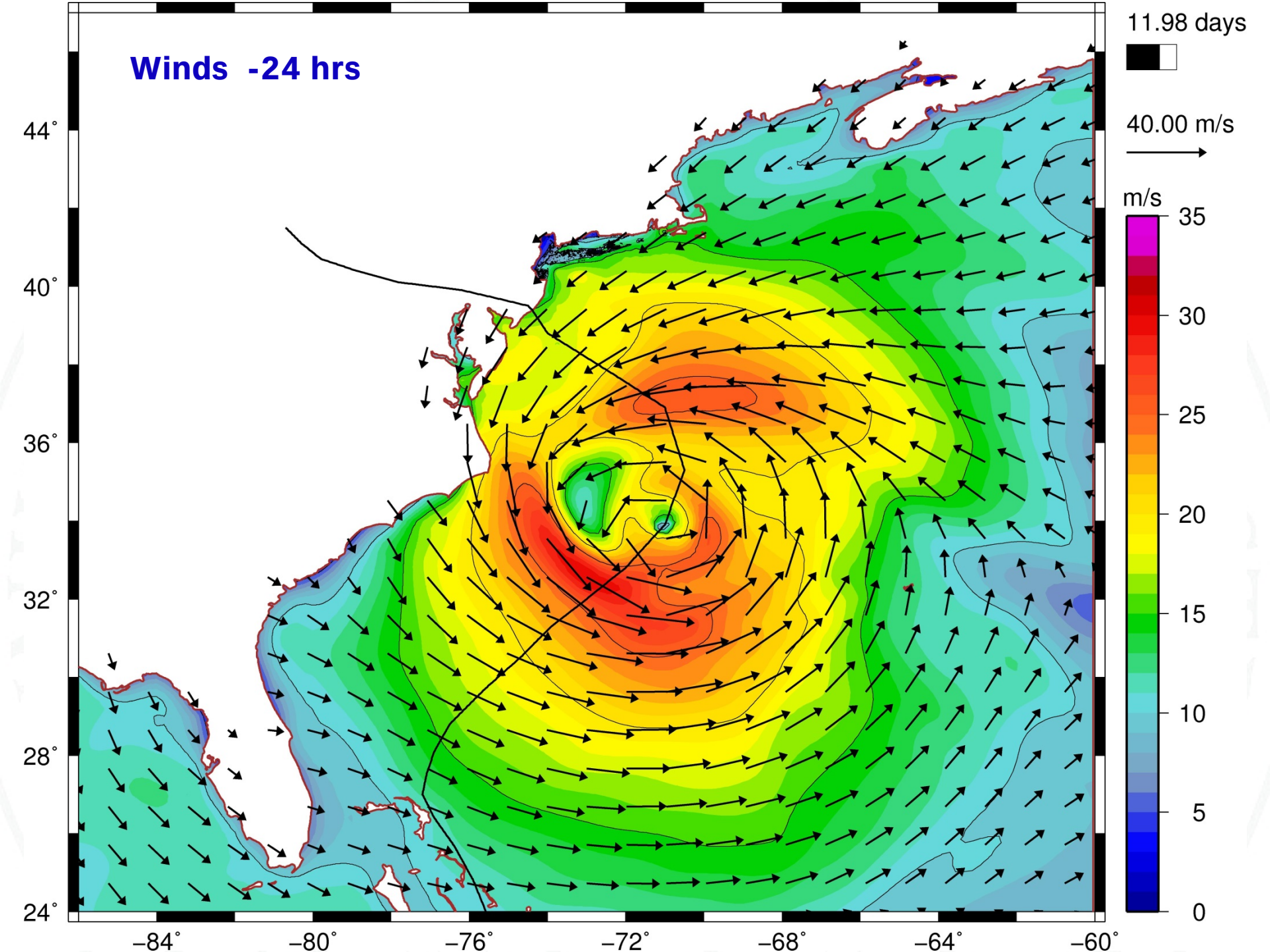

Winds -44 hrs
11.15 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

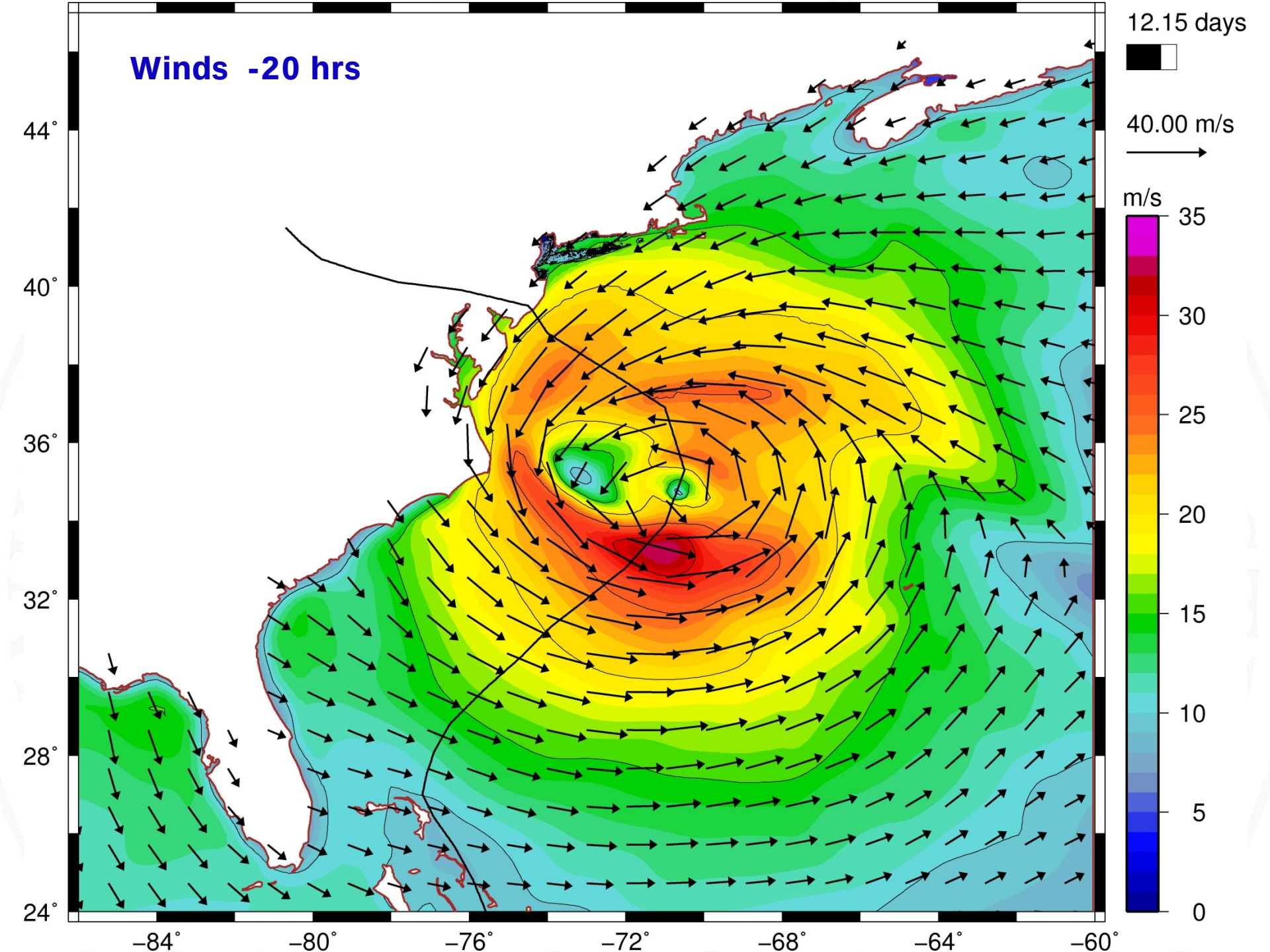

Winds -40 hrs
11.31 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

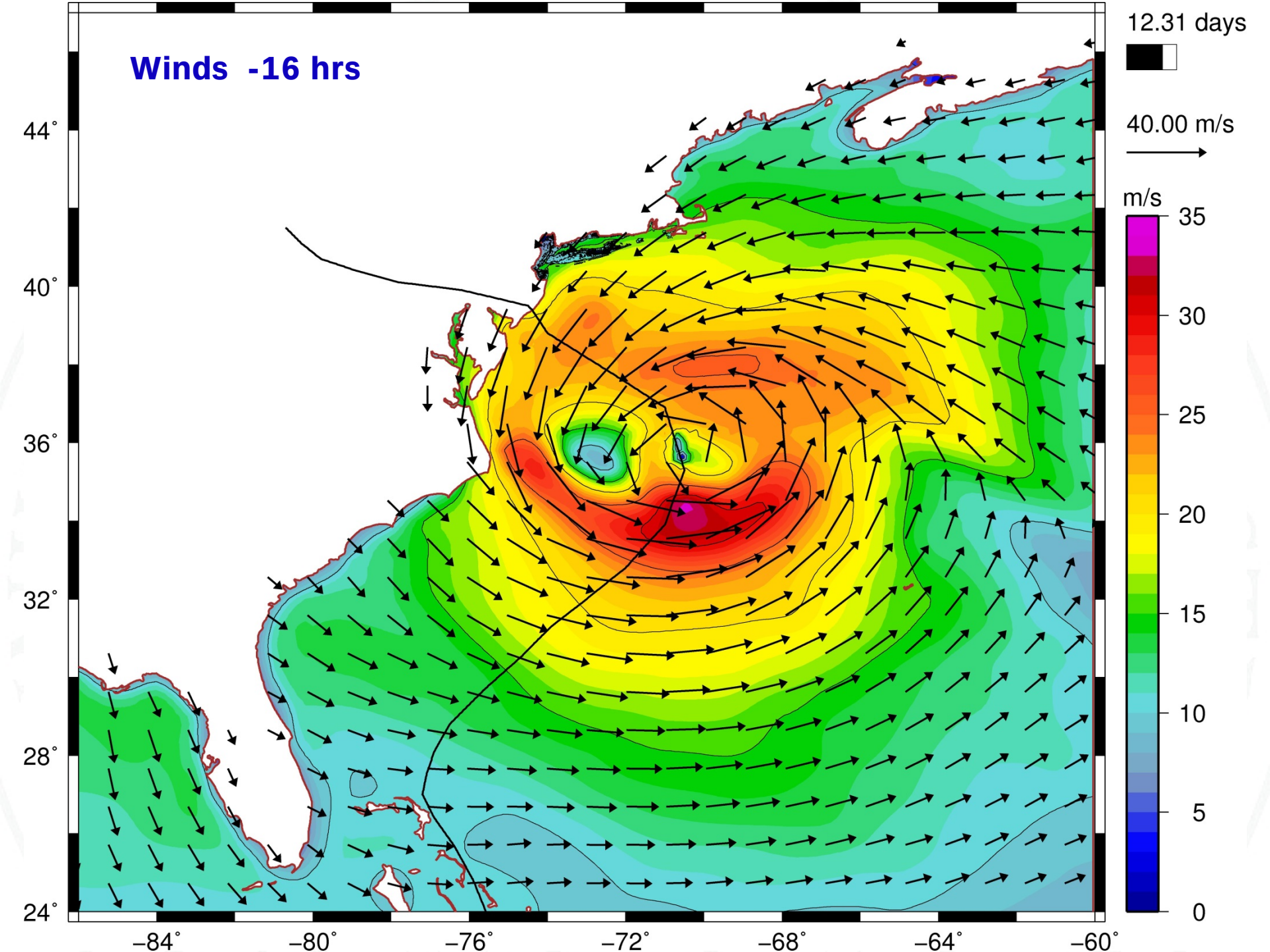

Winds -36 hrs
11.48 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

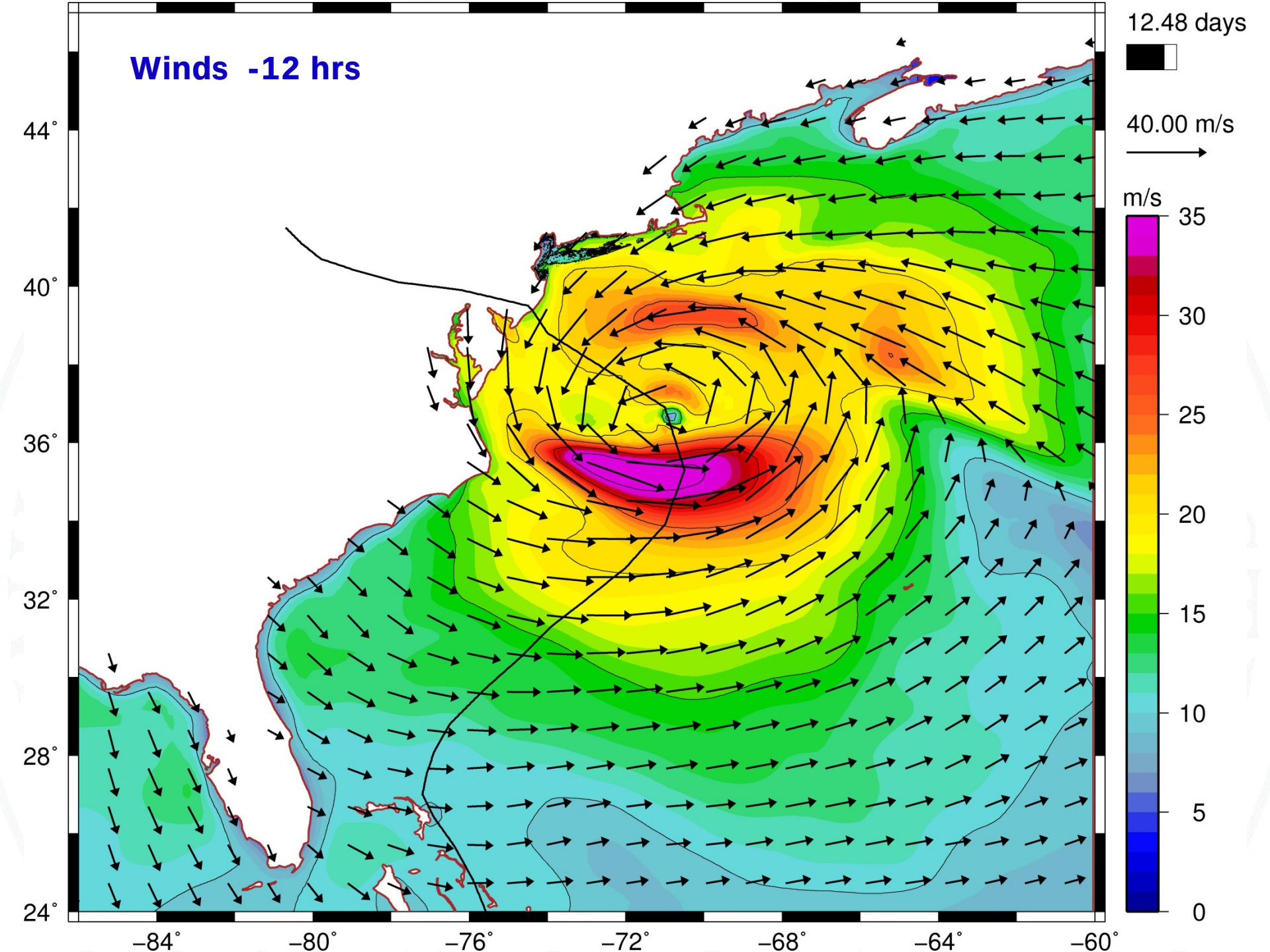

Winds -32 hrs
11.65 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

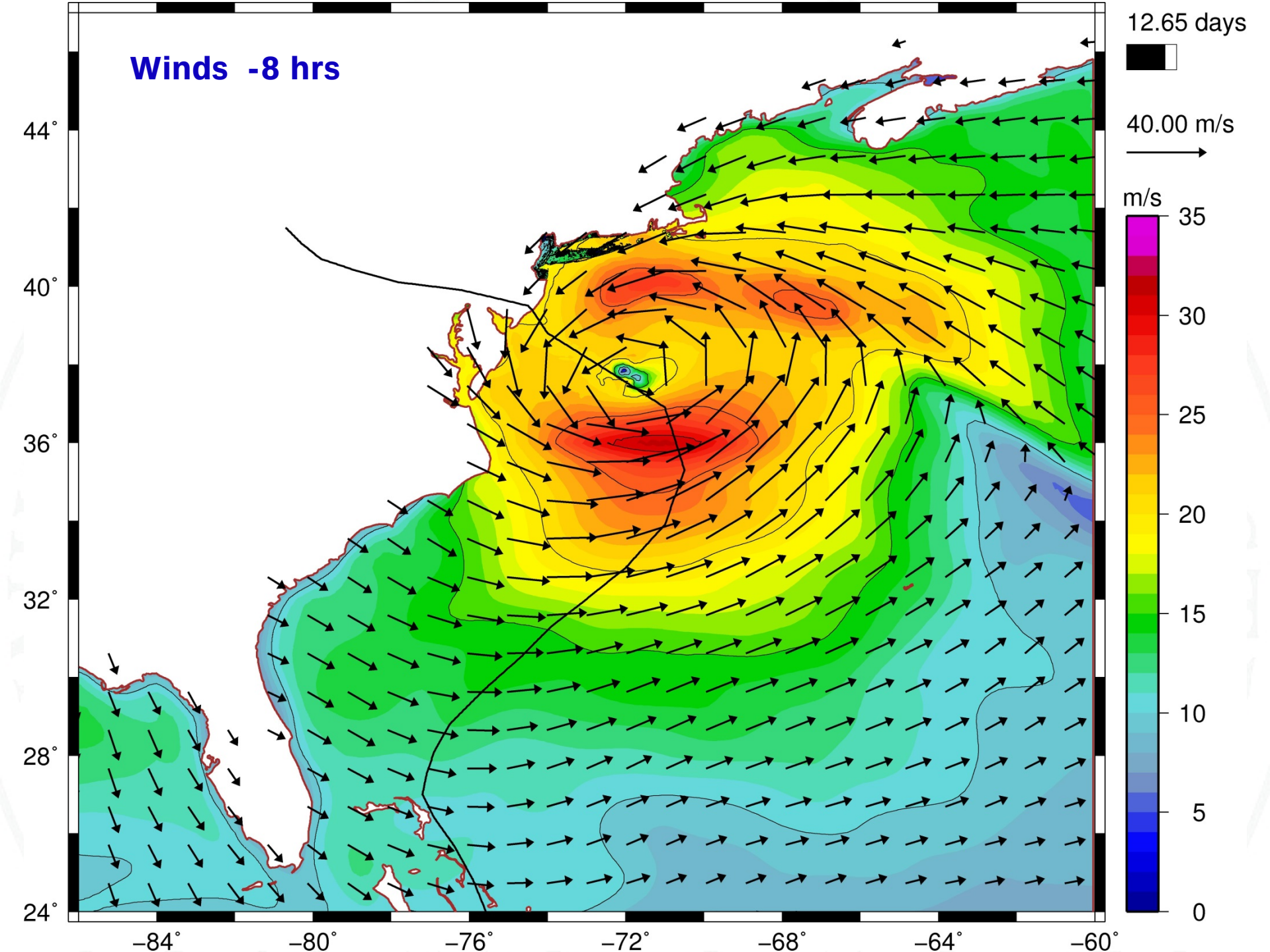

Winds -28 hrs
11.81 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

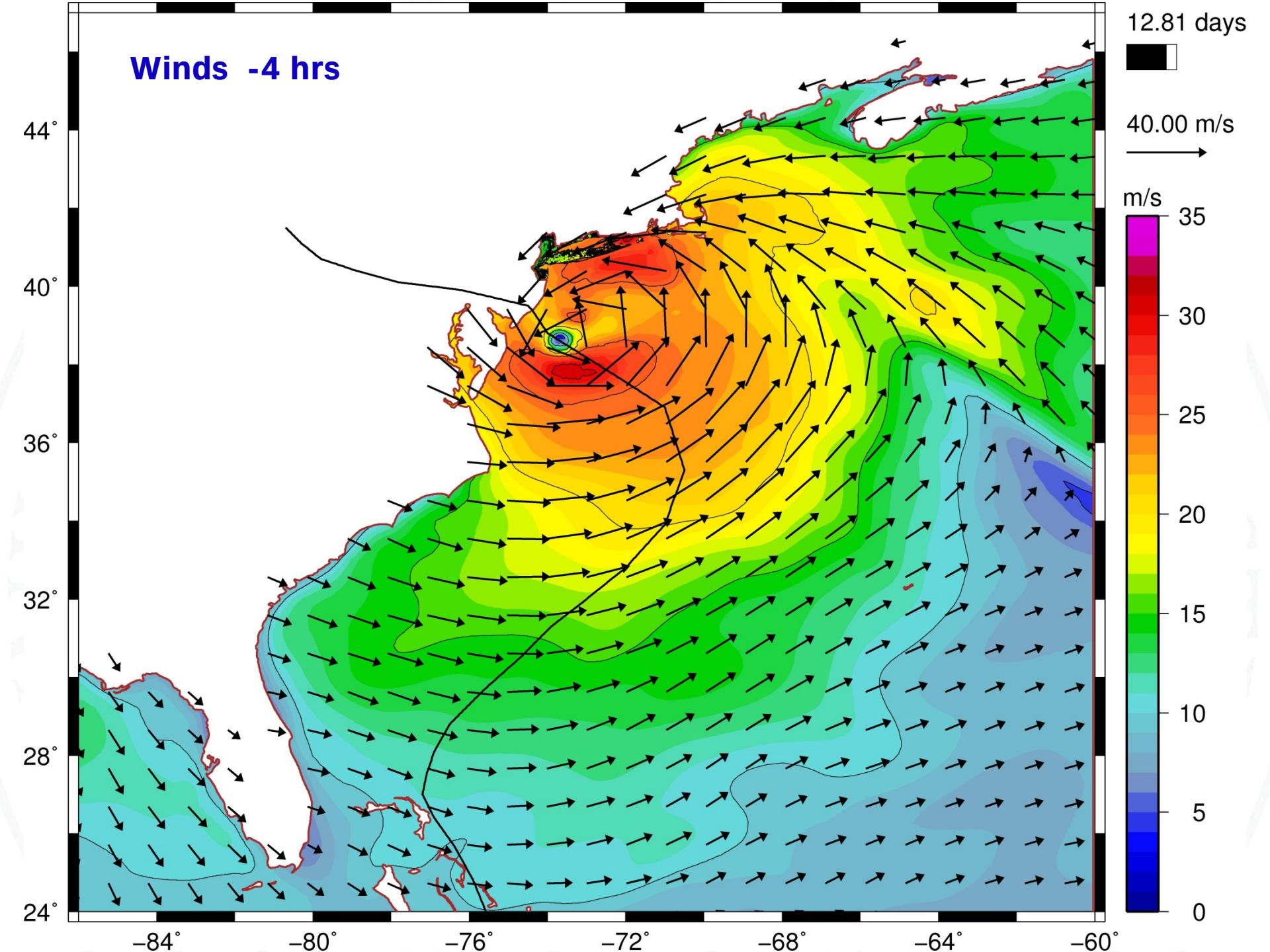

Winds -24 hrs
11.98 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

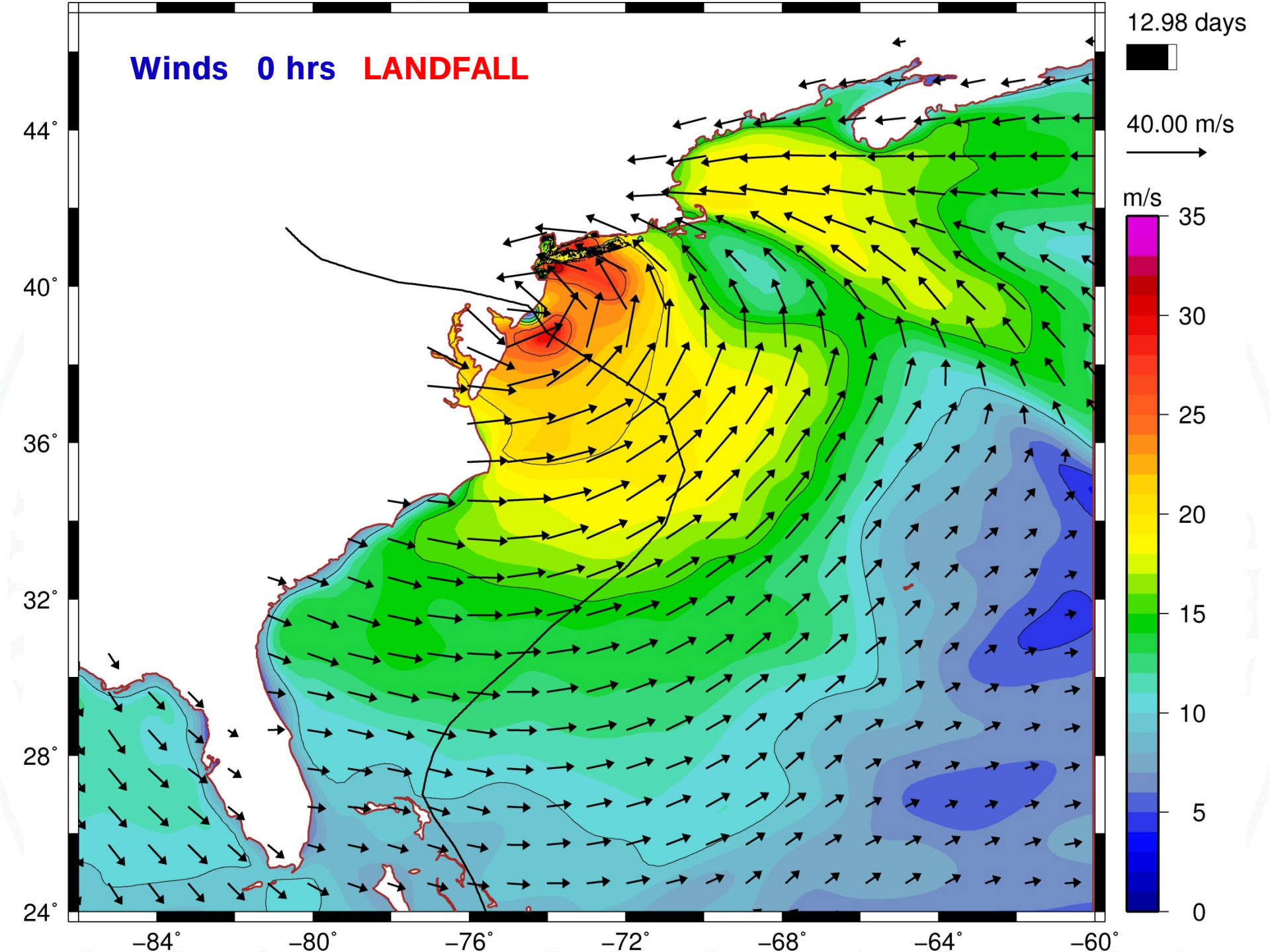

Winds -20 hrs
12.15 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

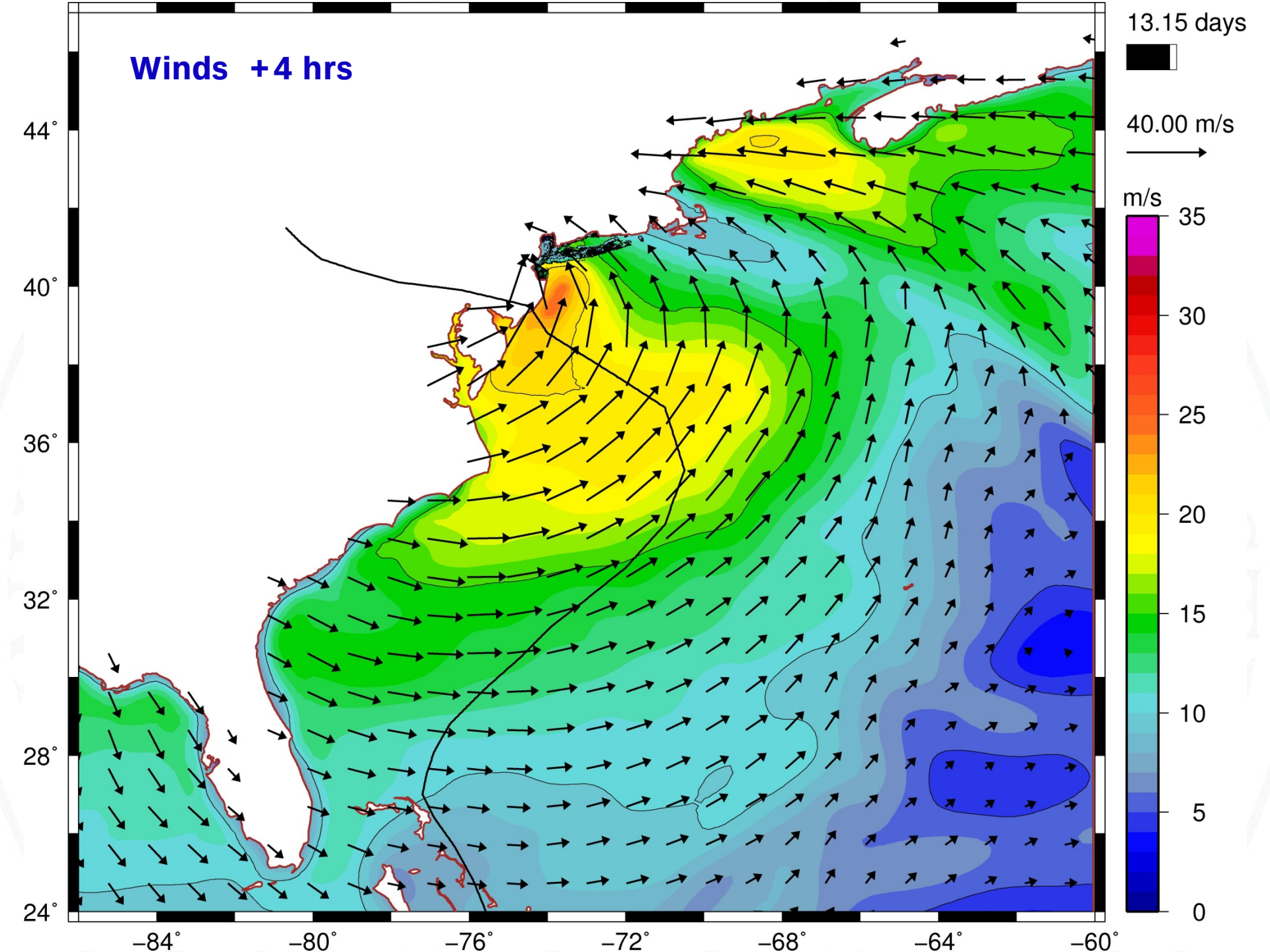

Winds -16 hrs
12.31 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

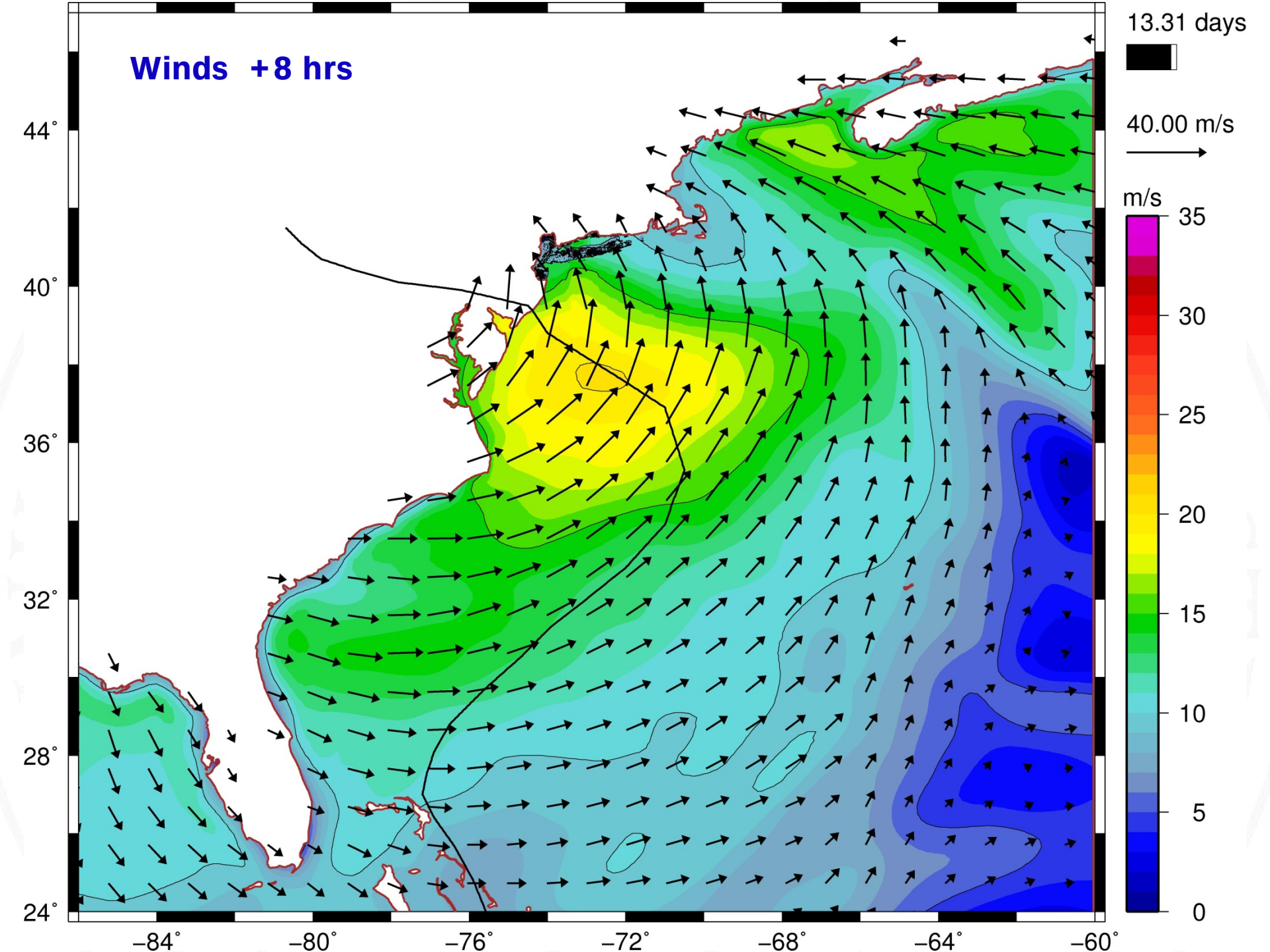

Winds -12 hrs
12.48 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

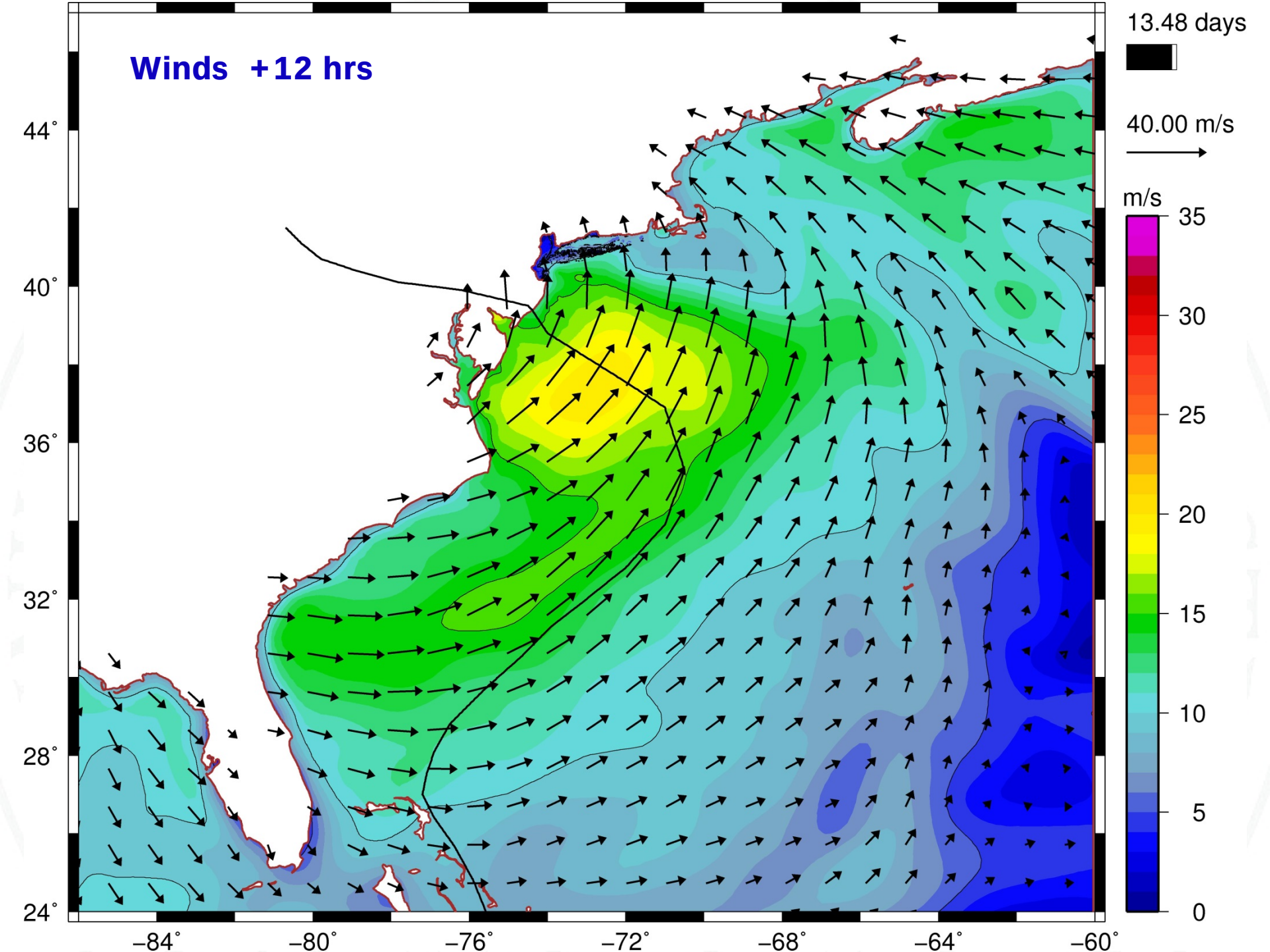

Winds -8 hrs
12.65 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

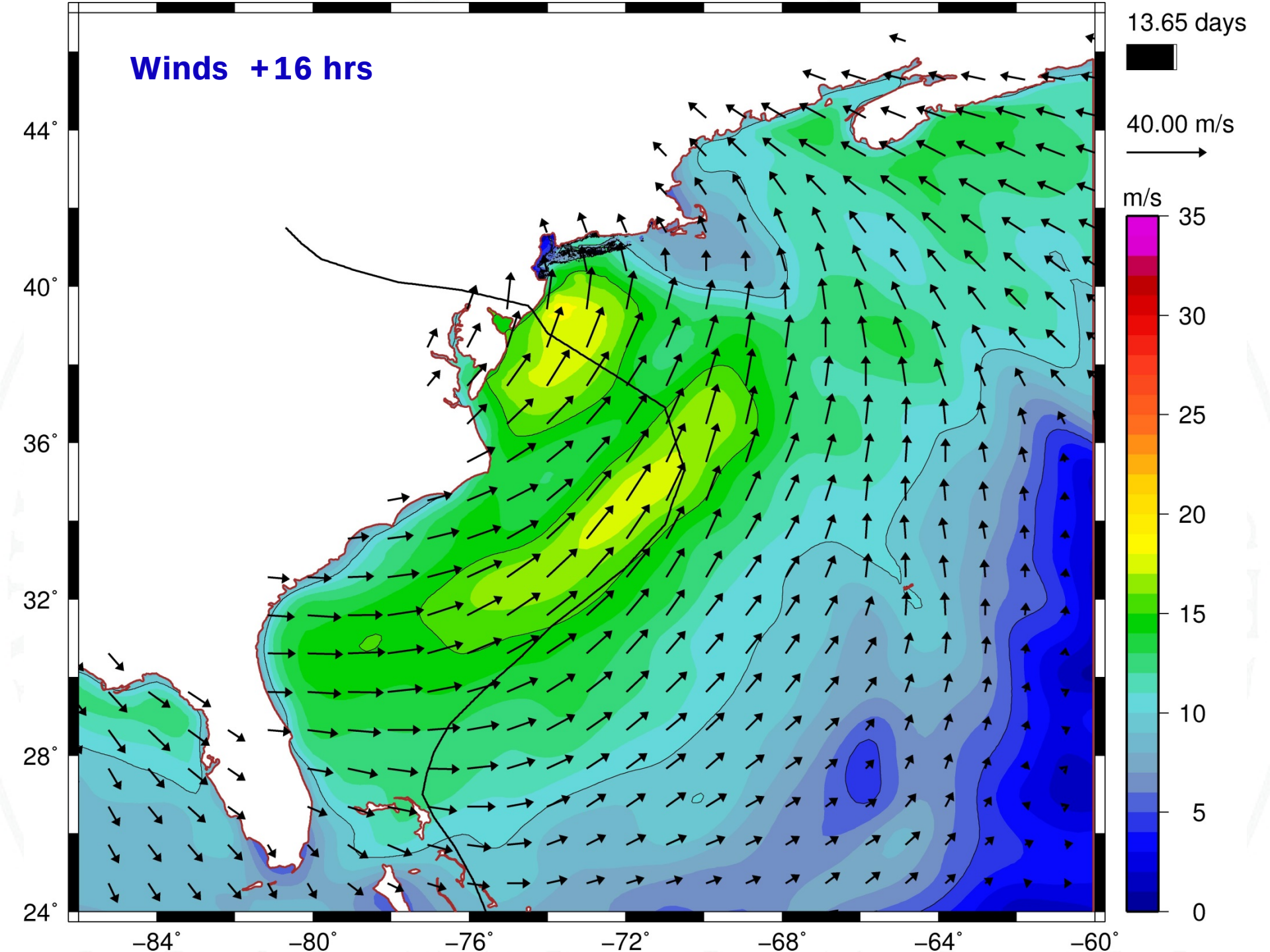

Winds -4 hrs
12.81 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

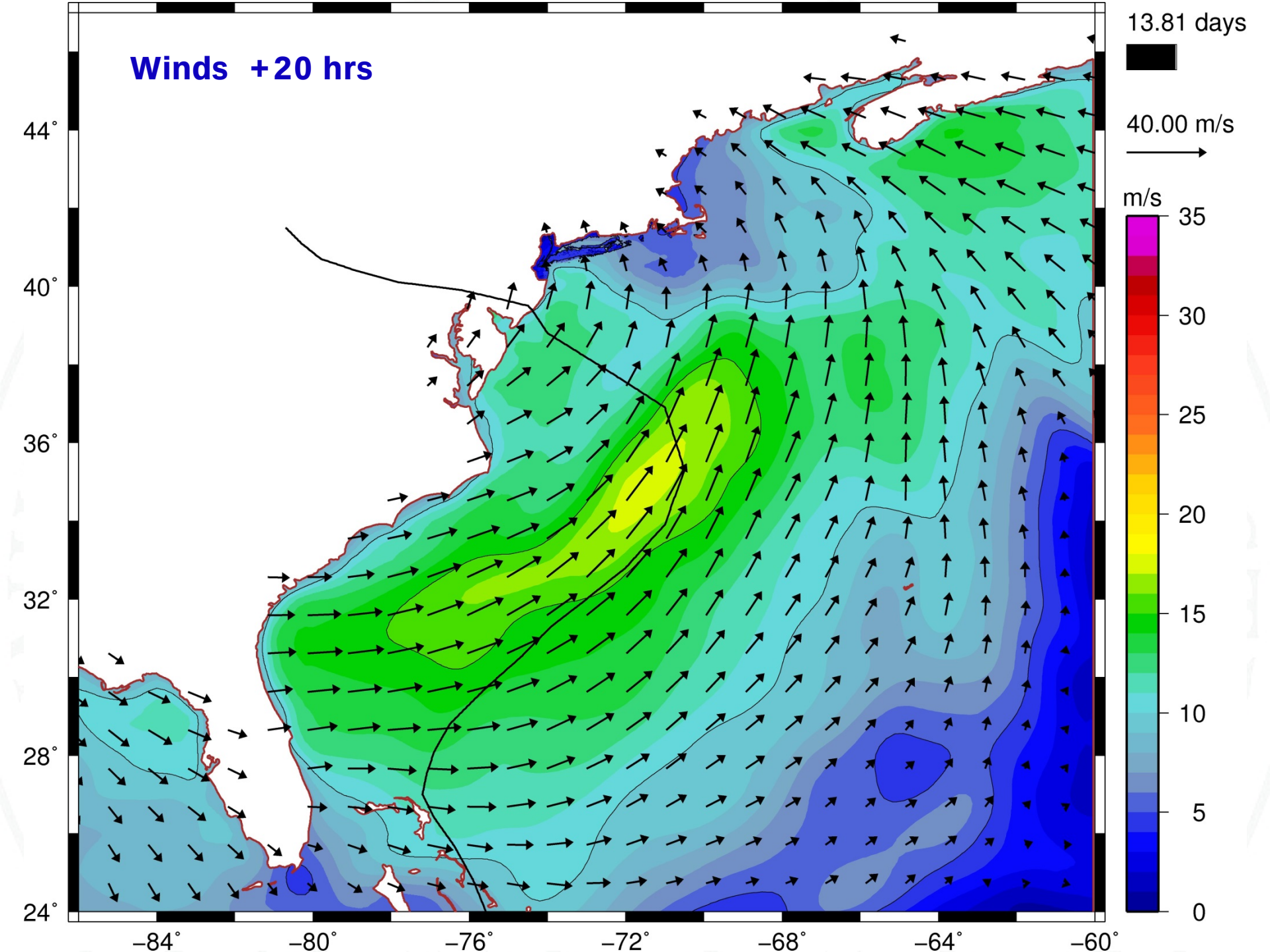

Winds 0 hrs LANDFALL
12.98 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Winds +4 hrs
13.15 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

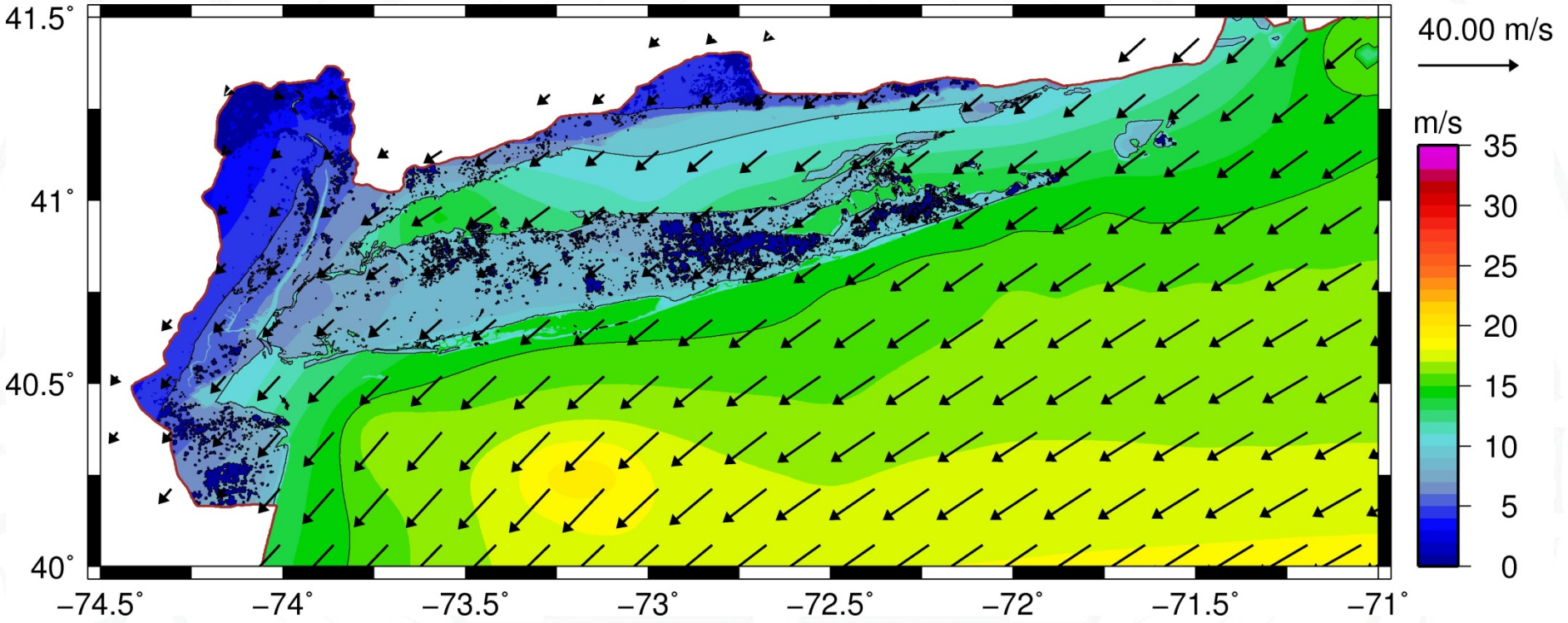

Winds +8 hrs
13.31 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Winds +12 hrs
13.48 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

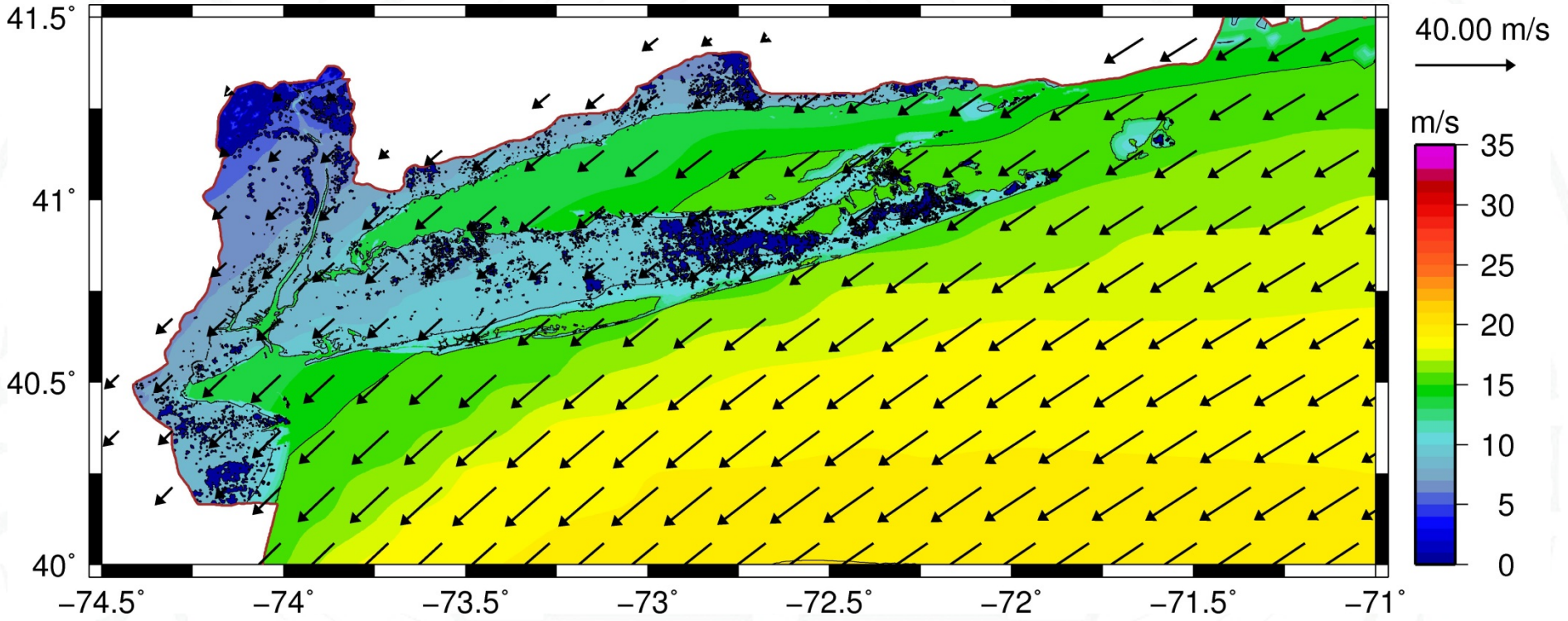

Winds +16 hrs
13.65 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Winds +20 hrs
13.81 days
40.00 m/s
m/s
35
30
25
20
15
10
5
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

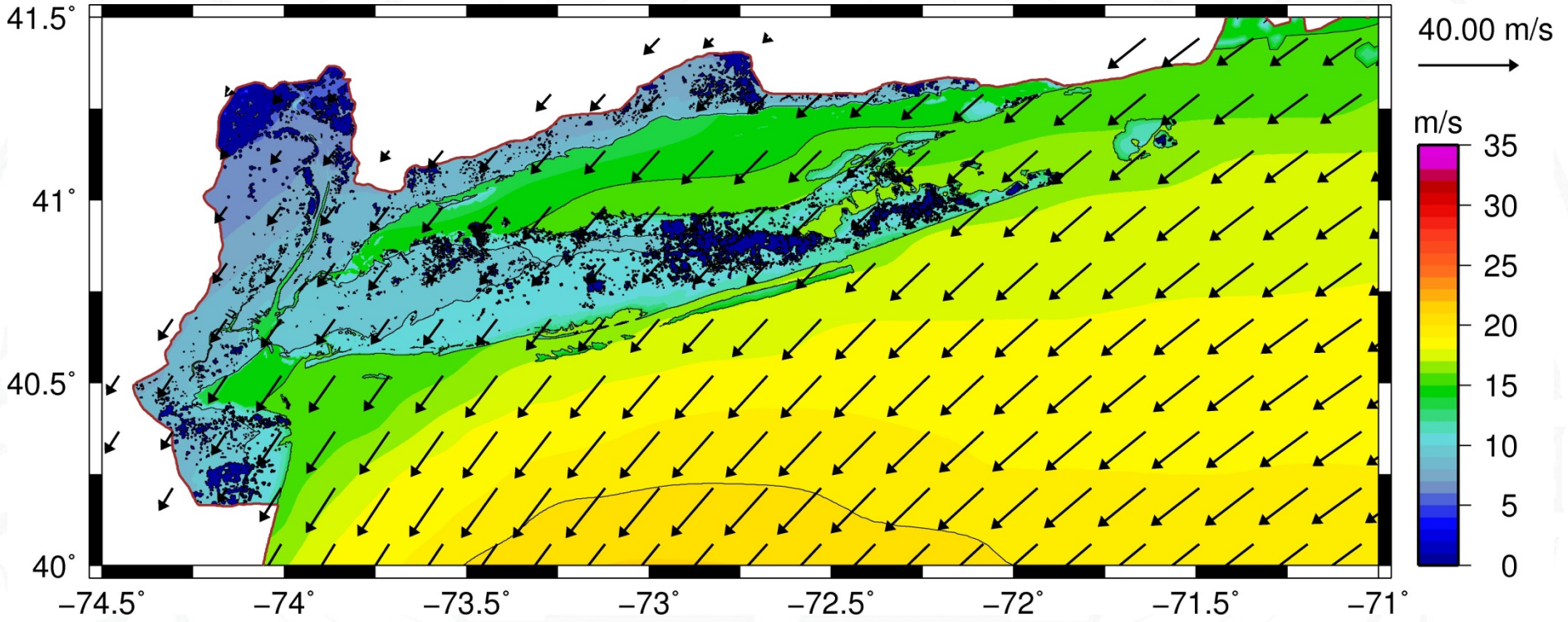
Winds -24 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

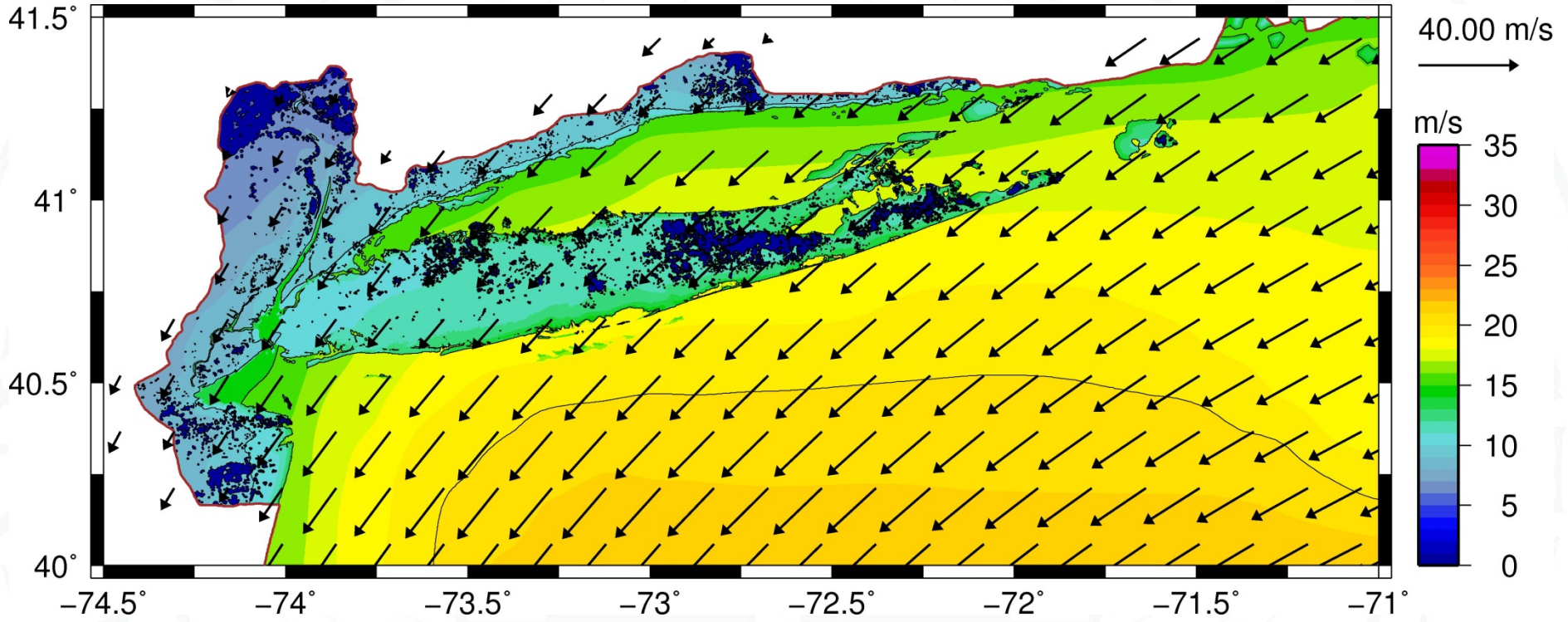
Winds -20 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

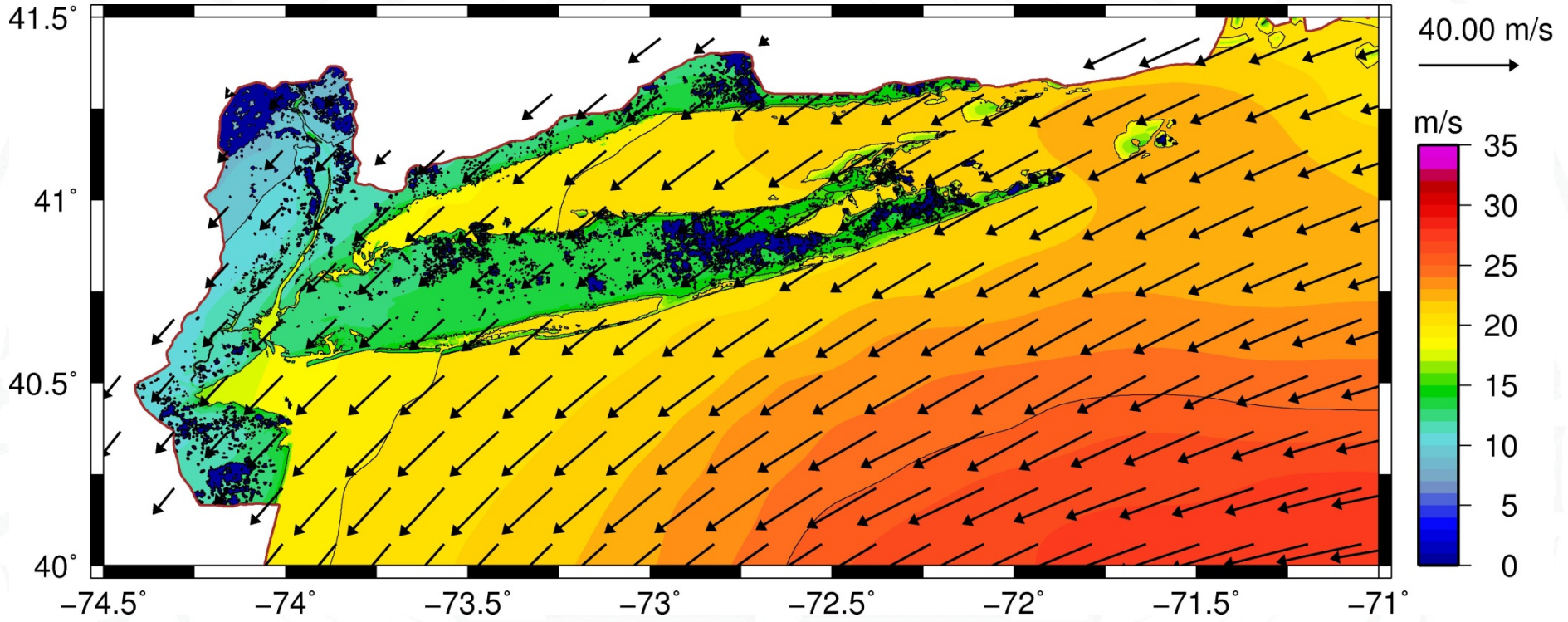
Winds -16 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

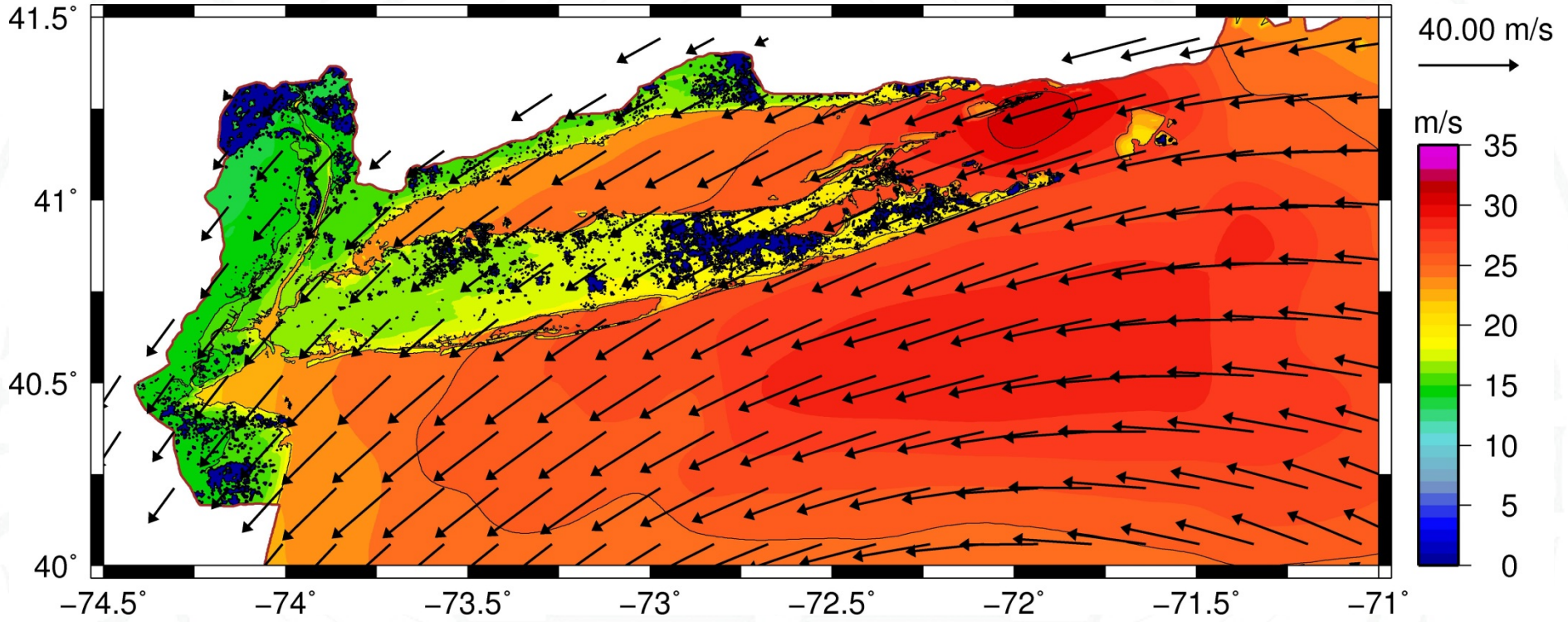
Winds -12 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

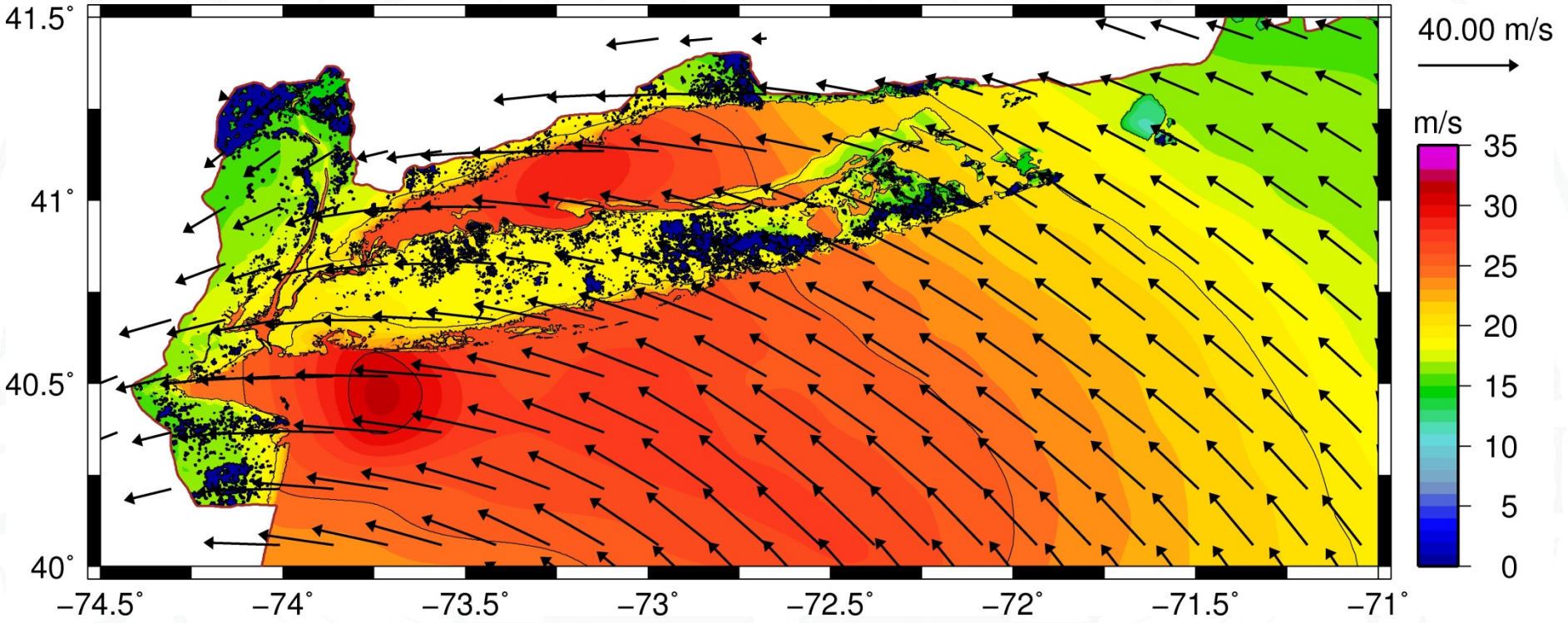
Winds -8 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

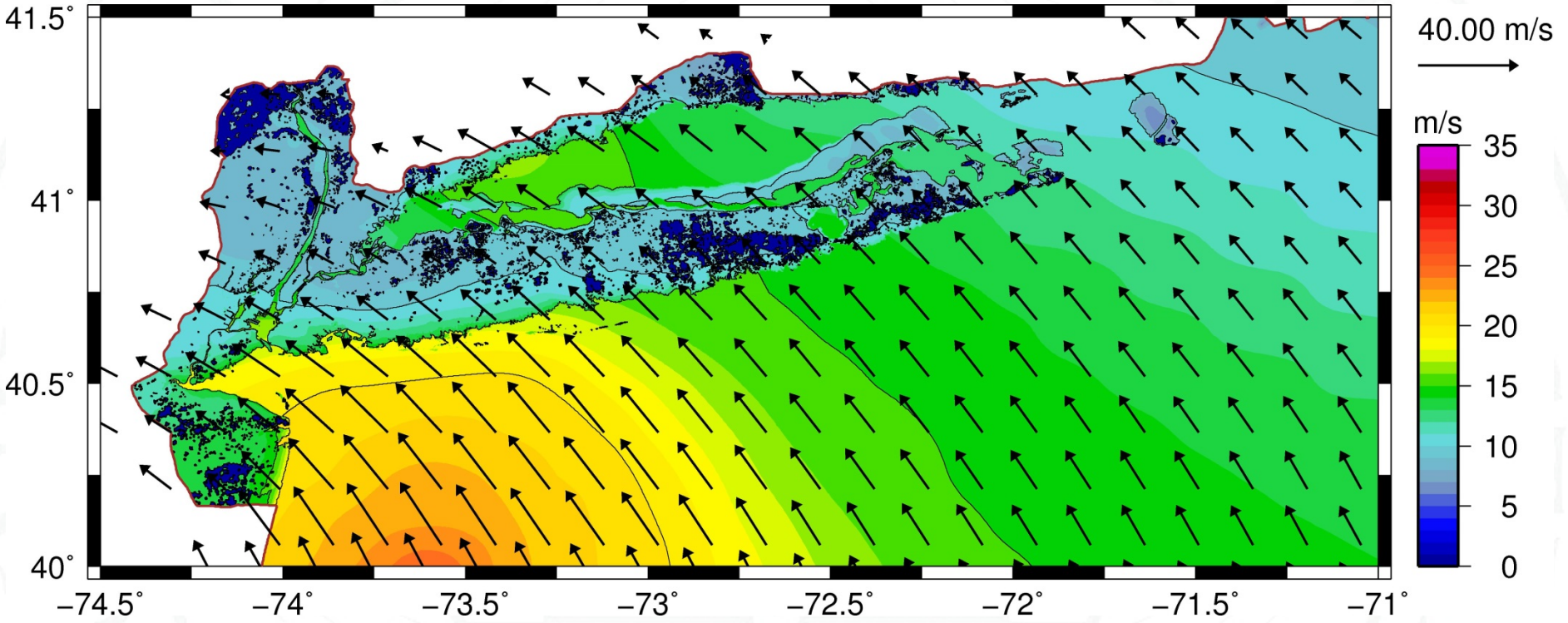
Winds -4 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

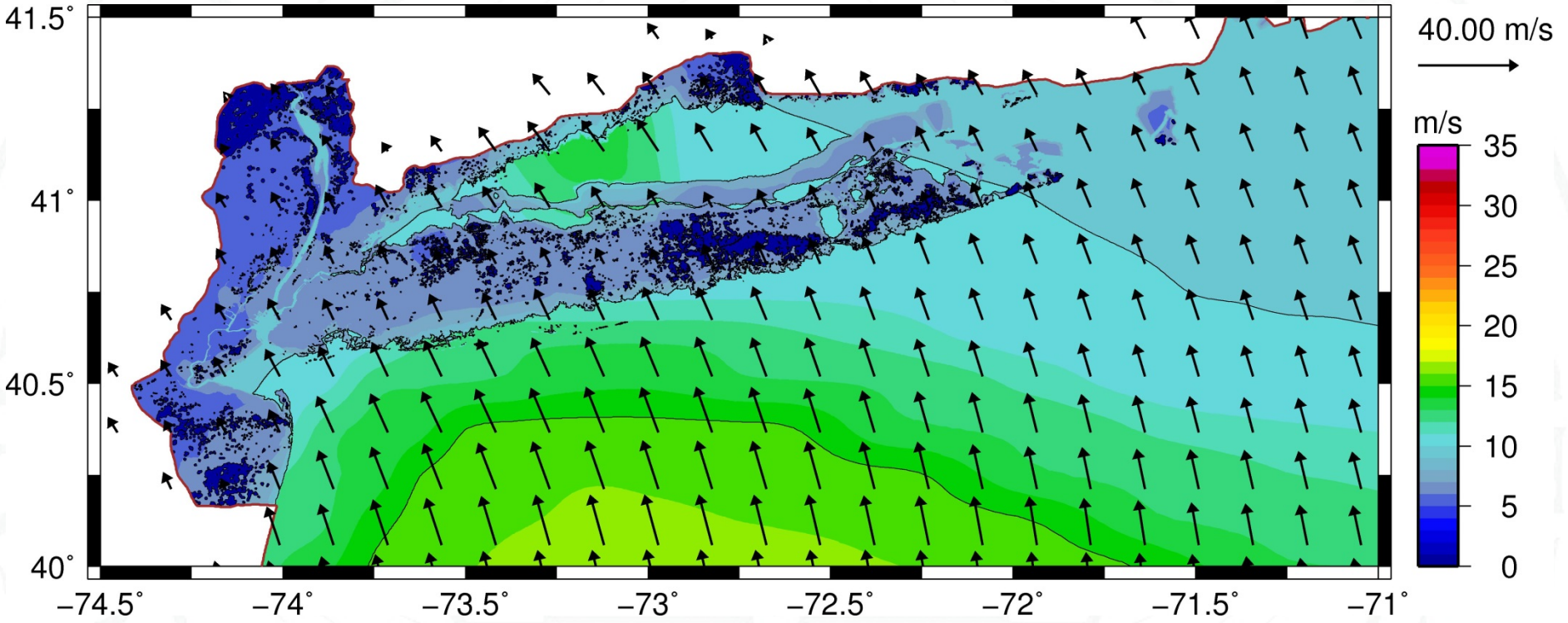
Winds 0 hrs LANDFALL



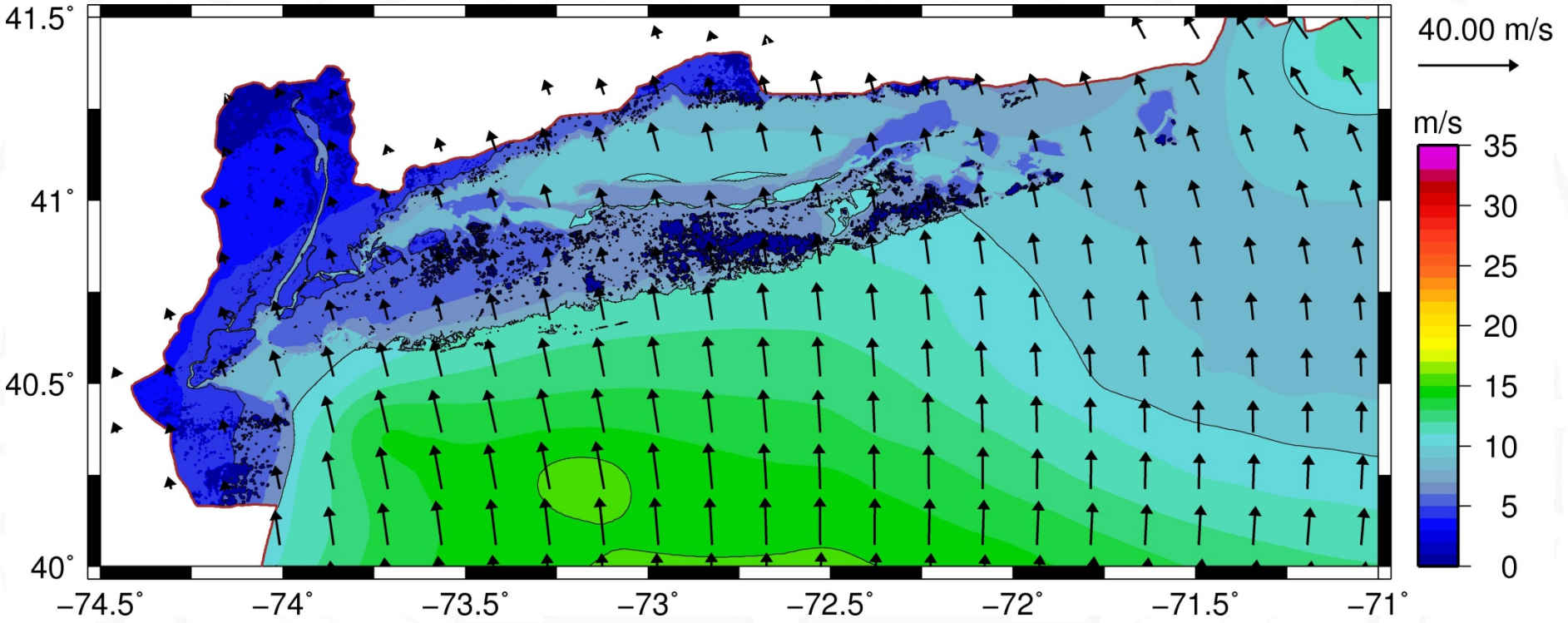
Winds +4 hrs

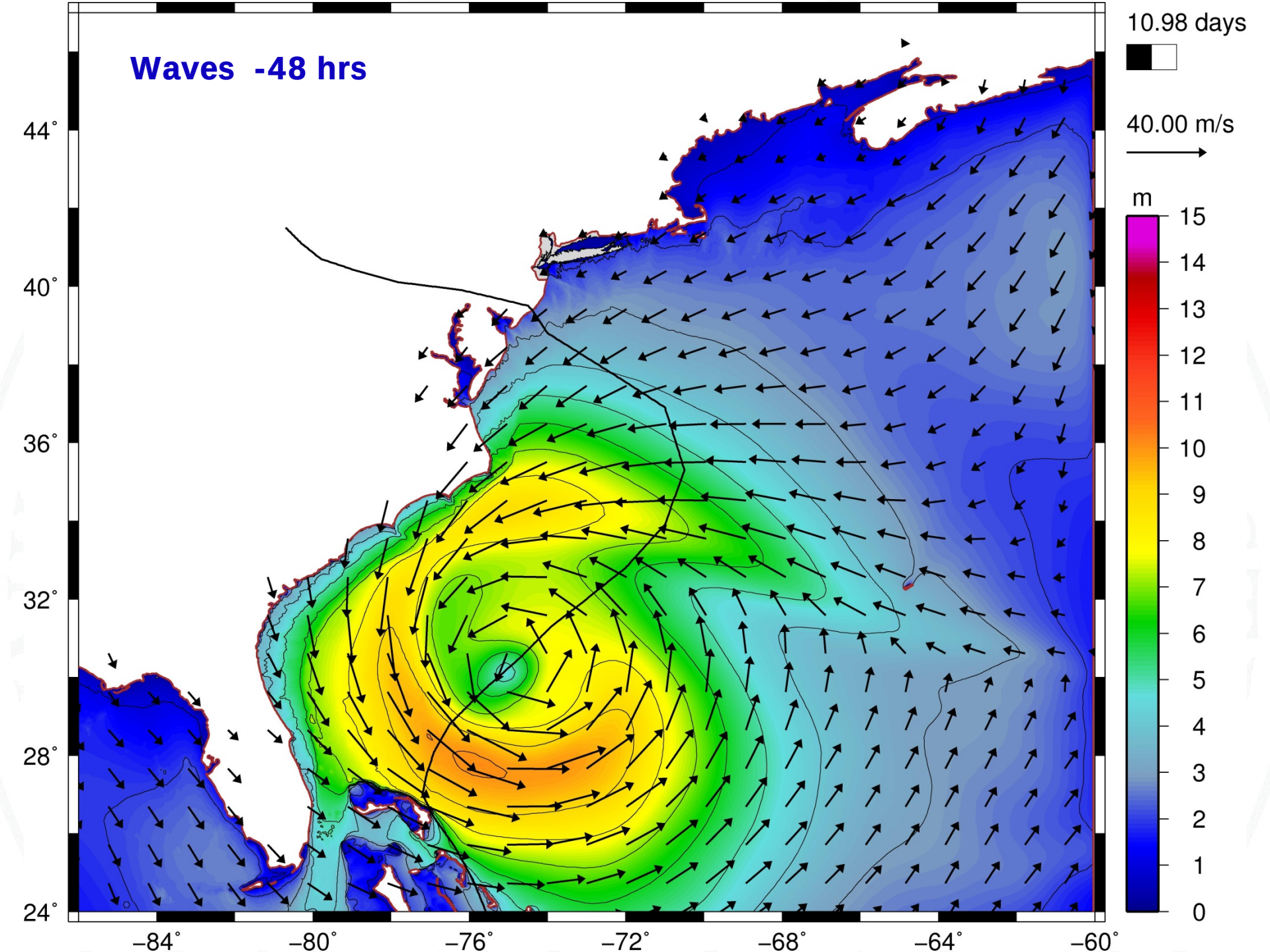

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

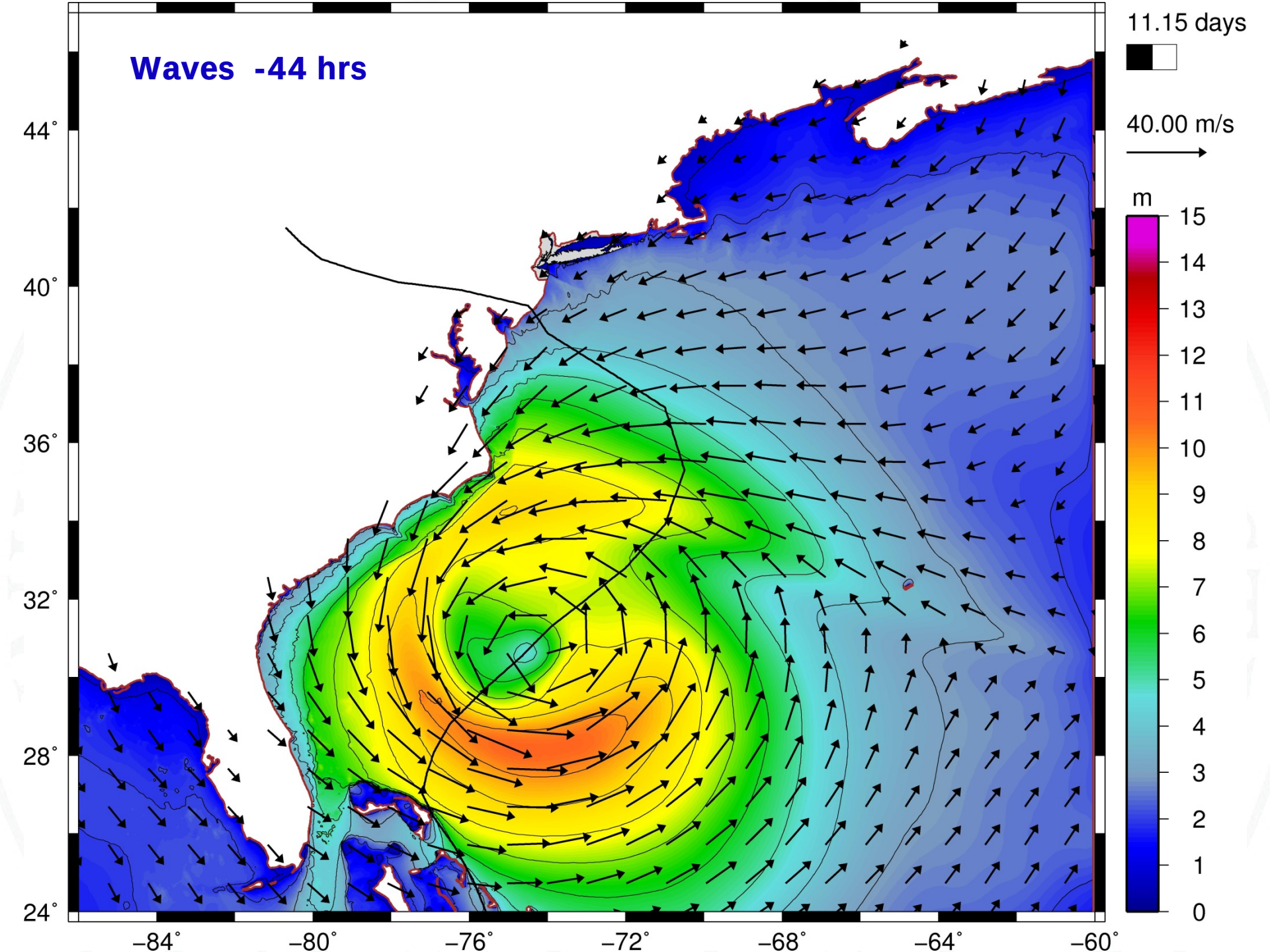
Winds +8 hrs

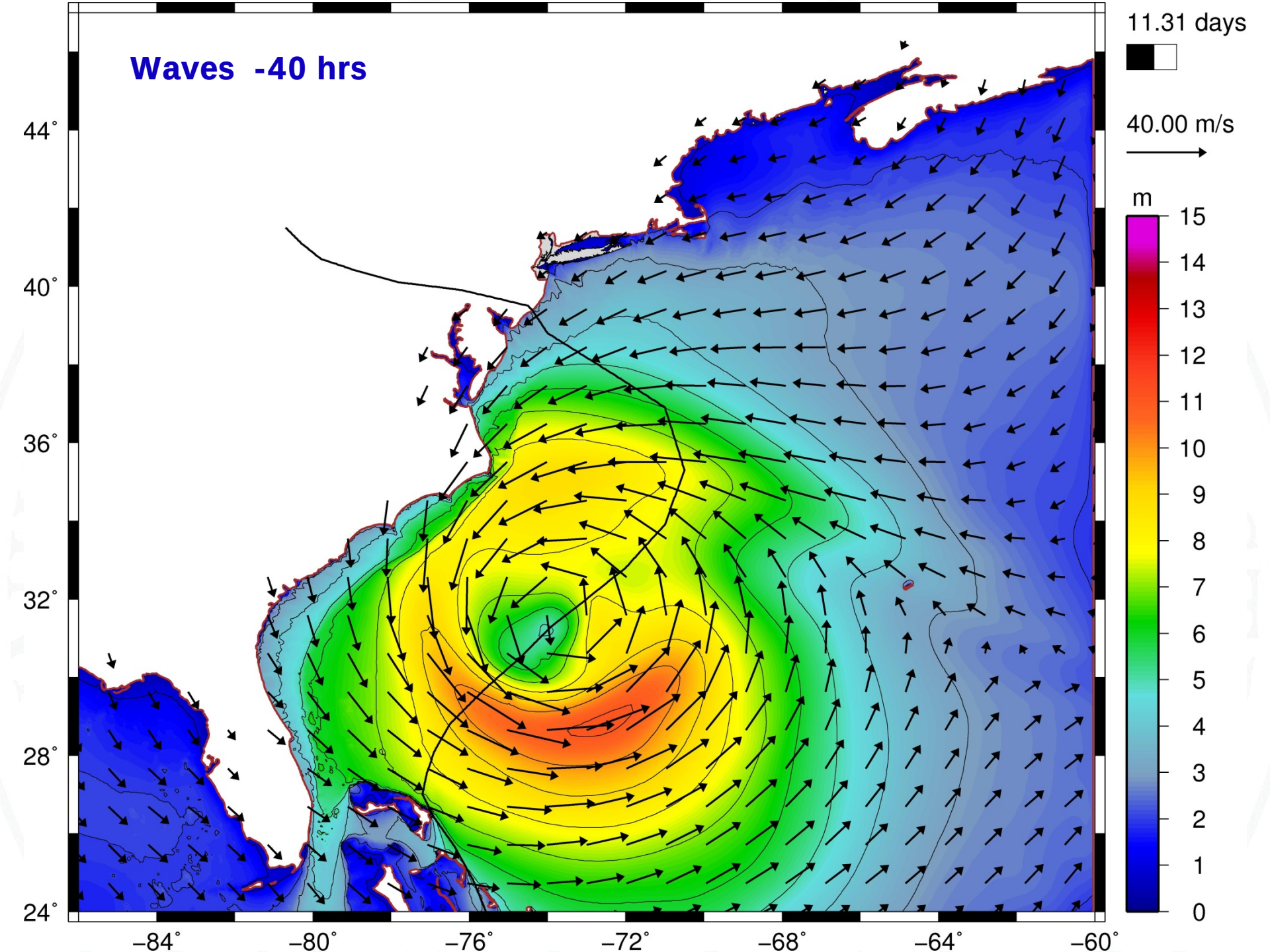

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

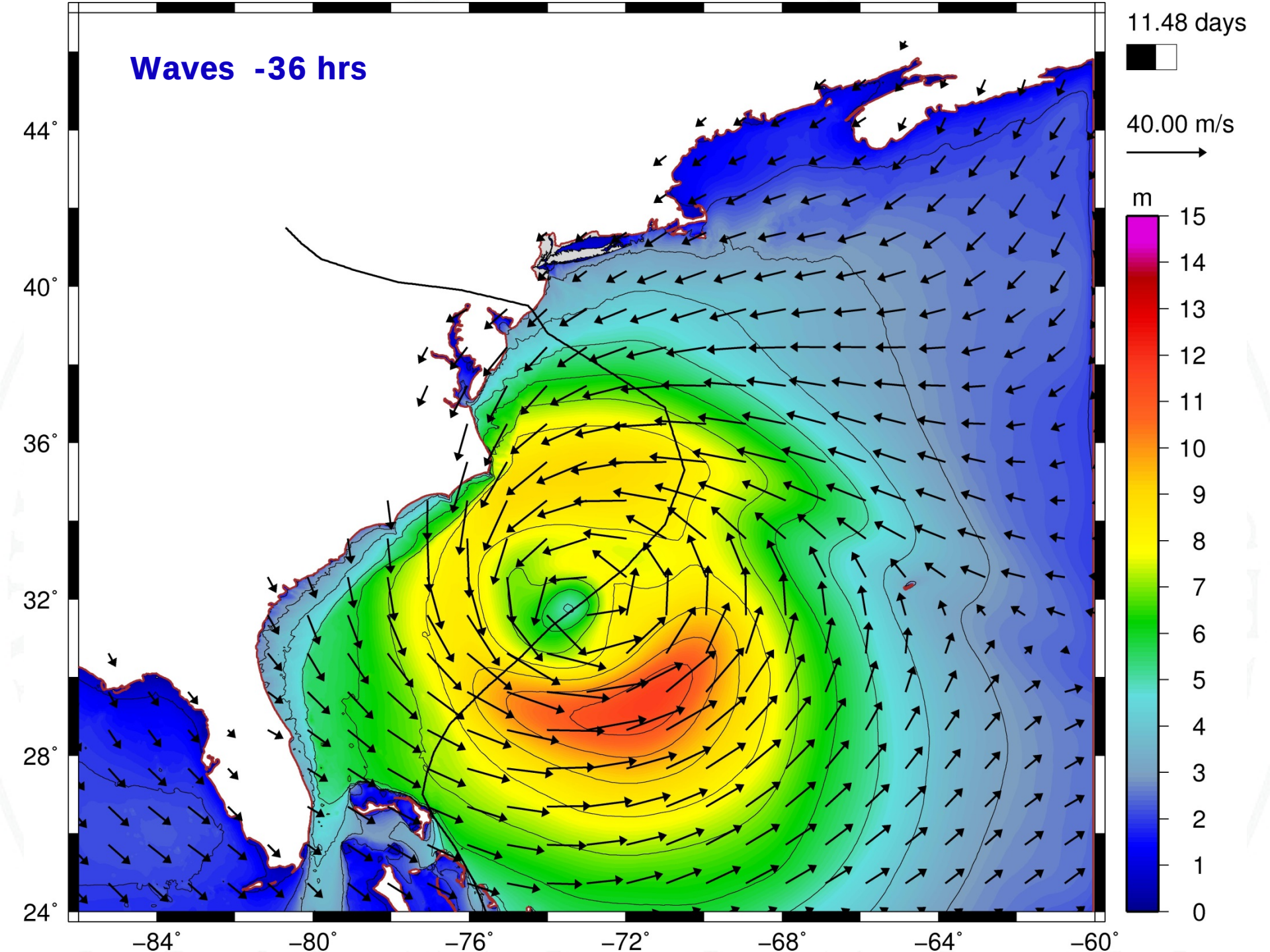
Winds +12 hrs

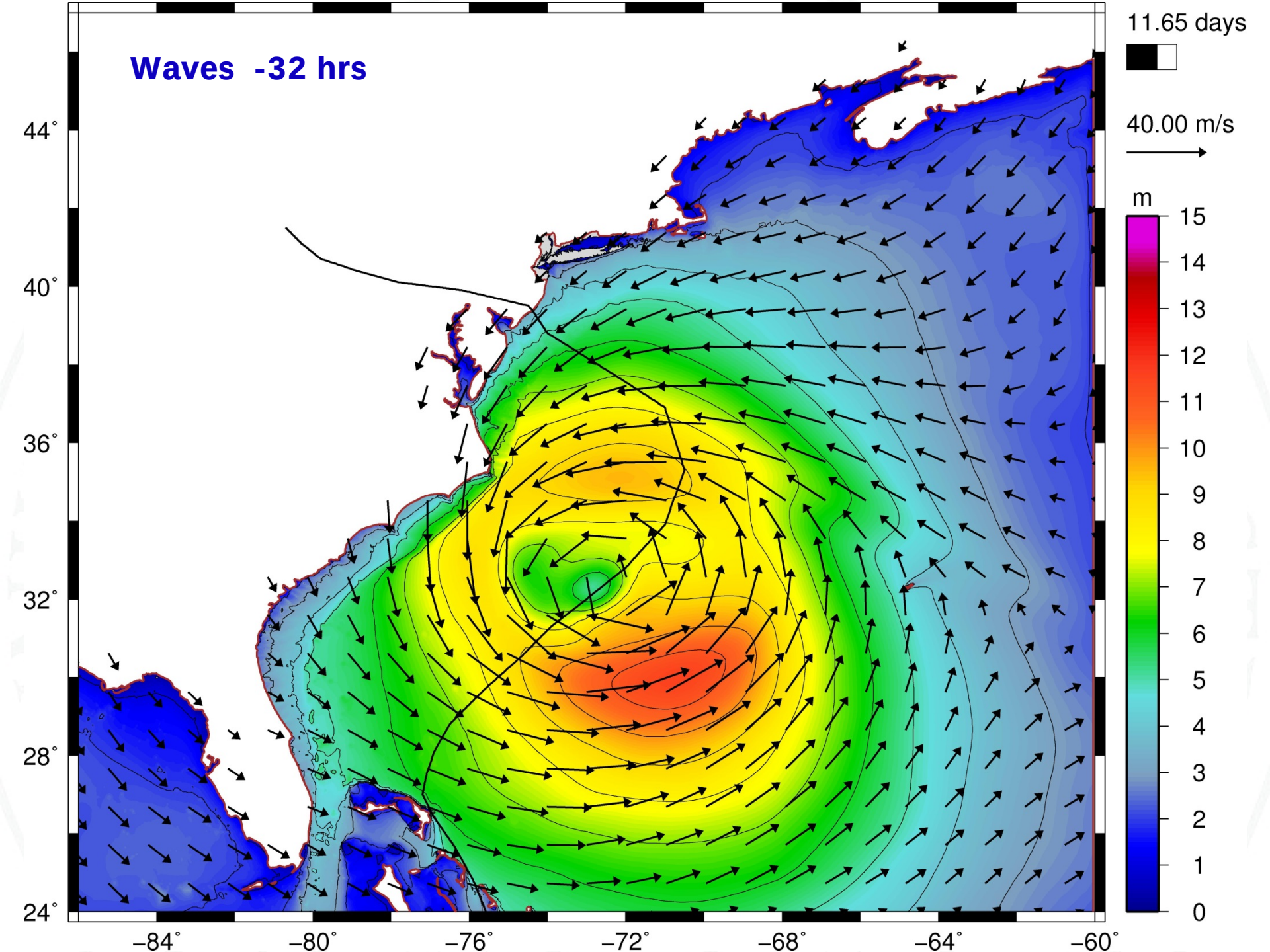

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
40.00 m/s
m/s
35
30
25
20
15
10
5
0

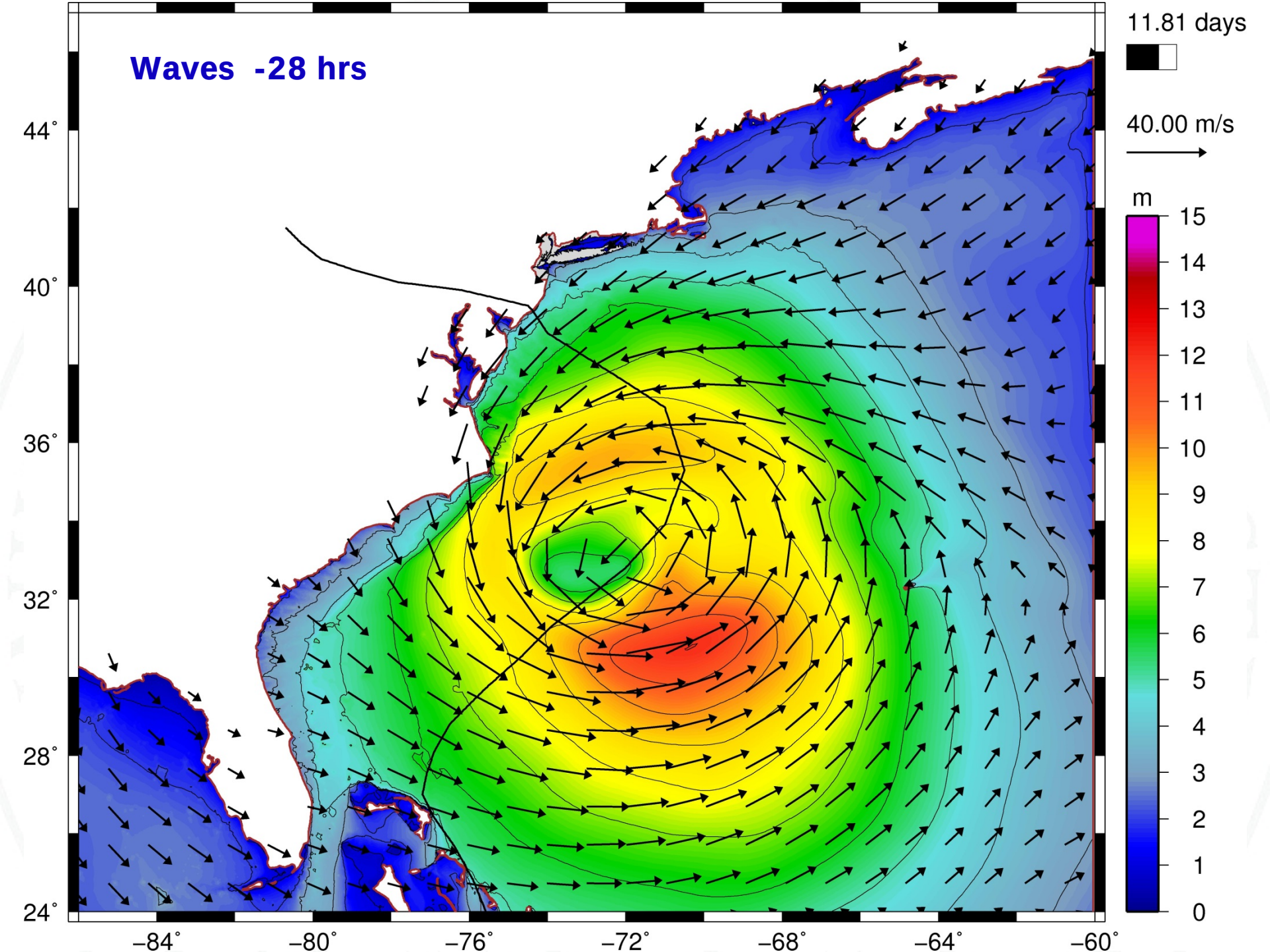

Waves -48 hrs
10.98 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

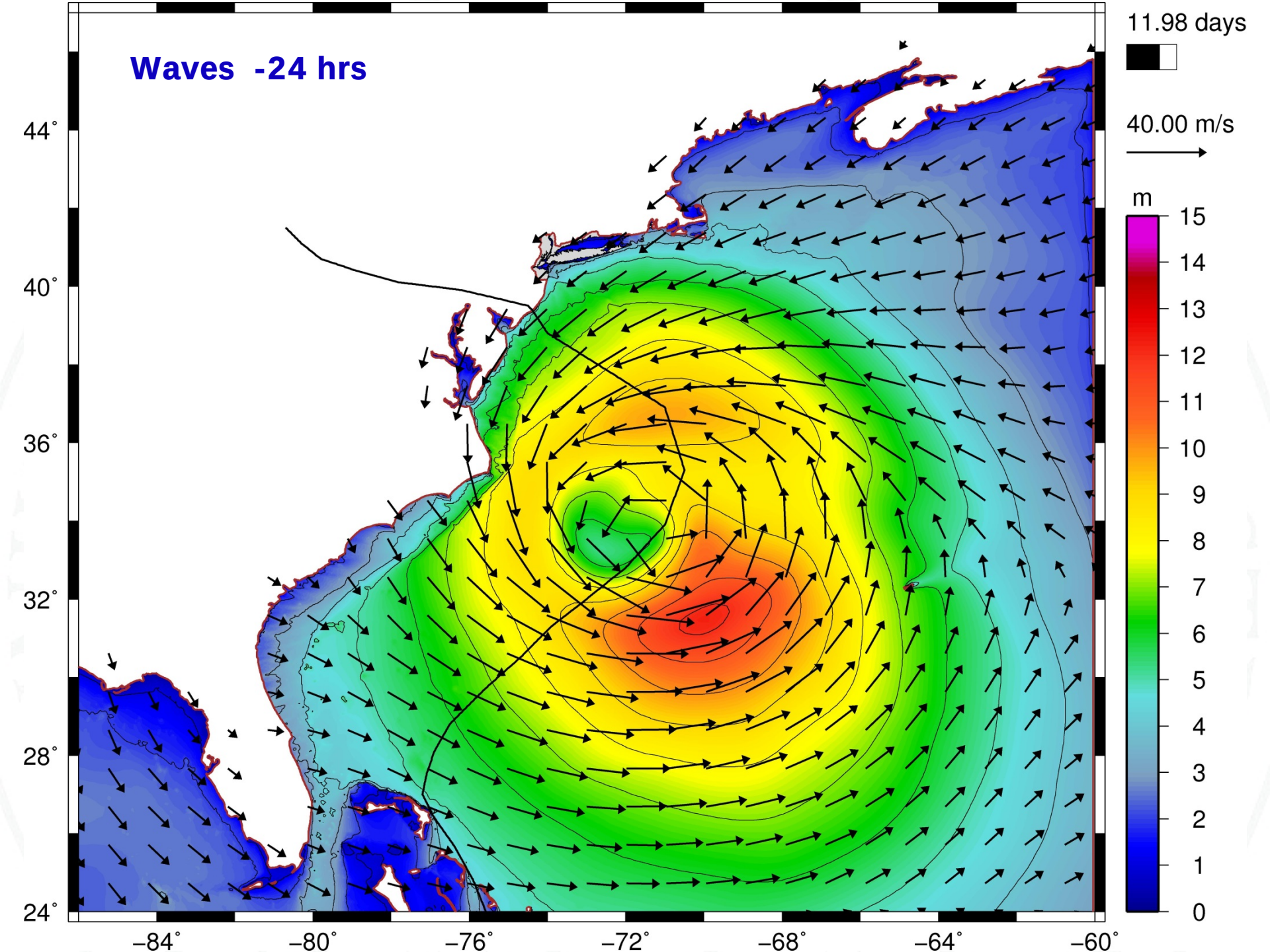

Waves -44 hrs
11.15 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -40 hrs
11.31 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -36 hrs
11.48 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -32 hrs
11.65 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -28 hrs
11.81 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -24 hrs
11.98 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
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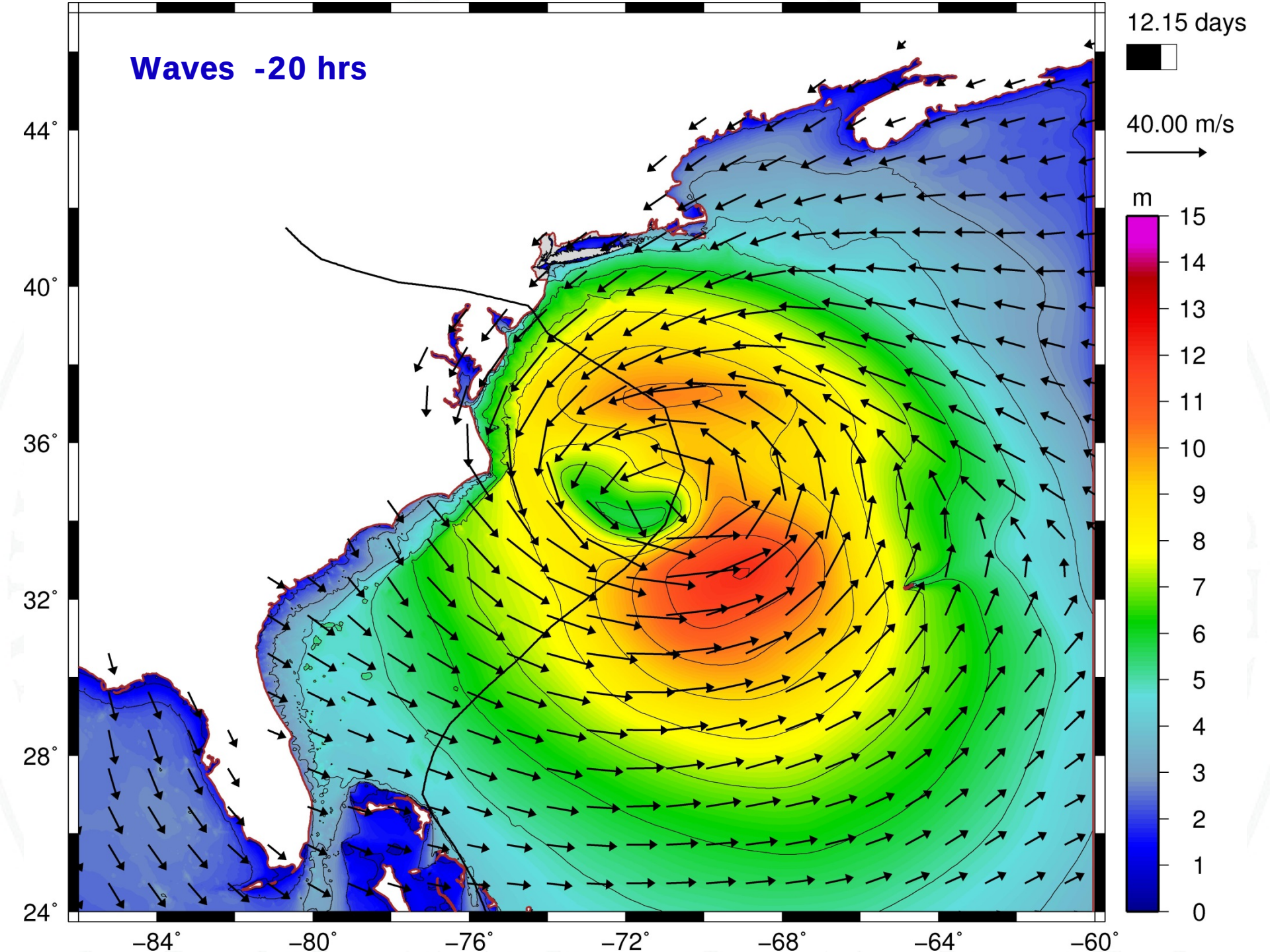
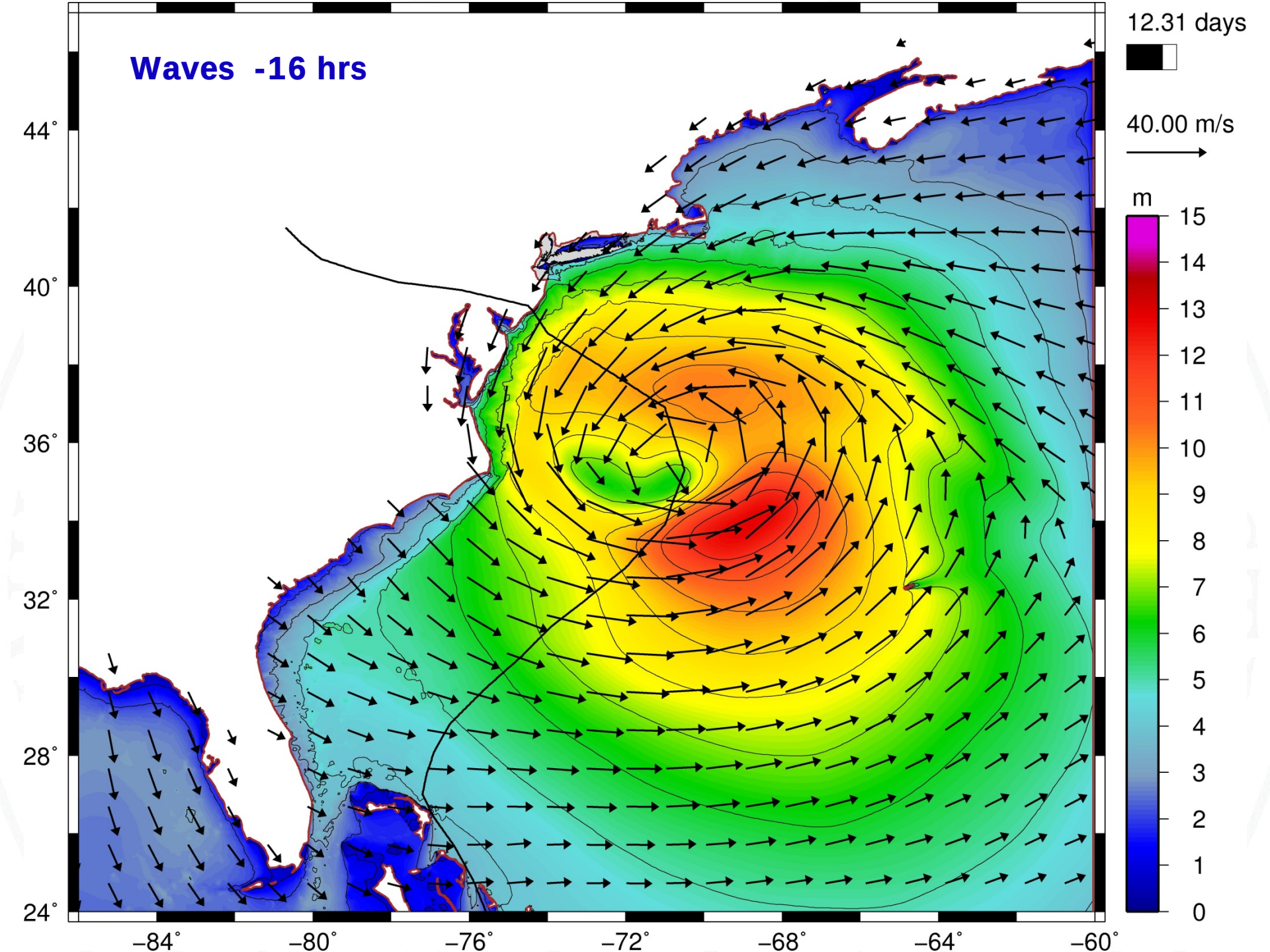
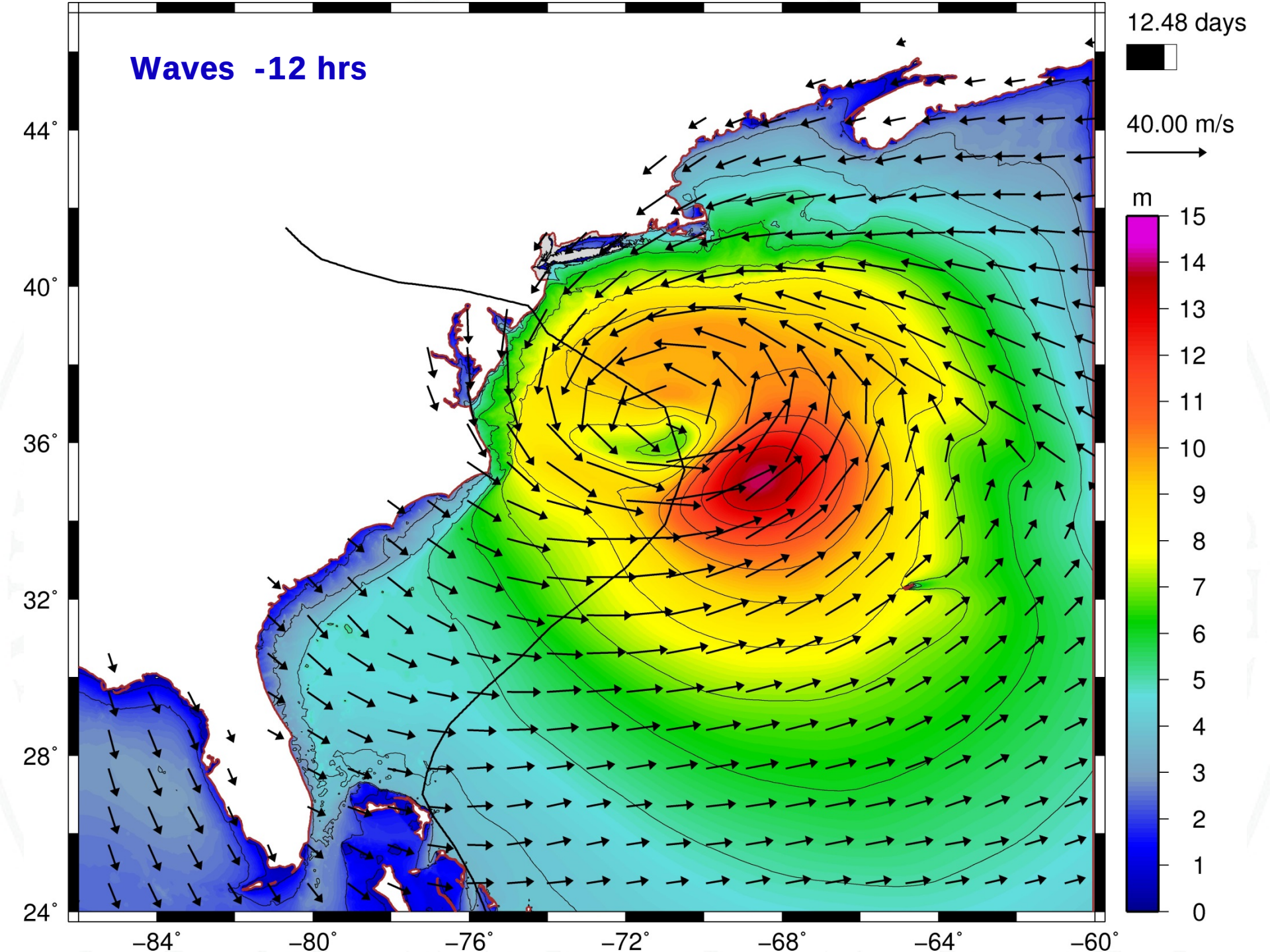
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -20 hrs
12.15 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -16 hrs
12.31 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -12 hrs
12.48 days
40.00 m/s
m
15
14
13
12
11
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9
8
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6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
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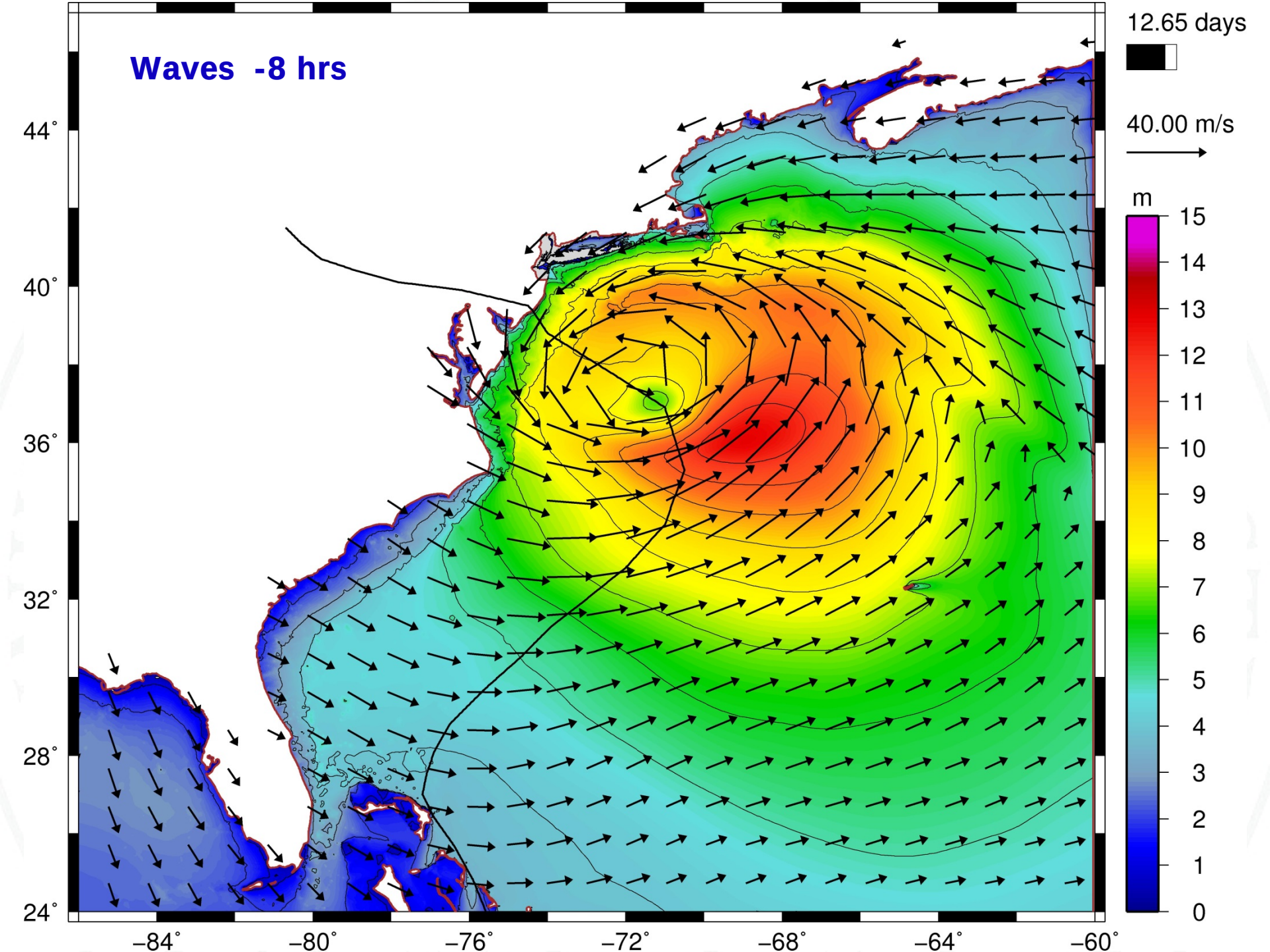
Waves -8 hrs
12.65 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
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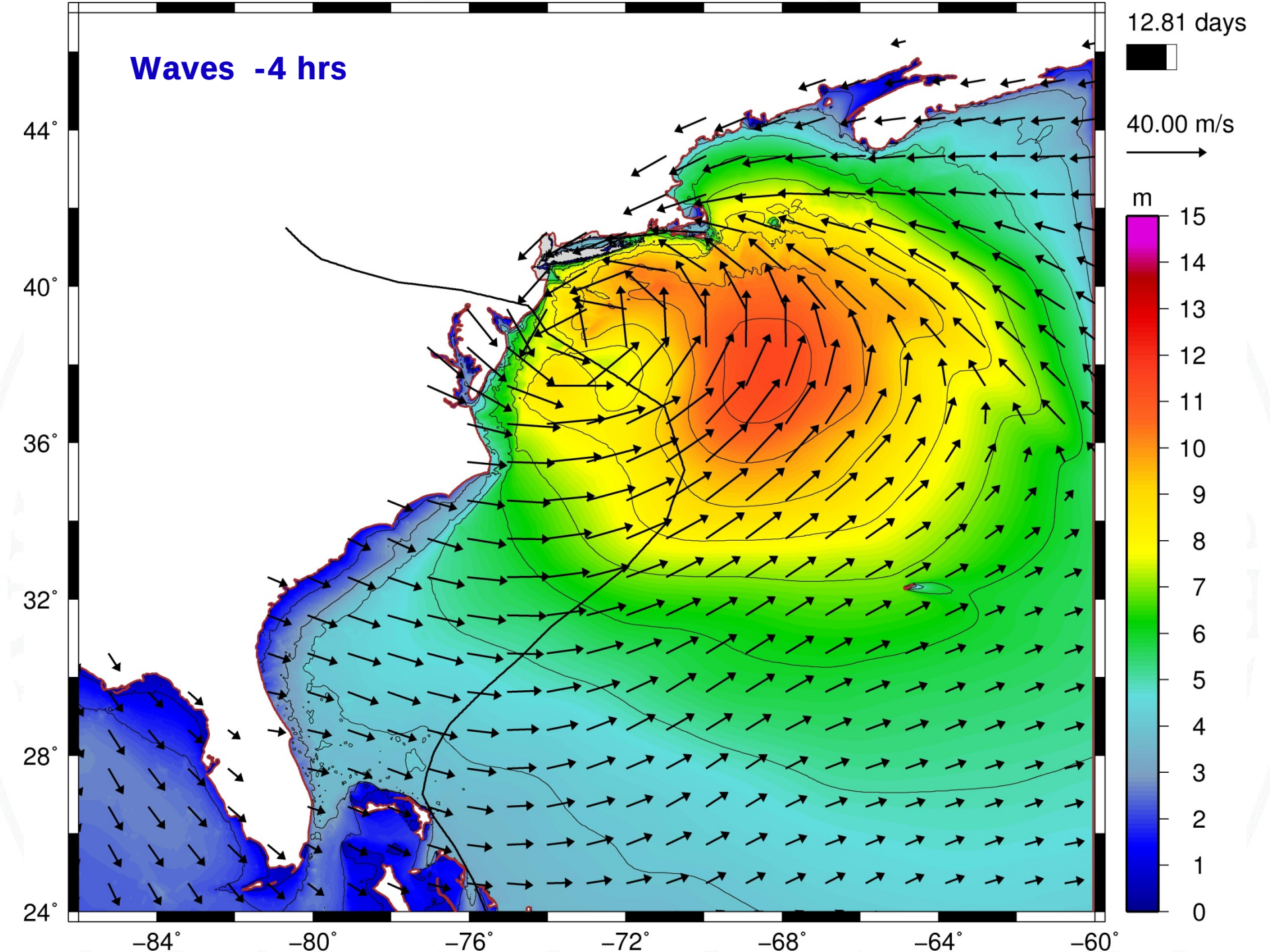
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves -4 hrs
12.81 days
40.00 m/s
m
15
14
13
12
11
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8
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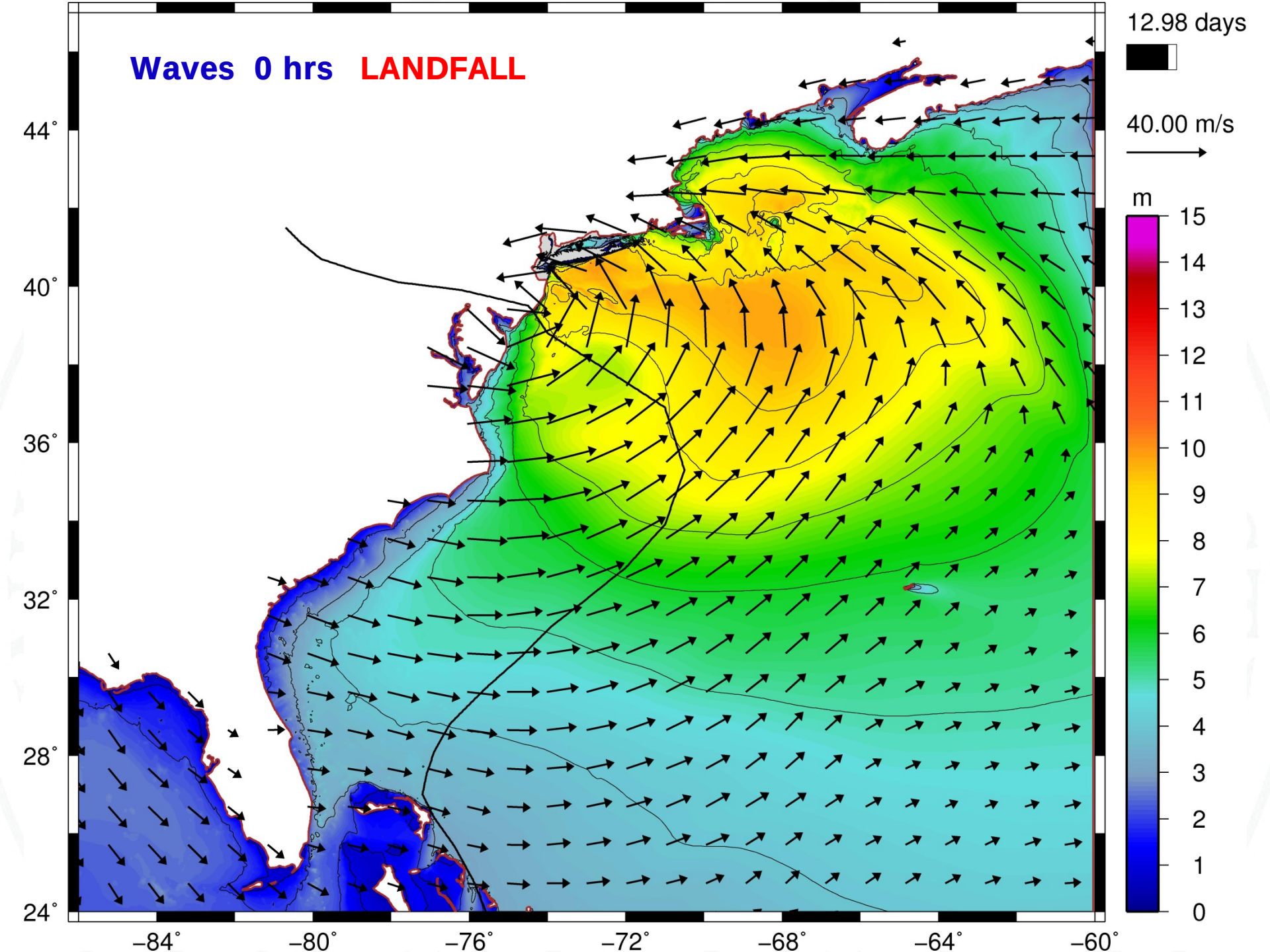
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves 0 hrs LANDFALL
12.98 days
40.00 m/s
m
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12
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3
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1
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44˚
40˚
36˚
32˚
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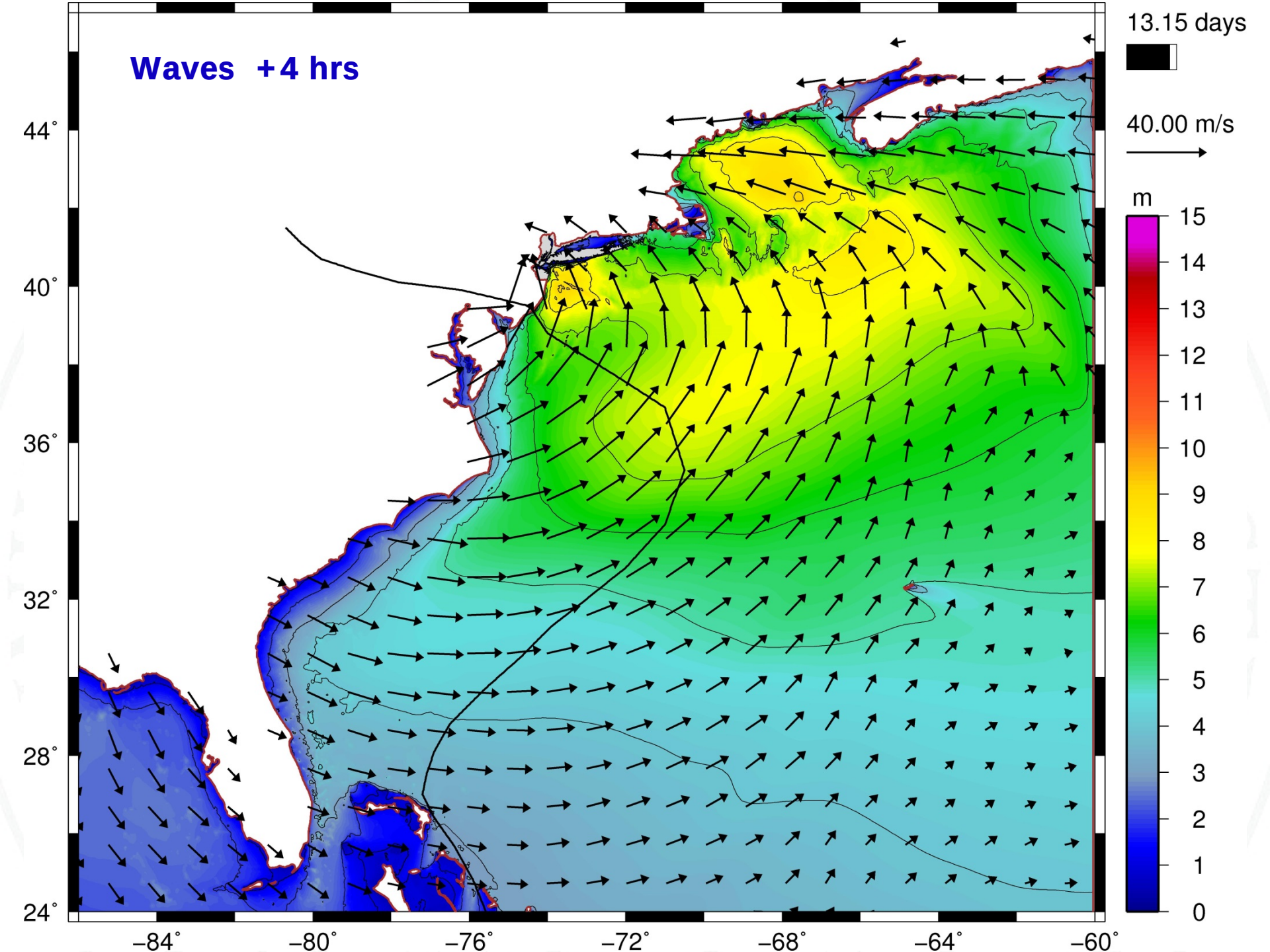
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves +4 hrs
13.15 days
40.00 m/s
m
15
14
13
12
11
10
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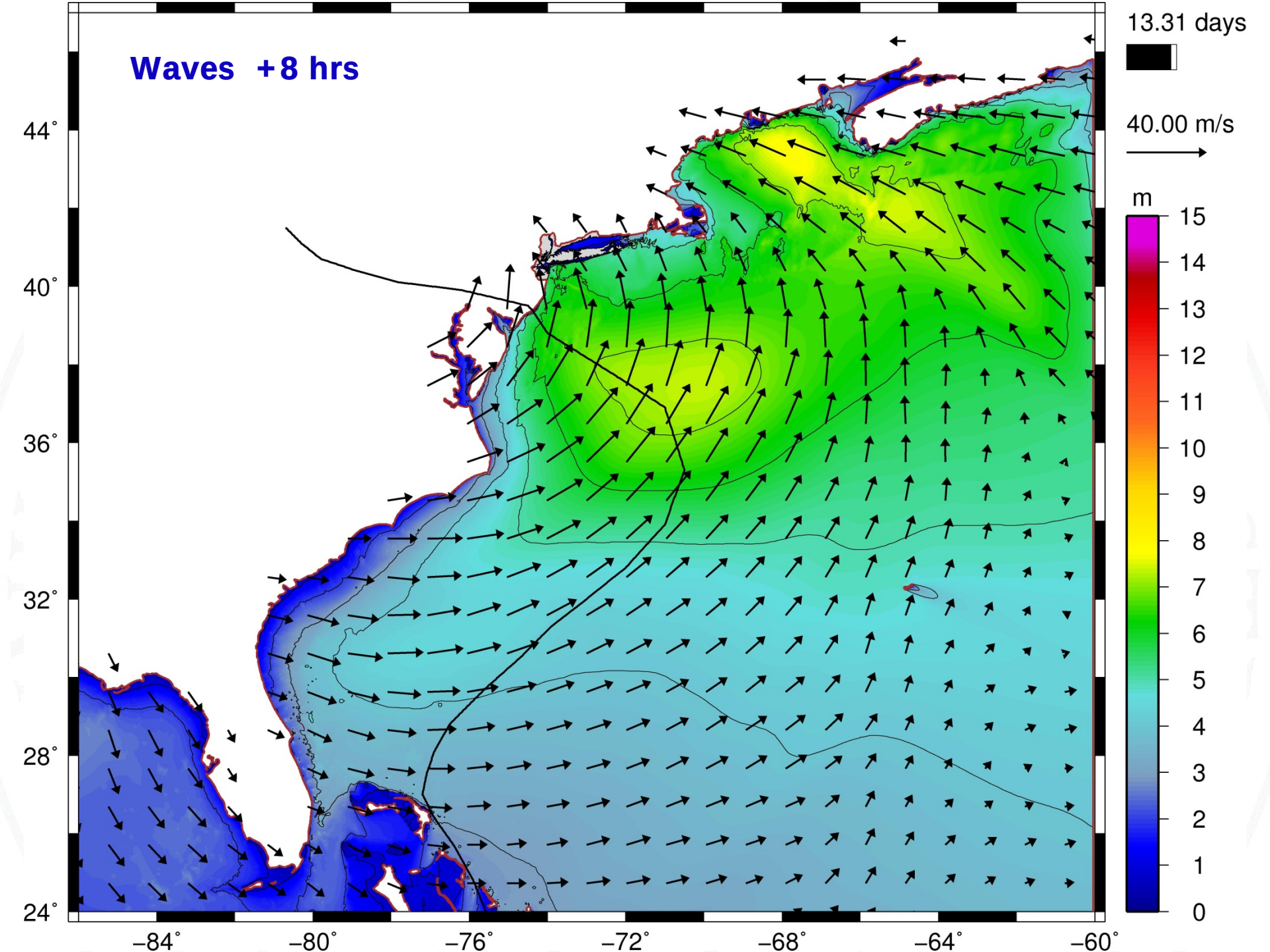
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves +8 hrs
13.31 days
40.00 m/s
m
15
14
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12
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4
3
2
1
0
44˚
40˚
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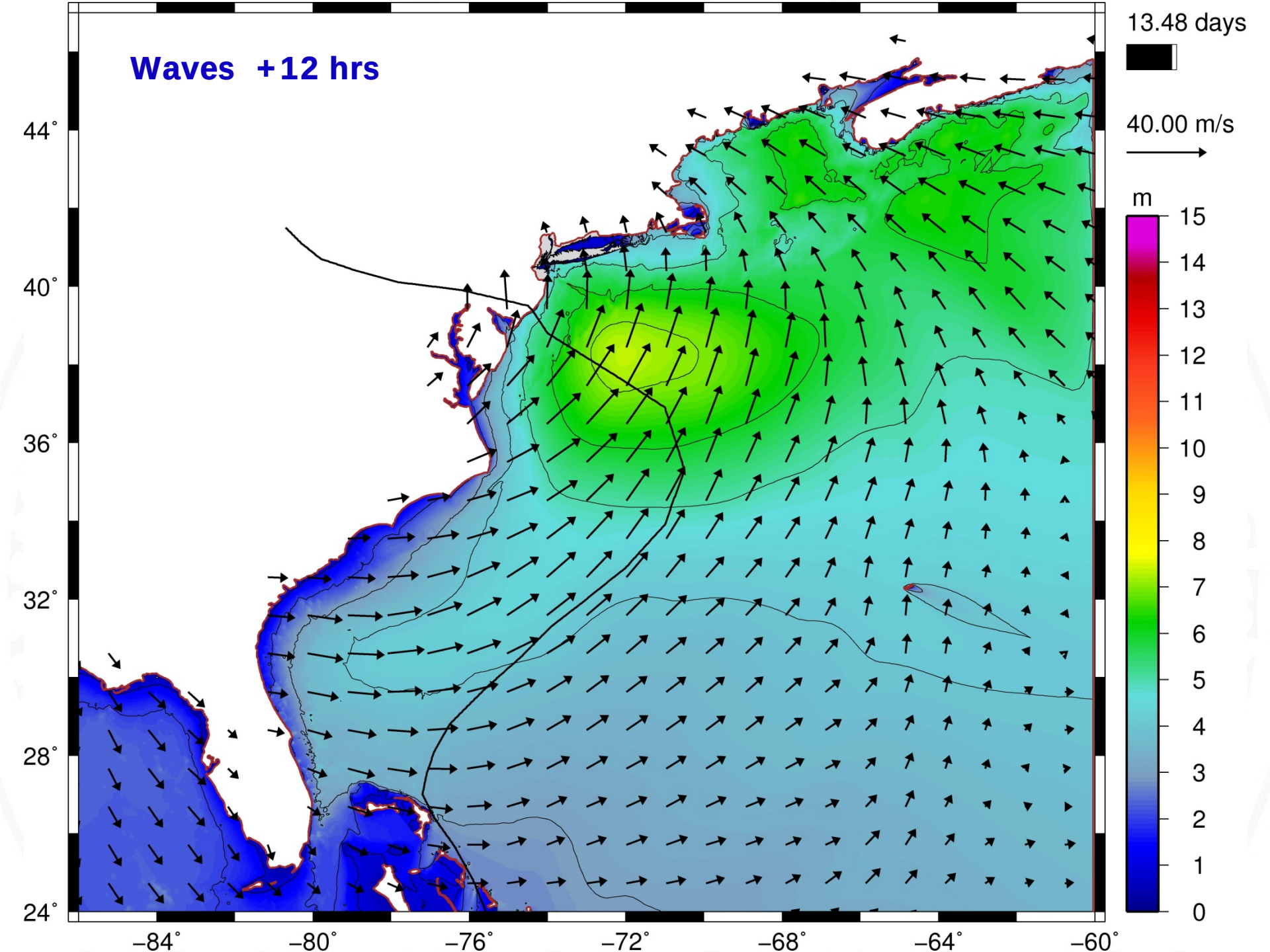
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves +12 hrs
13.48 days
40.00 m/s
m
15
14
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12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
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−80˚
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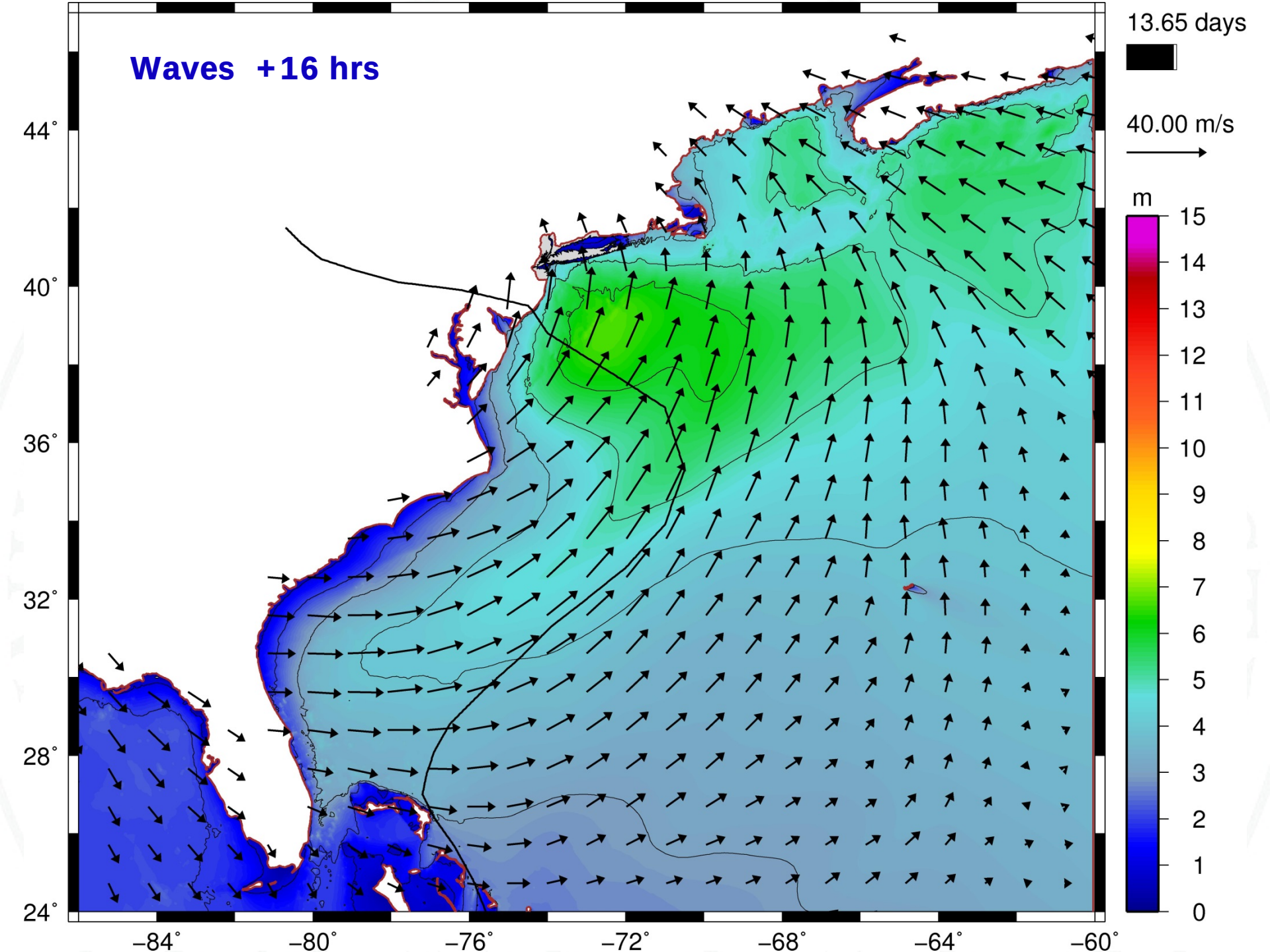
−72˚
−68˚
−64˚
−60˚


Waves +16 hrs
13.65 days
40.00 m/s
m
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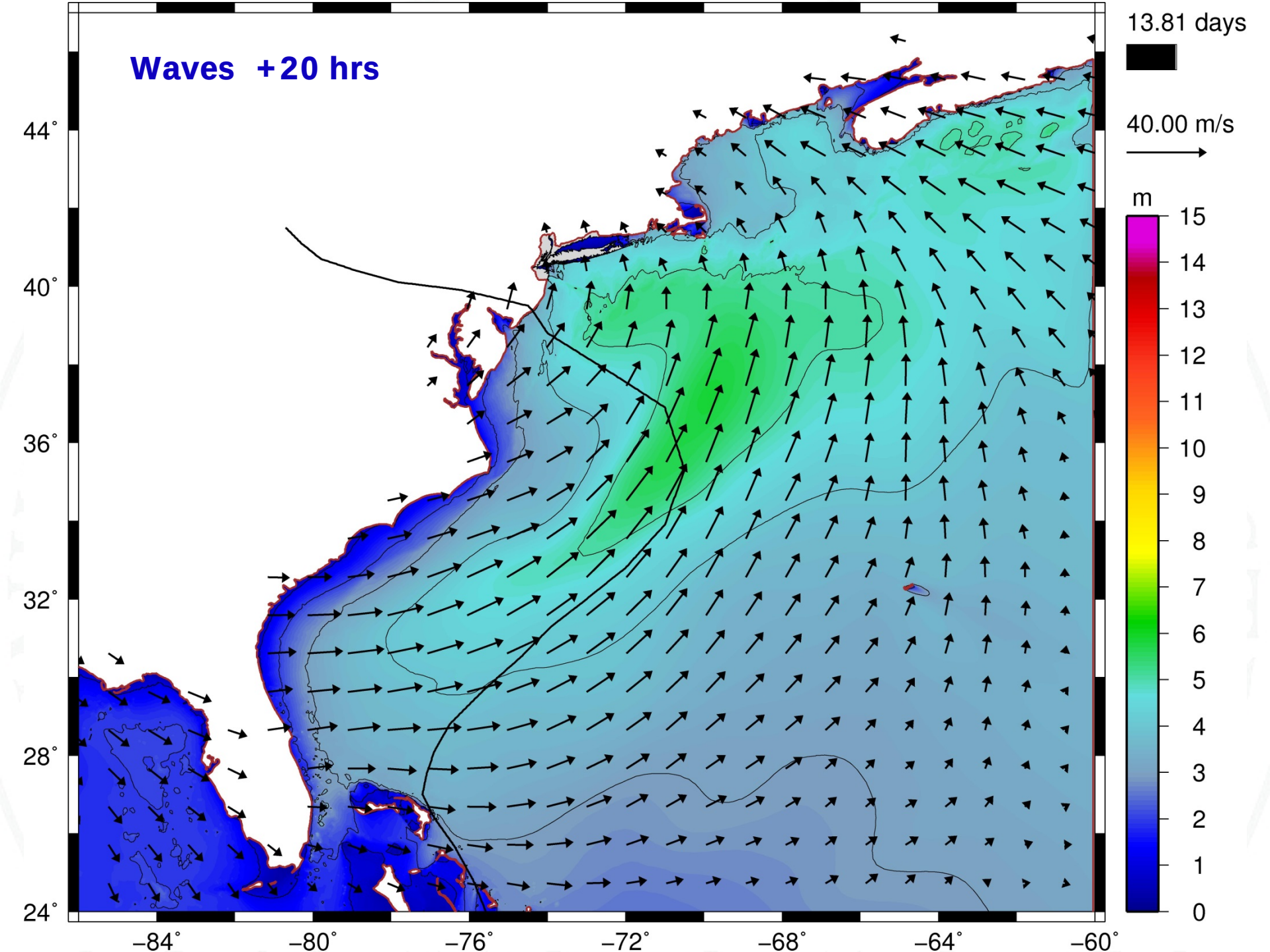
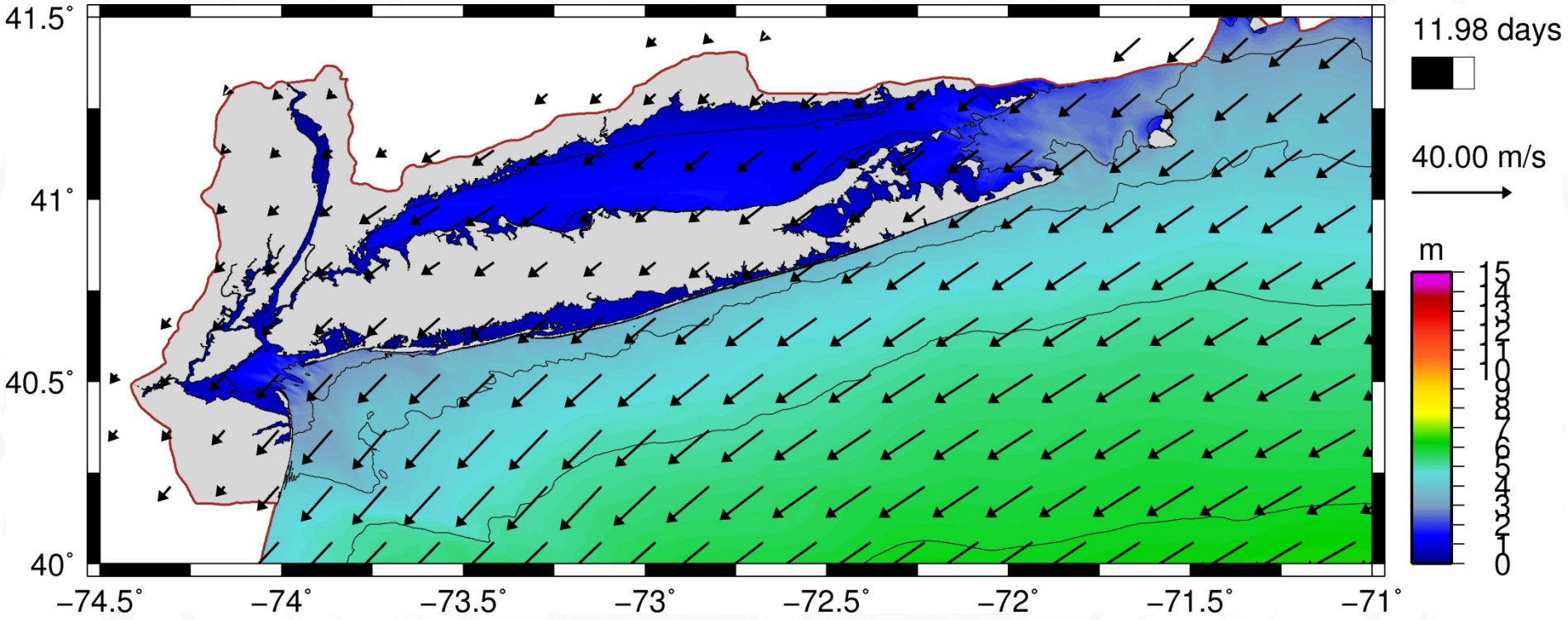
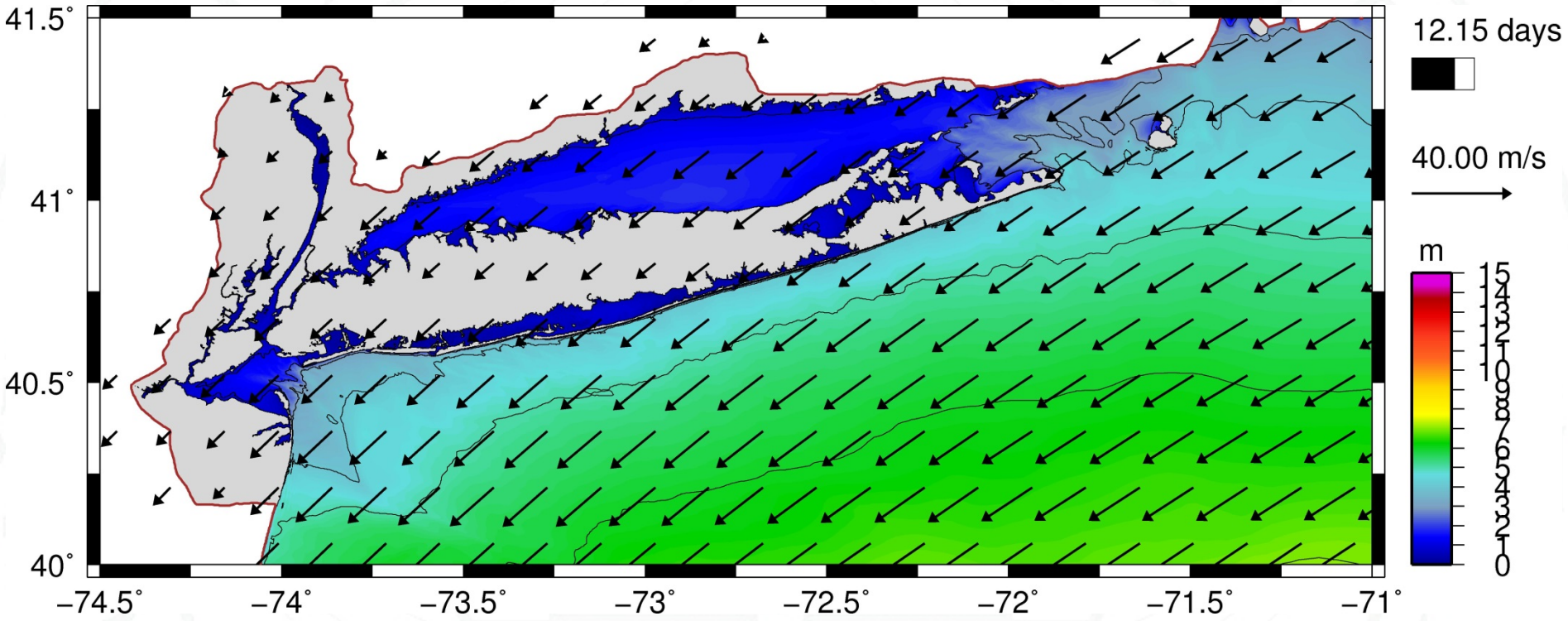
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


Waves +20 hrs
13.81 days
40.00 m/s
m
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

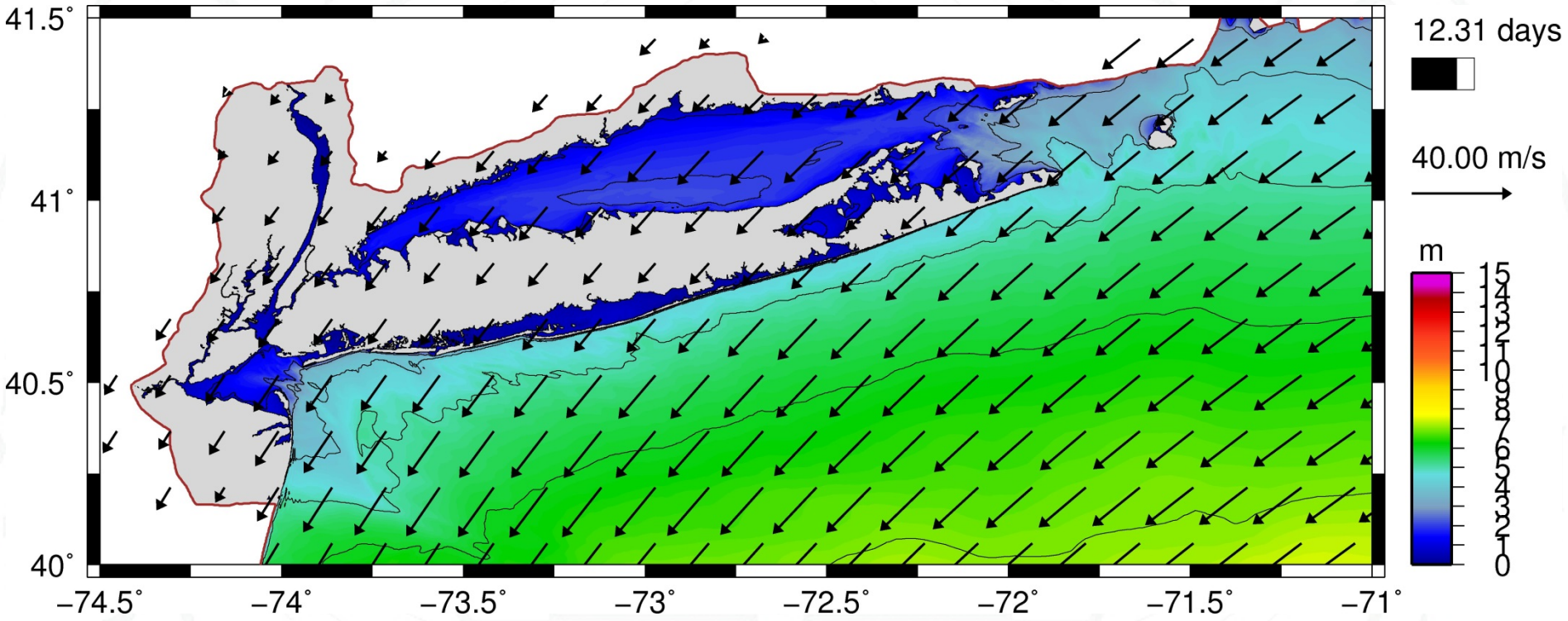
Waves -24 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
11.98 days
40.00 m/s
m
5
4
3
2
1
0

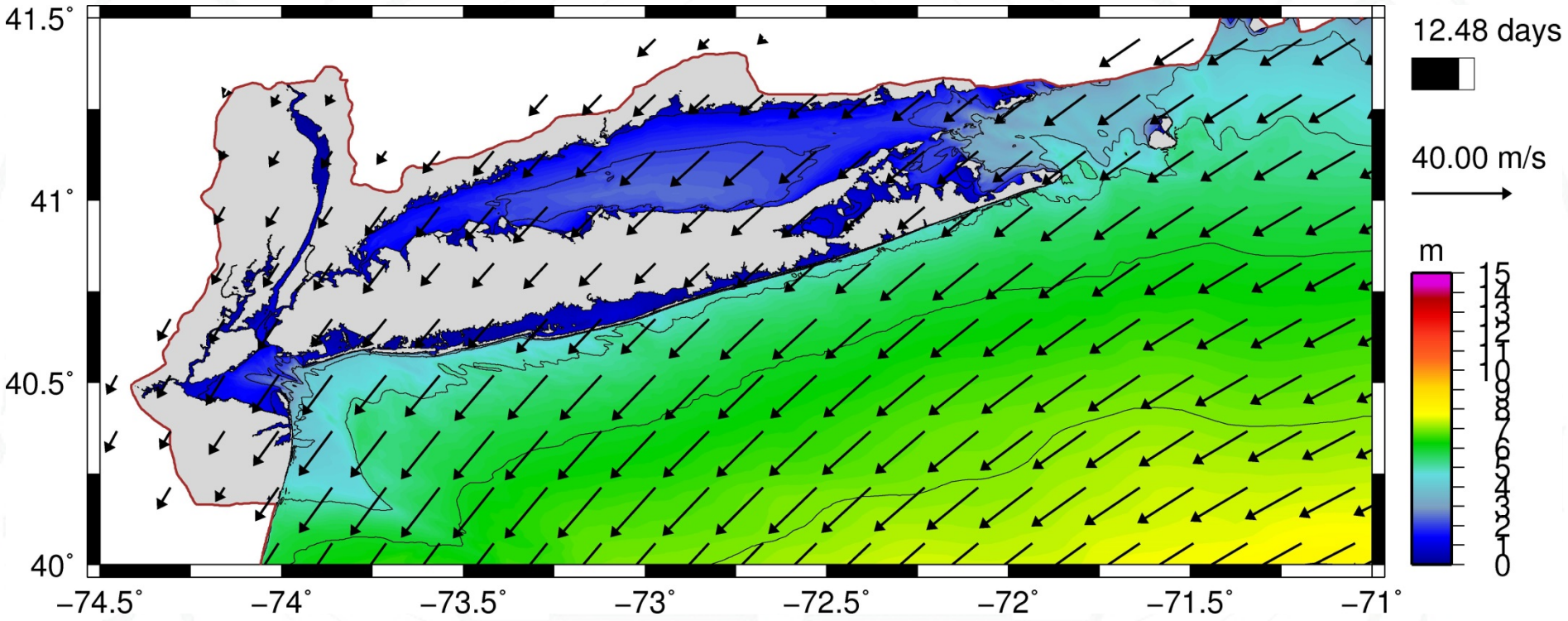
Waves -20 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.15 days
40.00 m/s
m
5
4
3
2
1
0

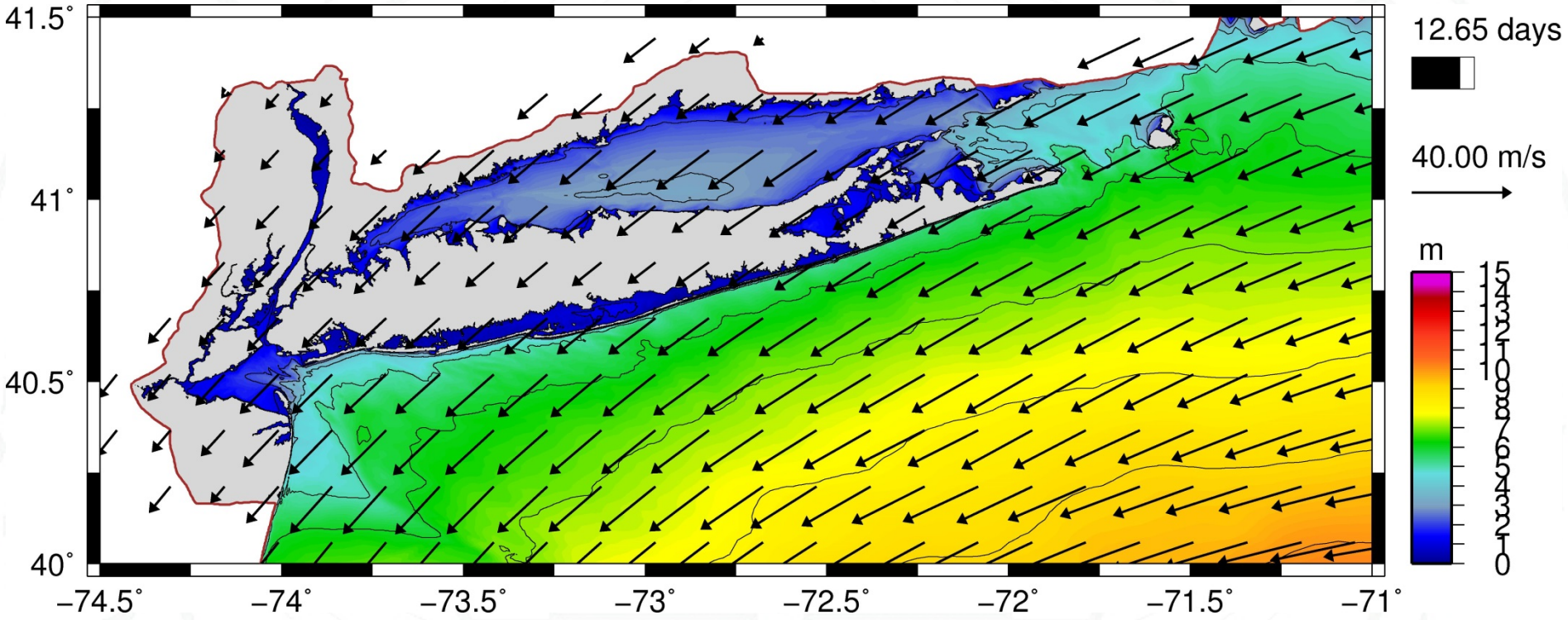
Waves -16 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.31 days
40.00 m/s
m
5
4
3
2
1
0

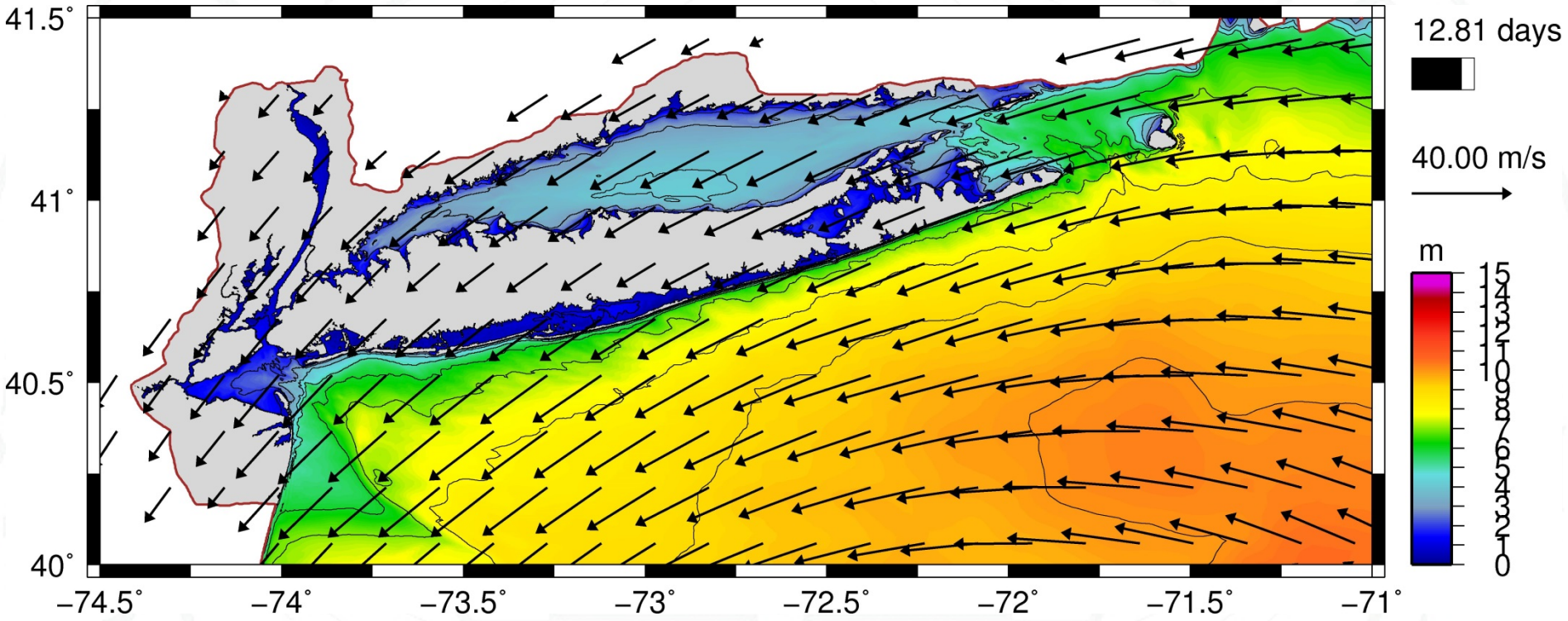
Waves -12 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.48 days
40.00 m/s
m
5
4
3
2
1
0

Waves -8 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.65 days
40.00 m/s
m
5
4
3
2
1
0

Waves -4 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.81 days
40.00 m/s
m
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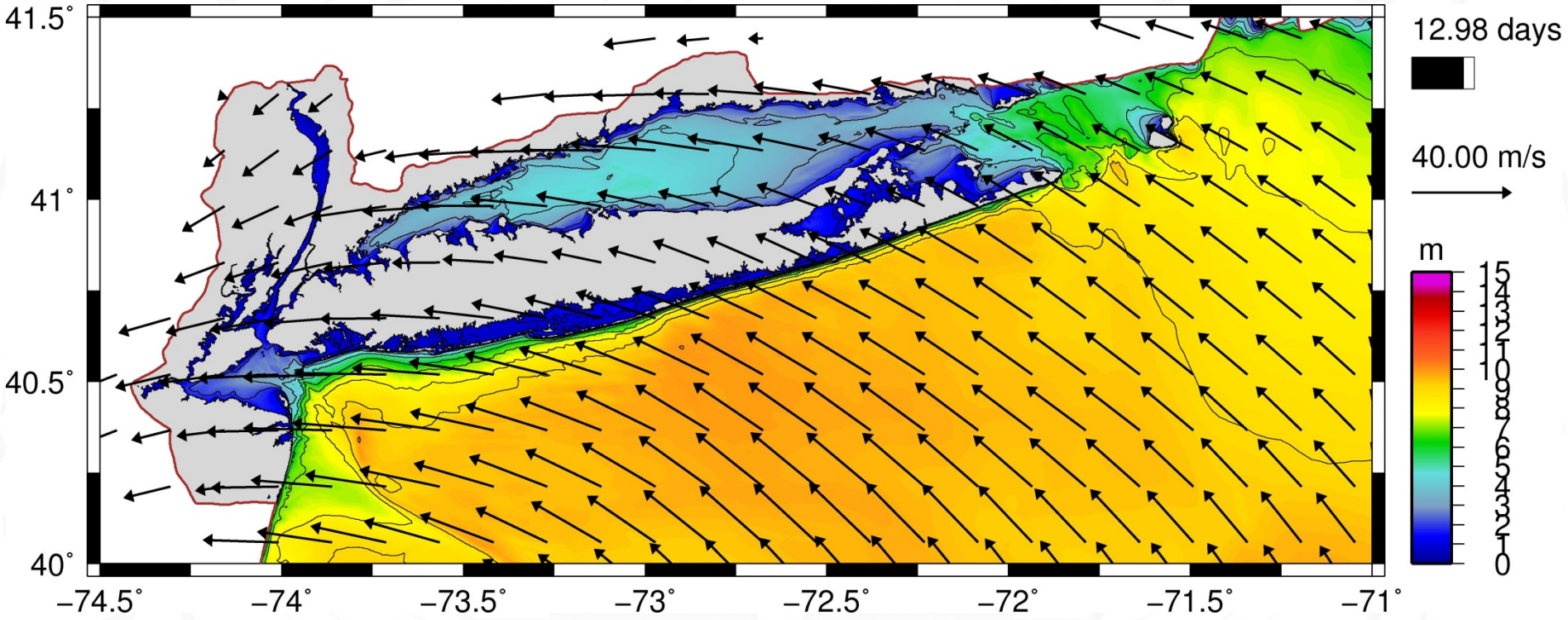
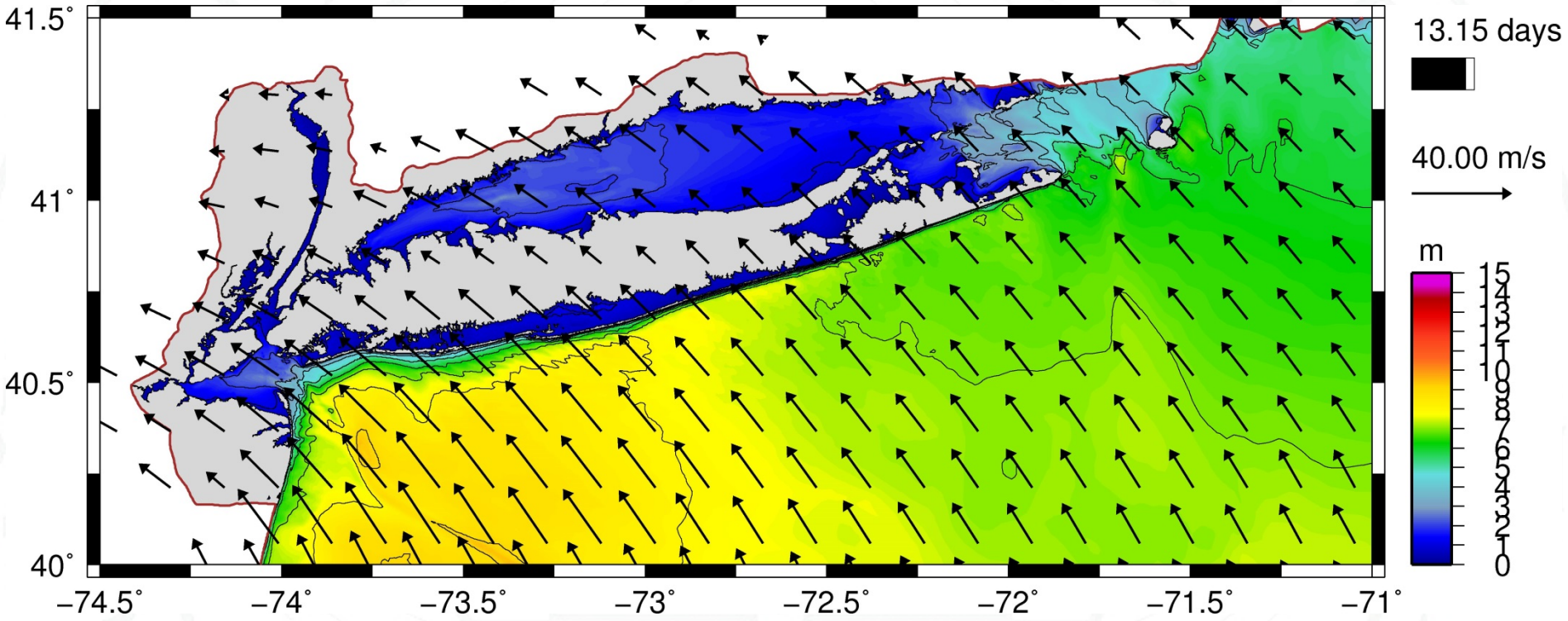
4
3
2
1
0

Waves 0 hrs LANDFALL



Waves +4 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
13.15 days
40.00 m/s
m
15
14
13
12
11
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4
3
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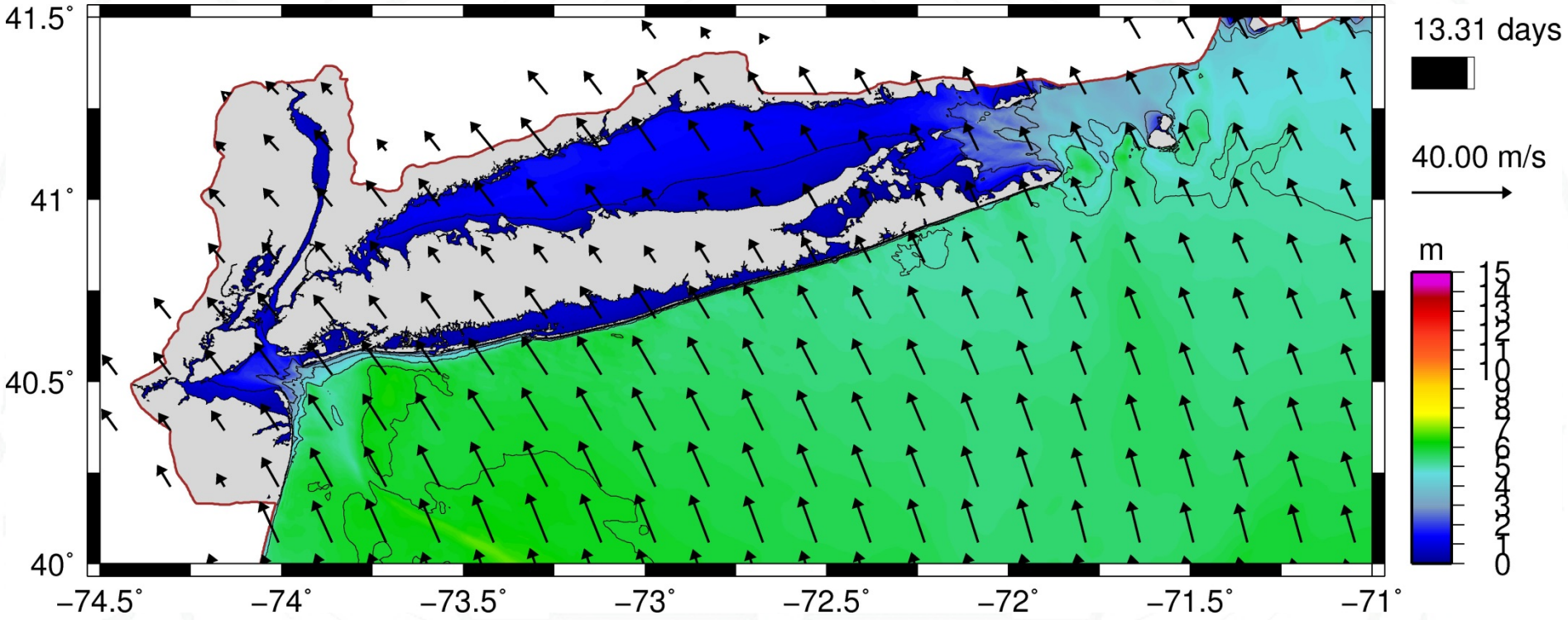
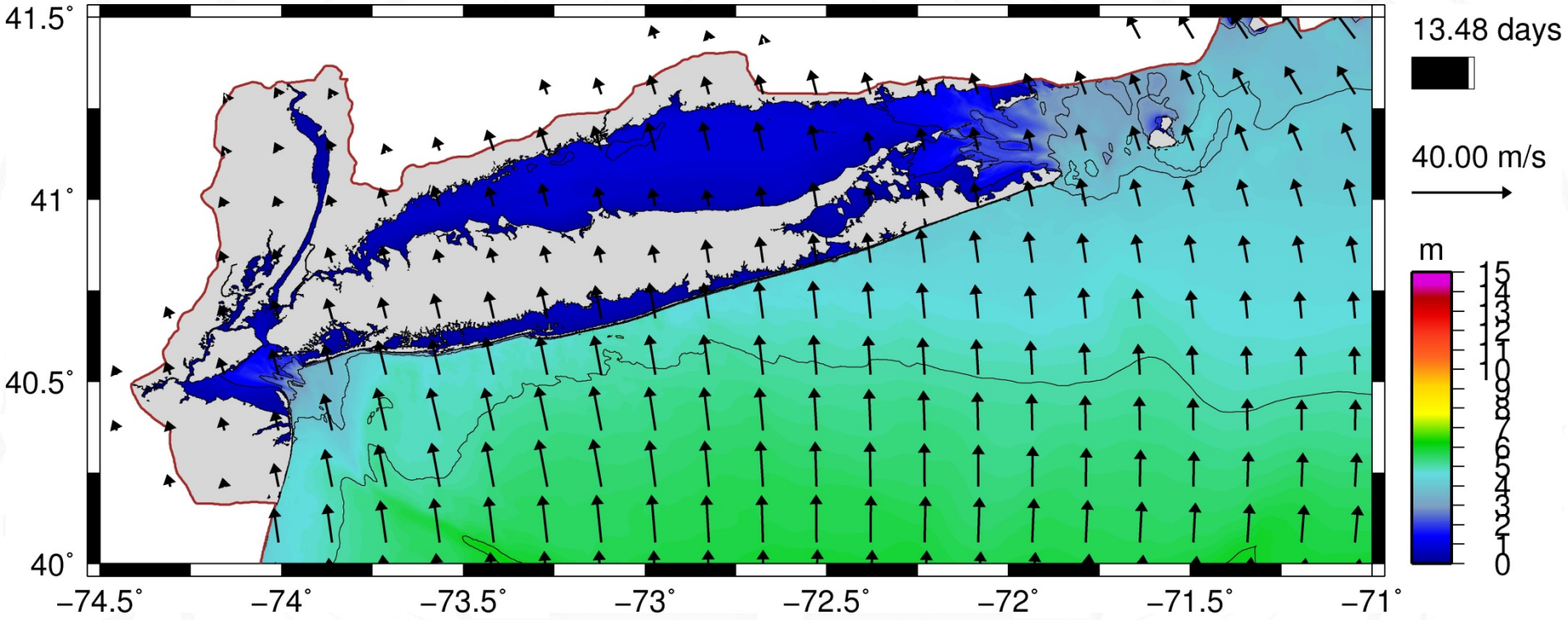
1
0

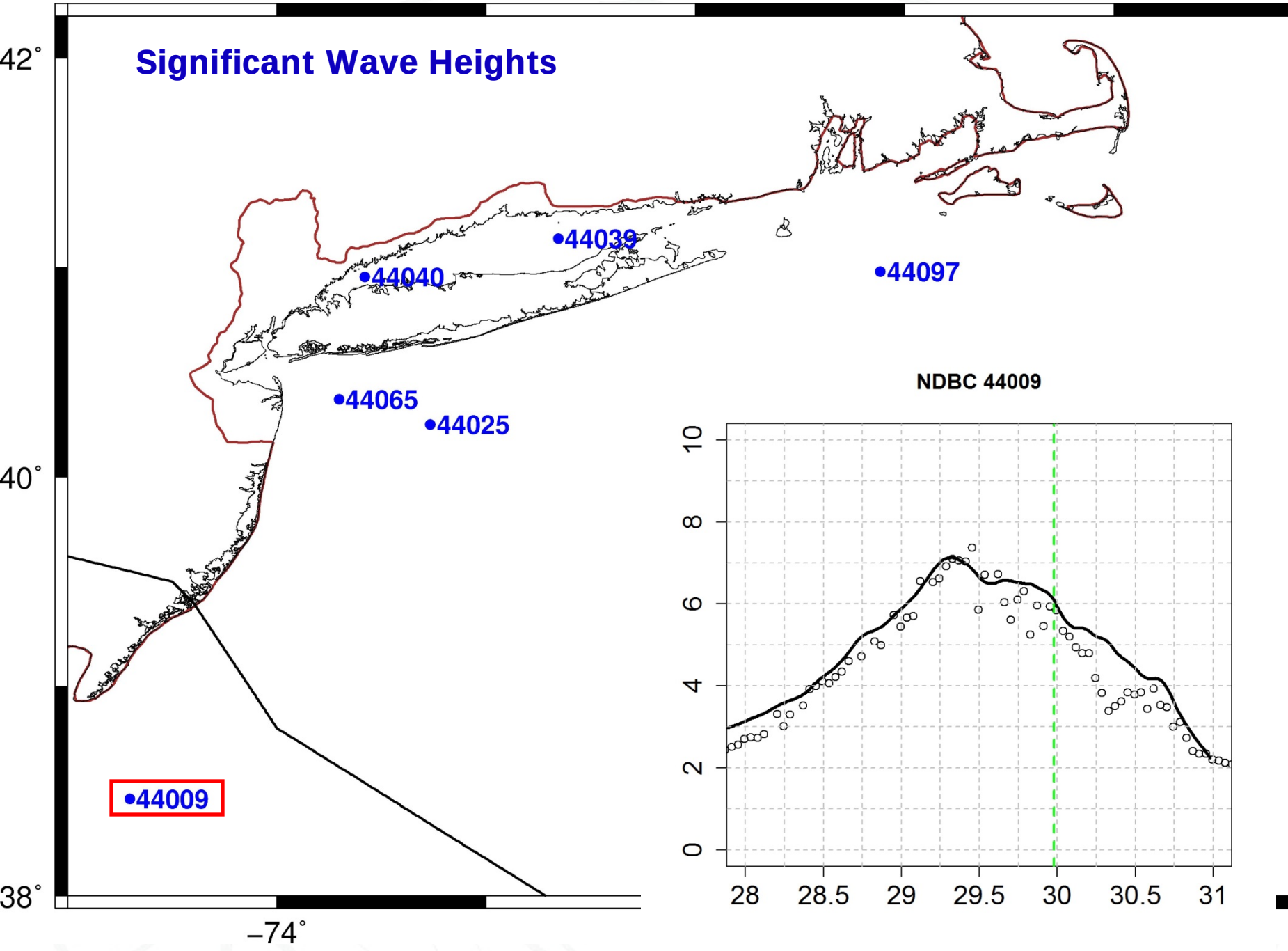
Waves +8 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
13.31 days
40.00 m/s
m
5
4
3
2
1
0

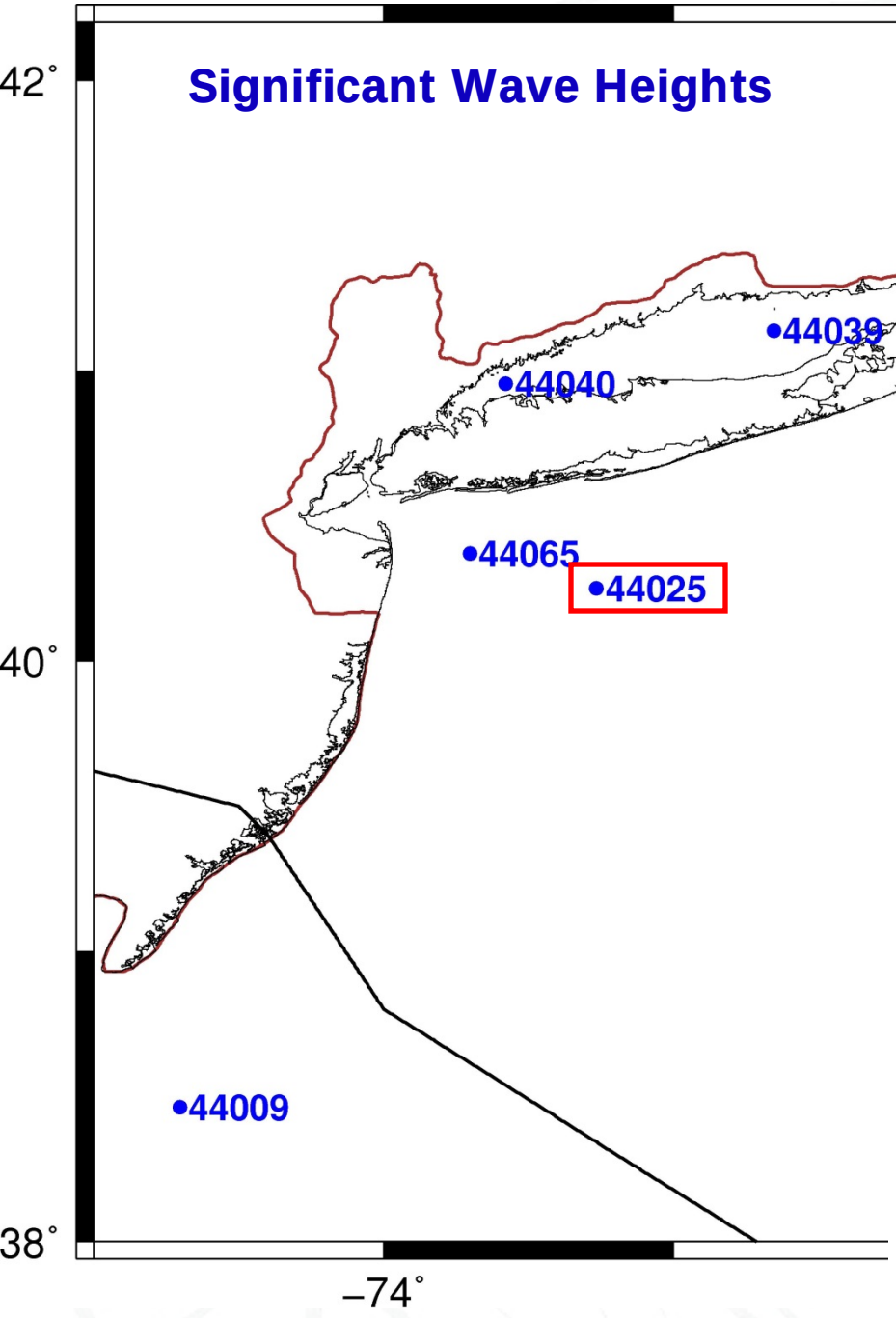
Waves + 12 hrs

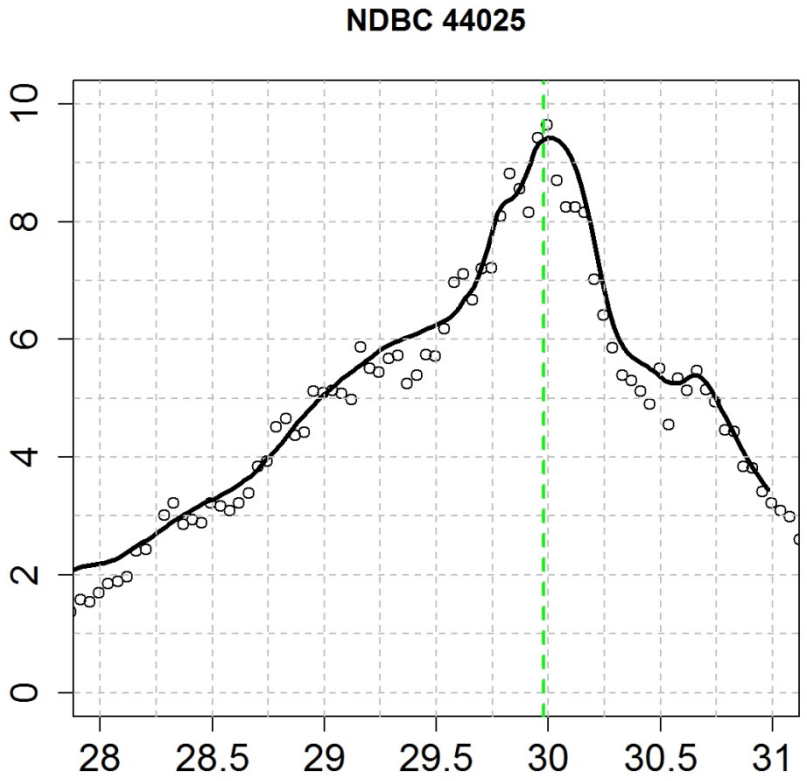

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
13.48 days
40.00 m/s
m
5
4
3
2
1
0

Significant Wave Heights

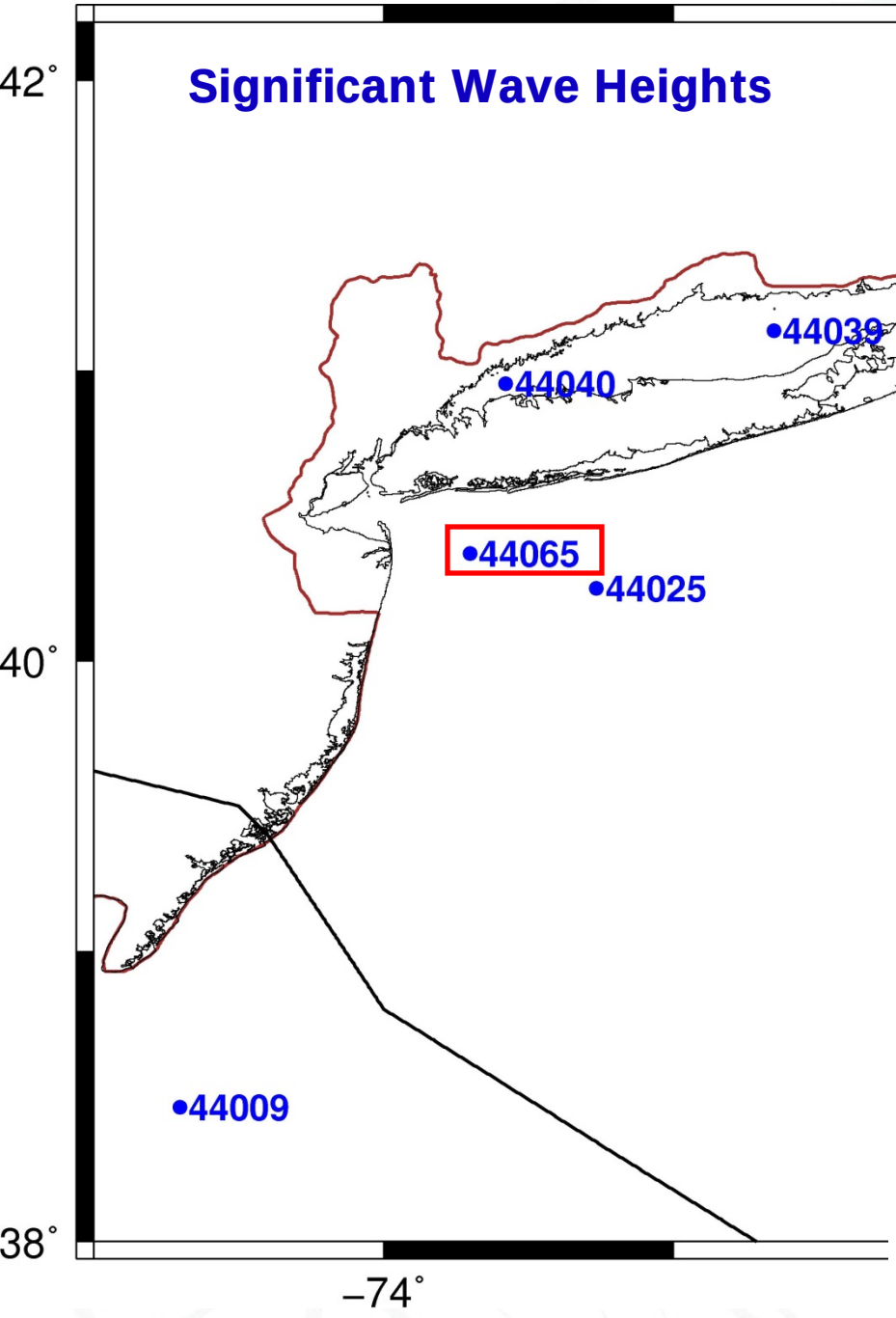


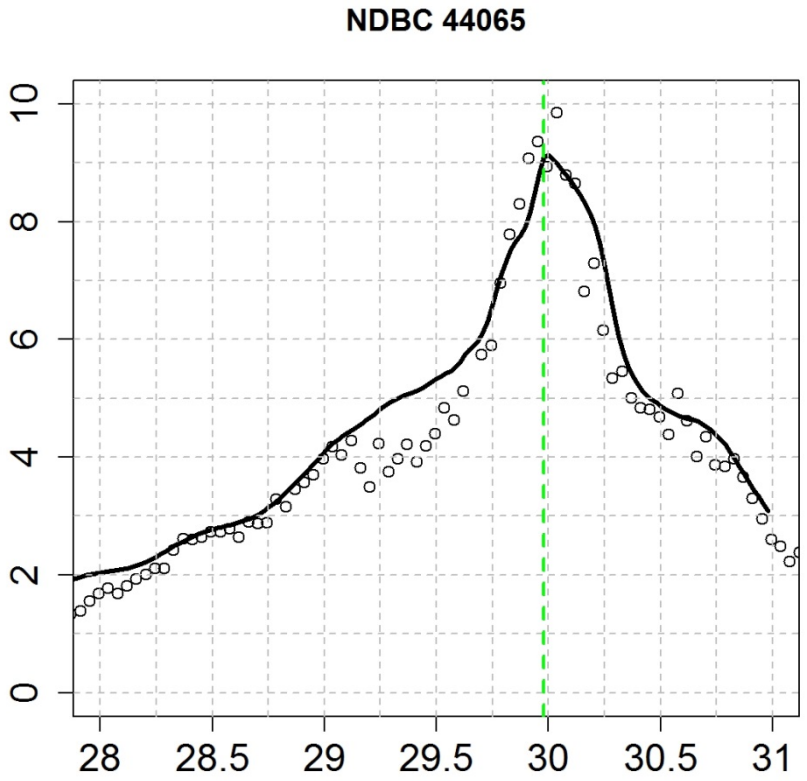
Significant Wave Heights



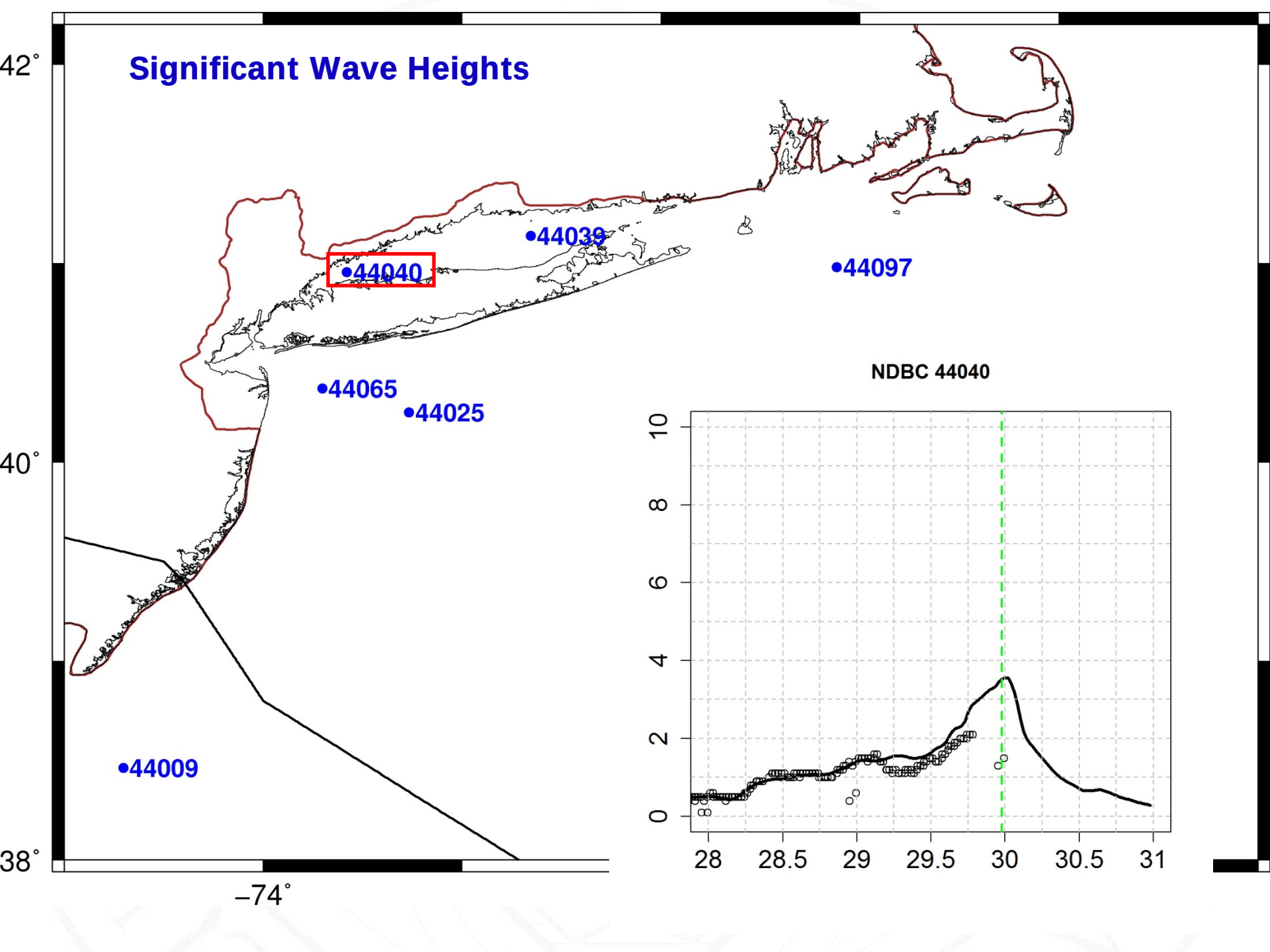


Significant Wave Heights

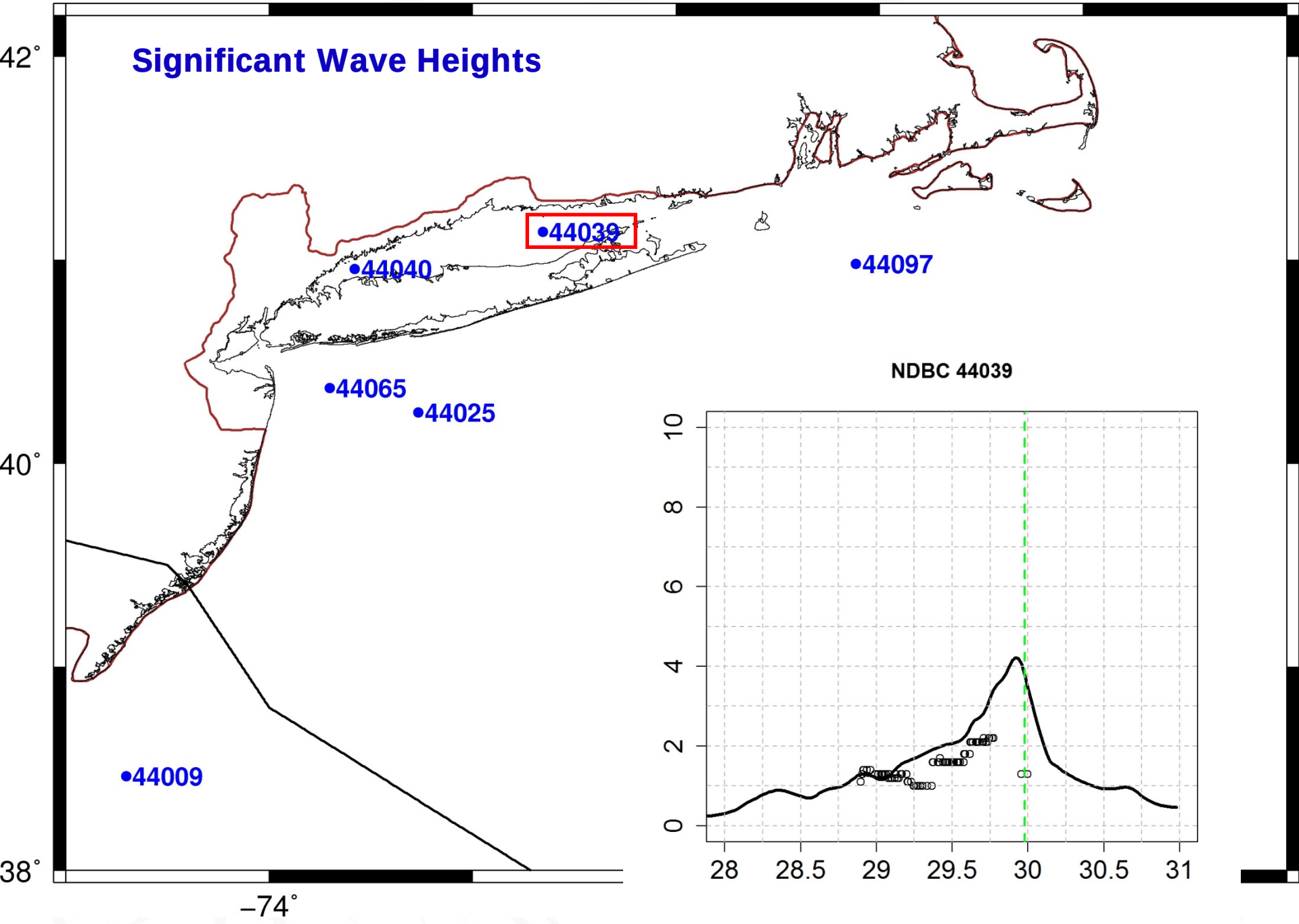




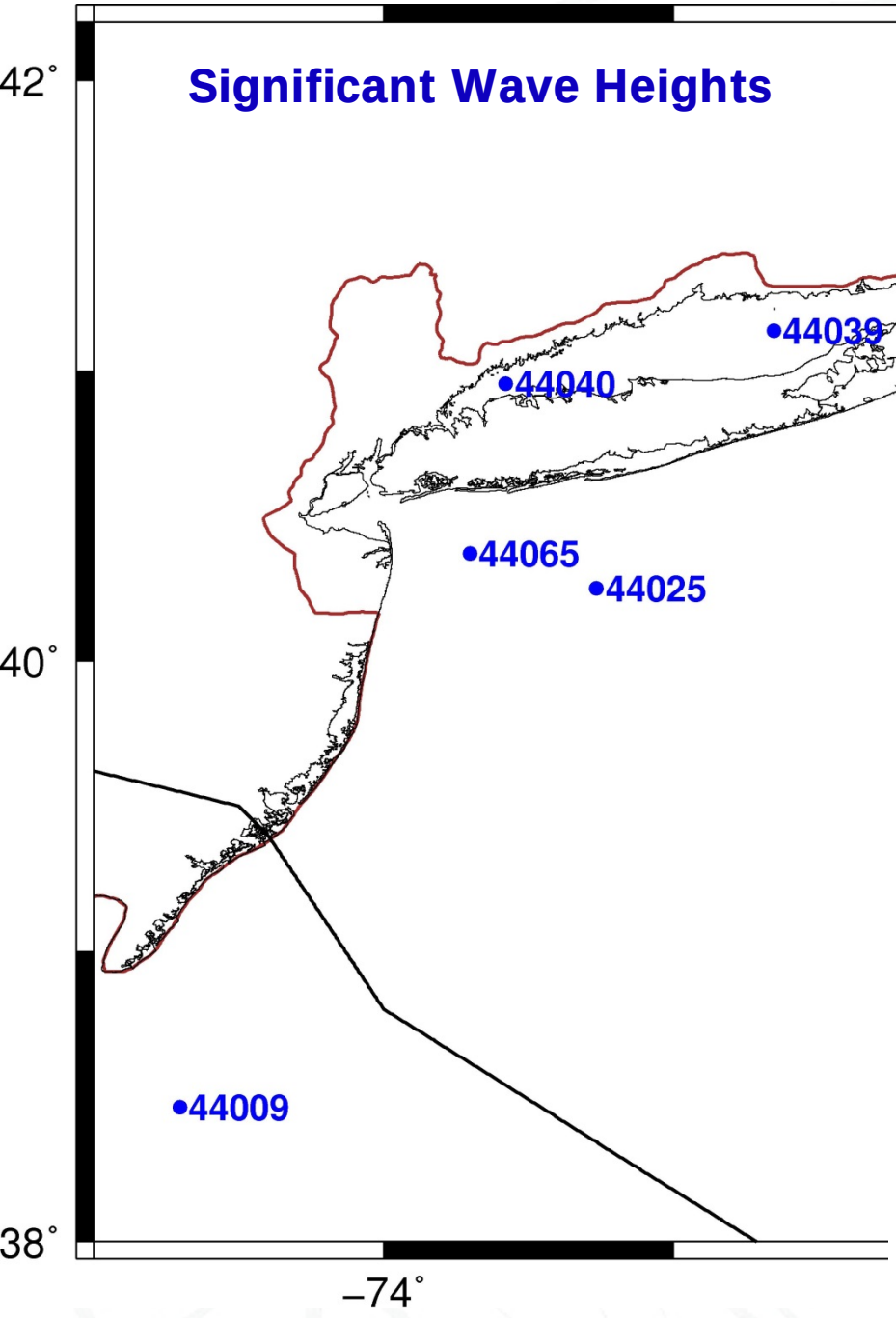
Significant Wave Heights

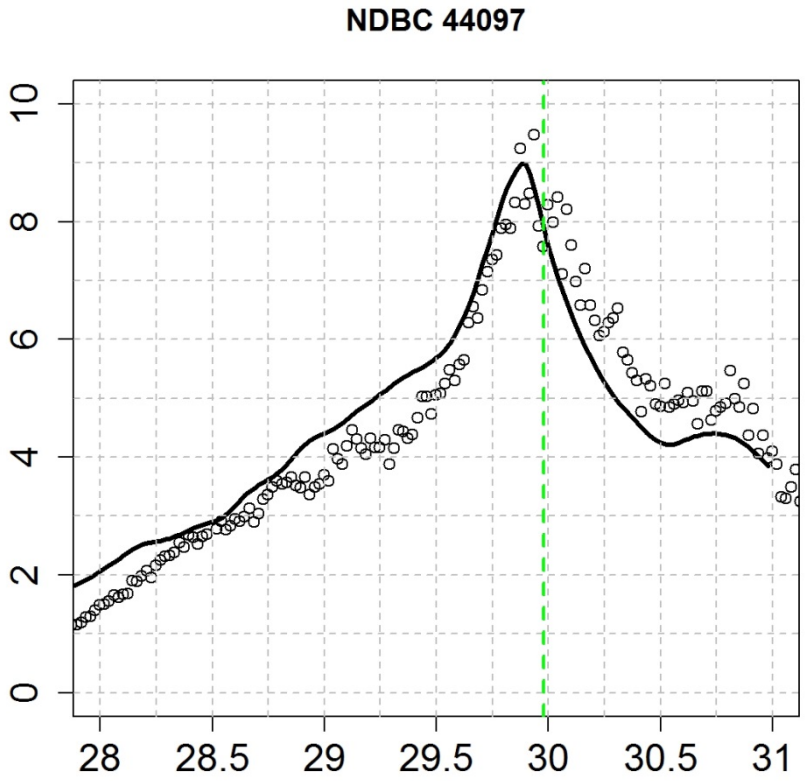


Significant Wave Heights

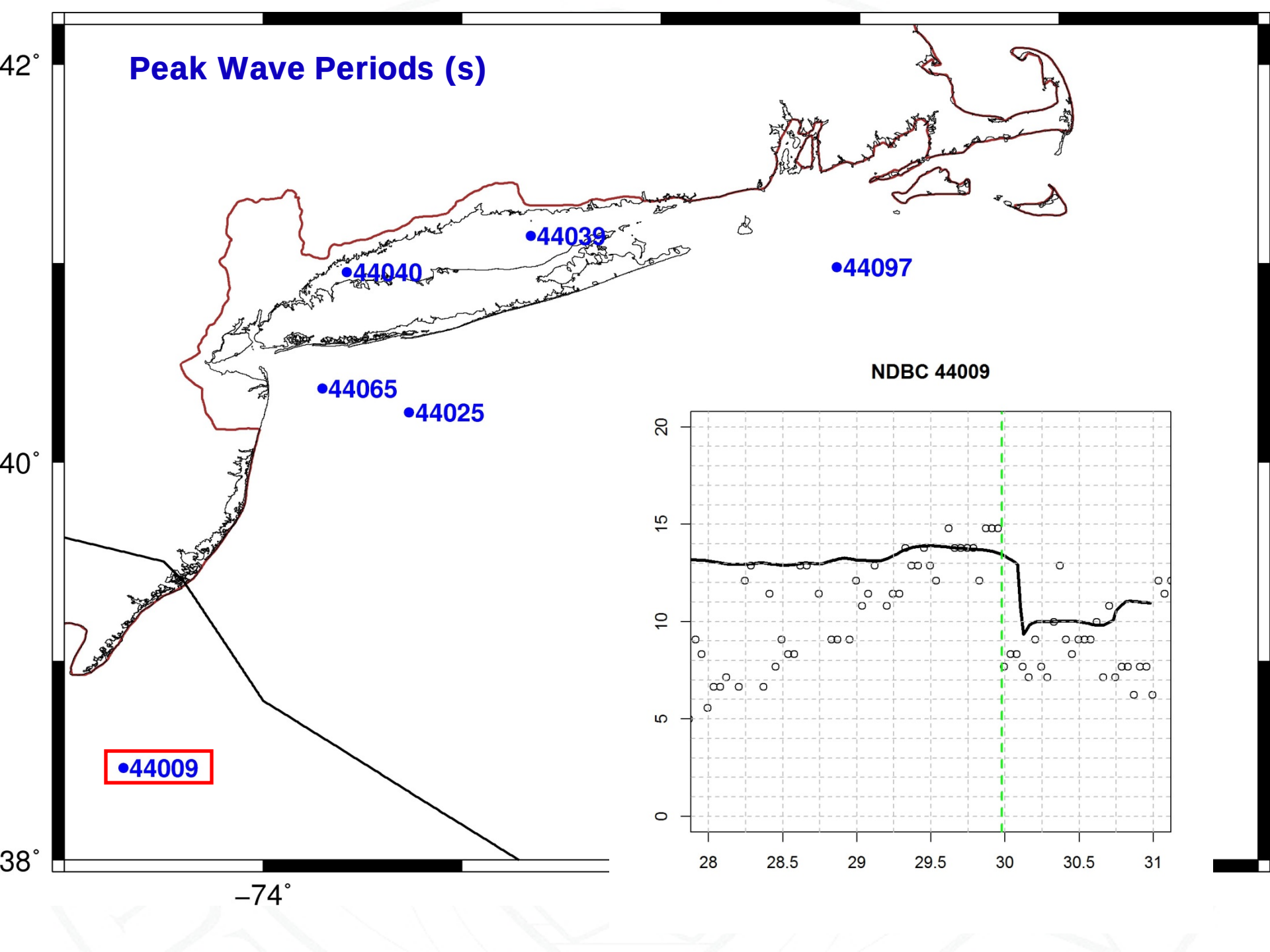


Significant Wave Heights

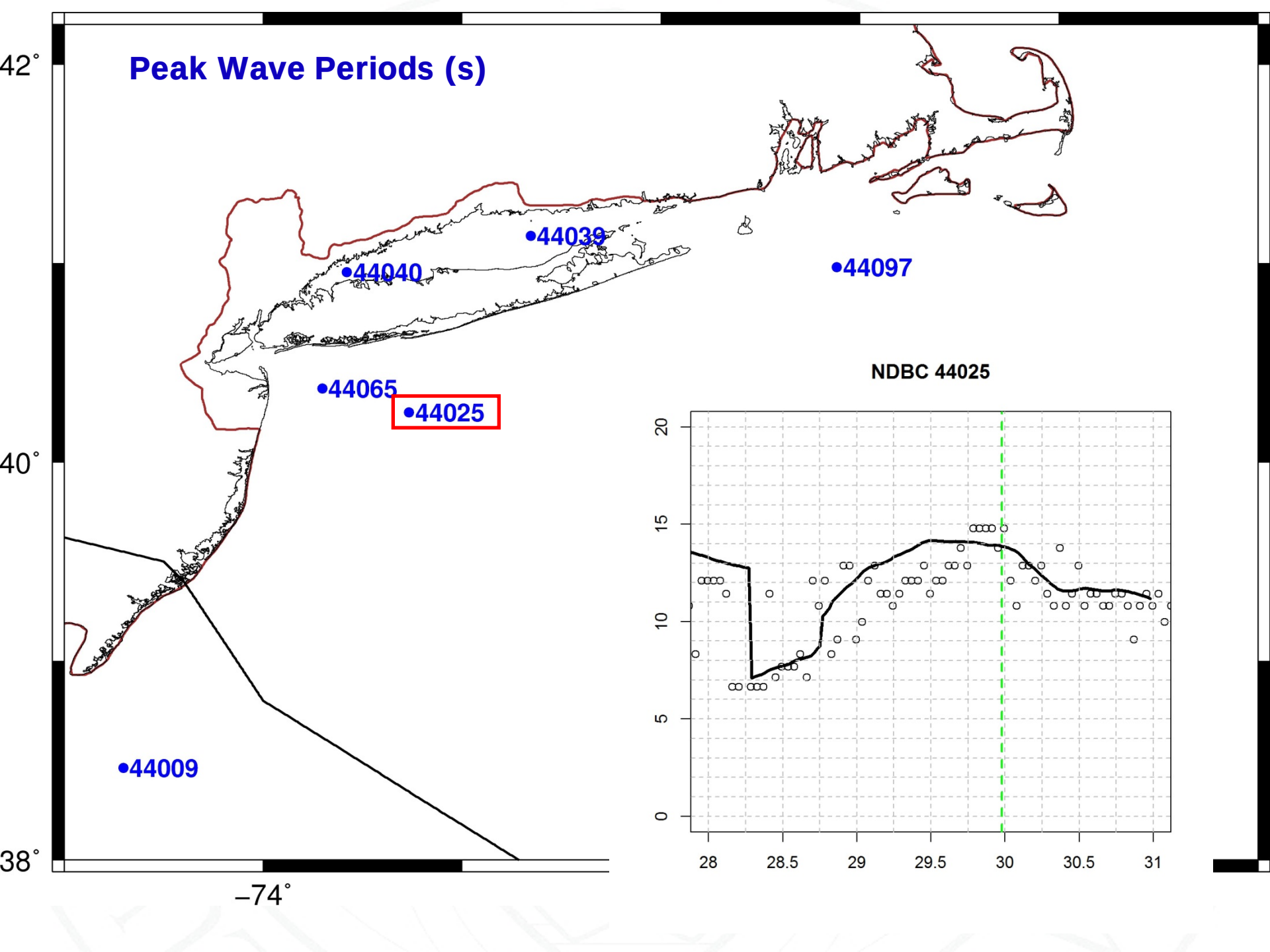




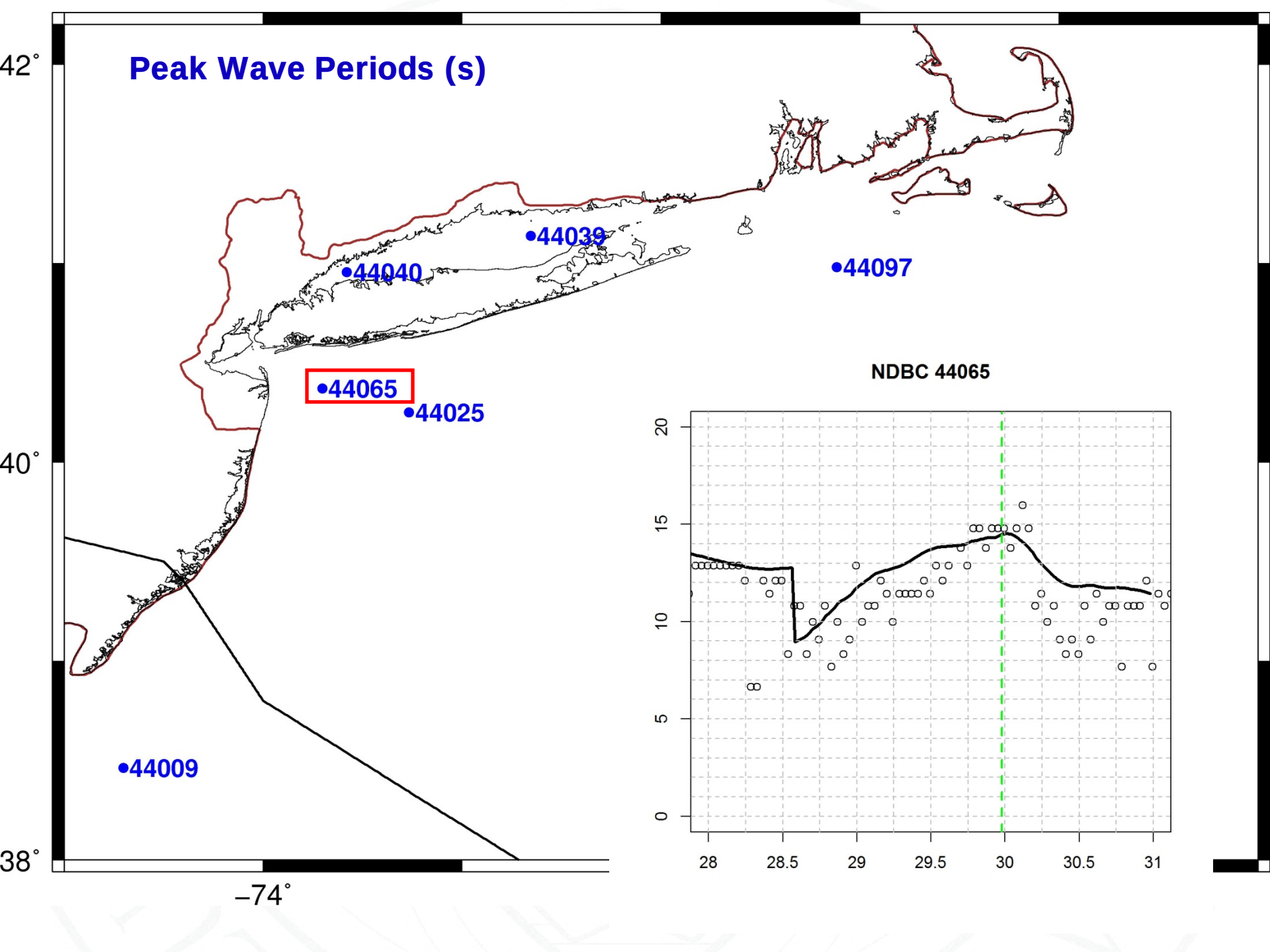
Peak Wave Periods (s)



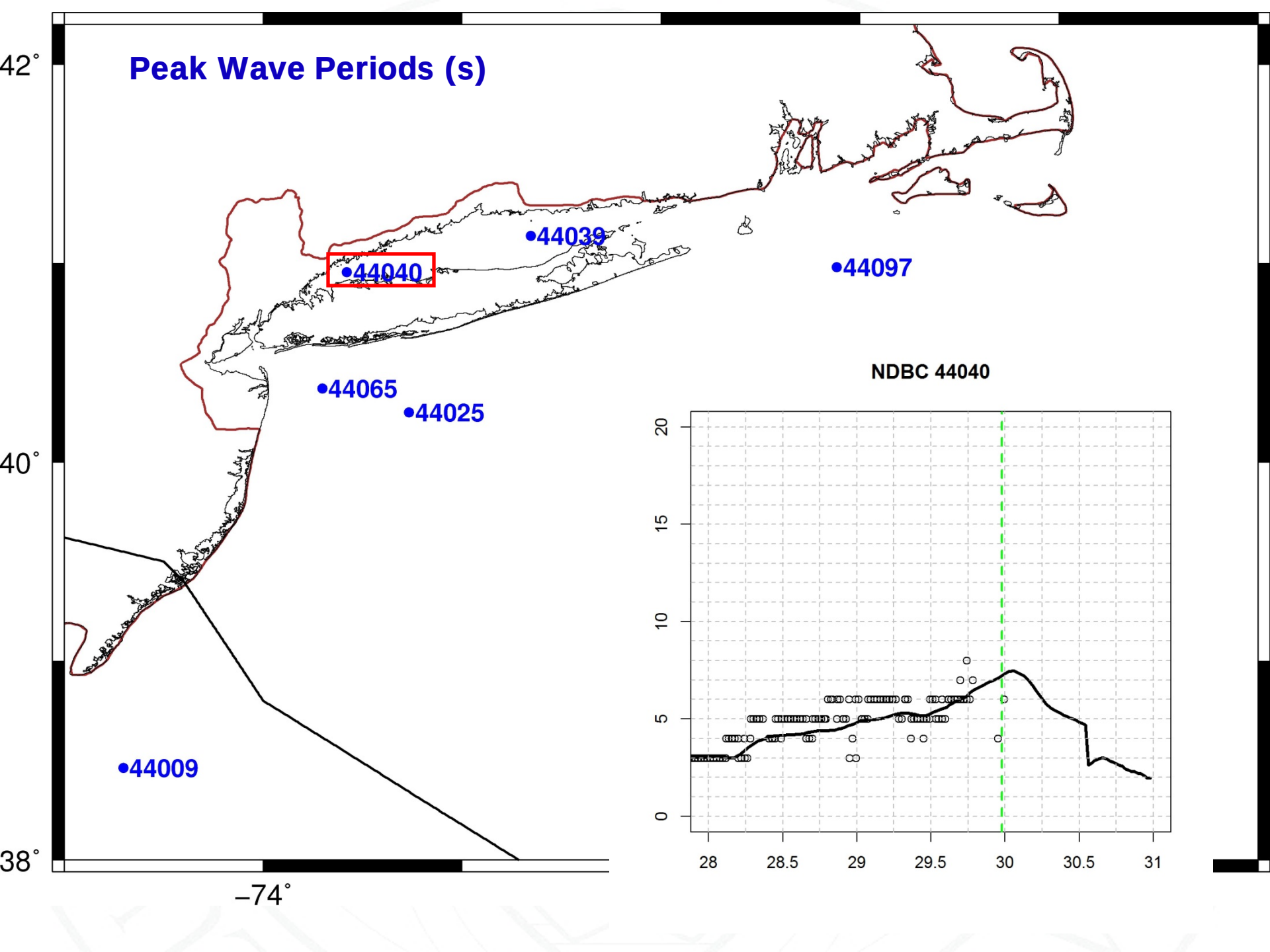
Peak Wave Periods (s)



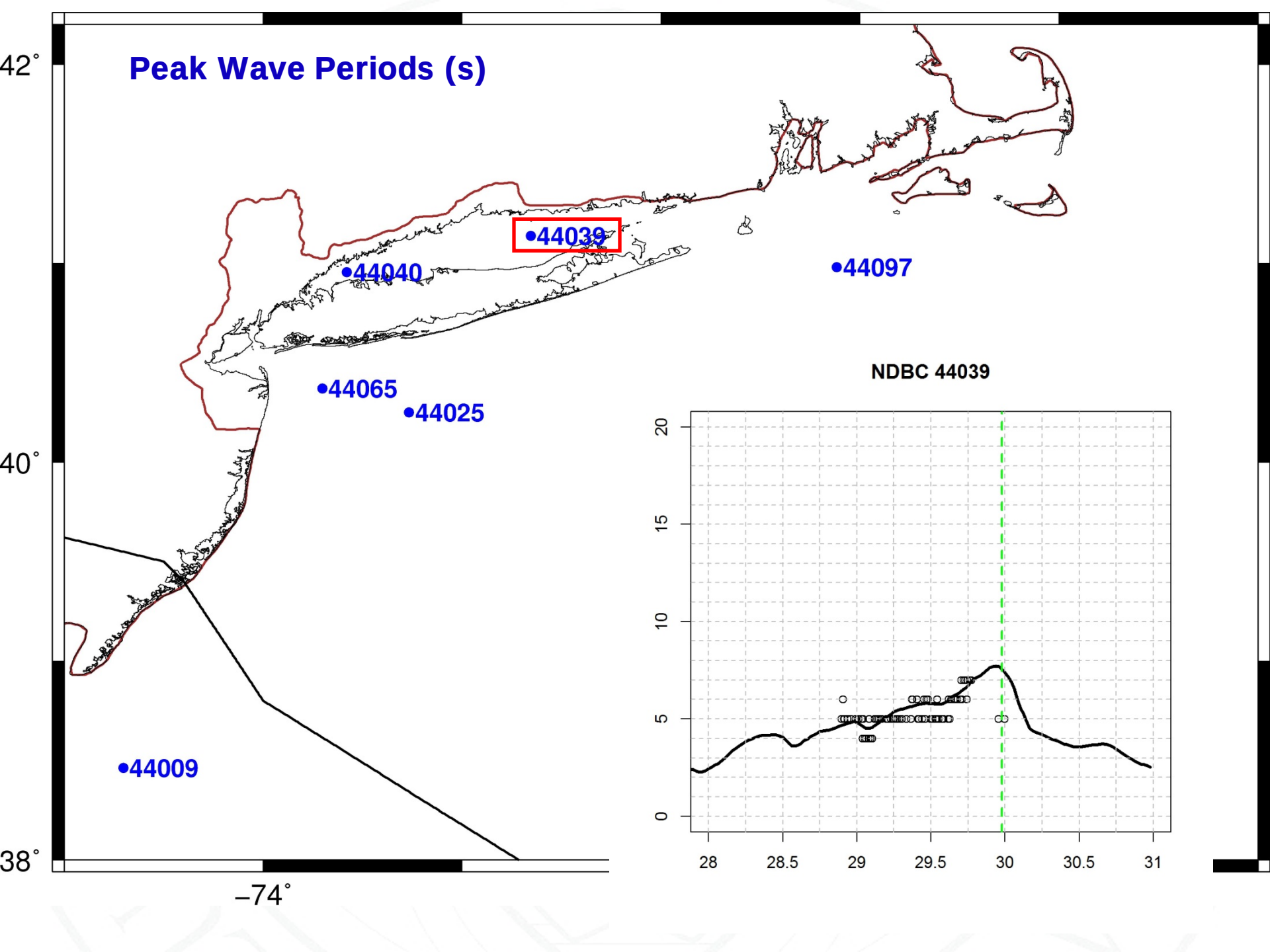
Peak Wave Periods (s)



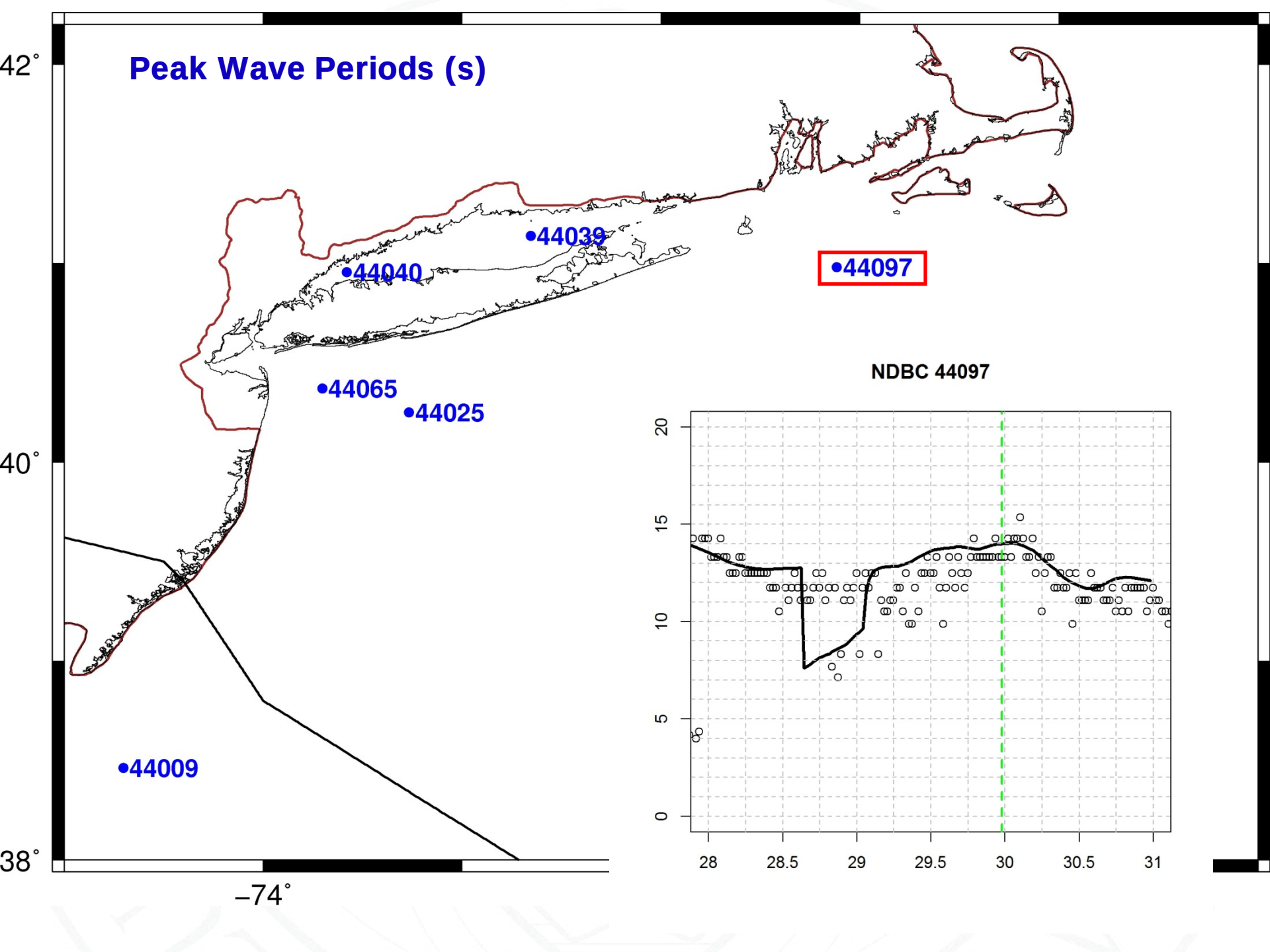
Peak Wave Periods (s)



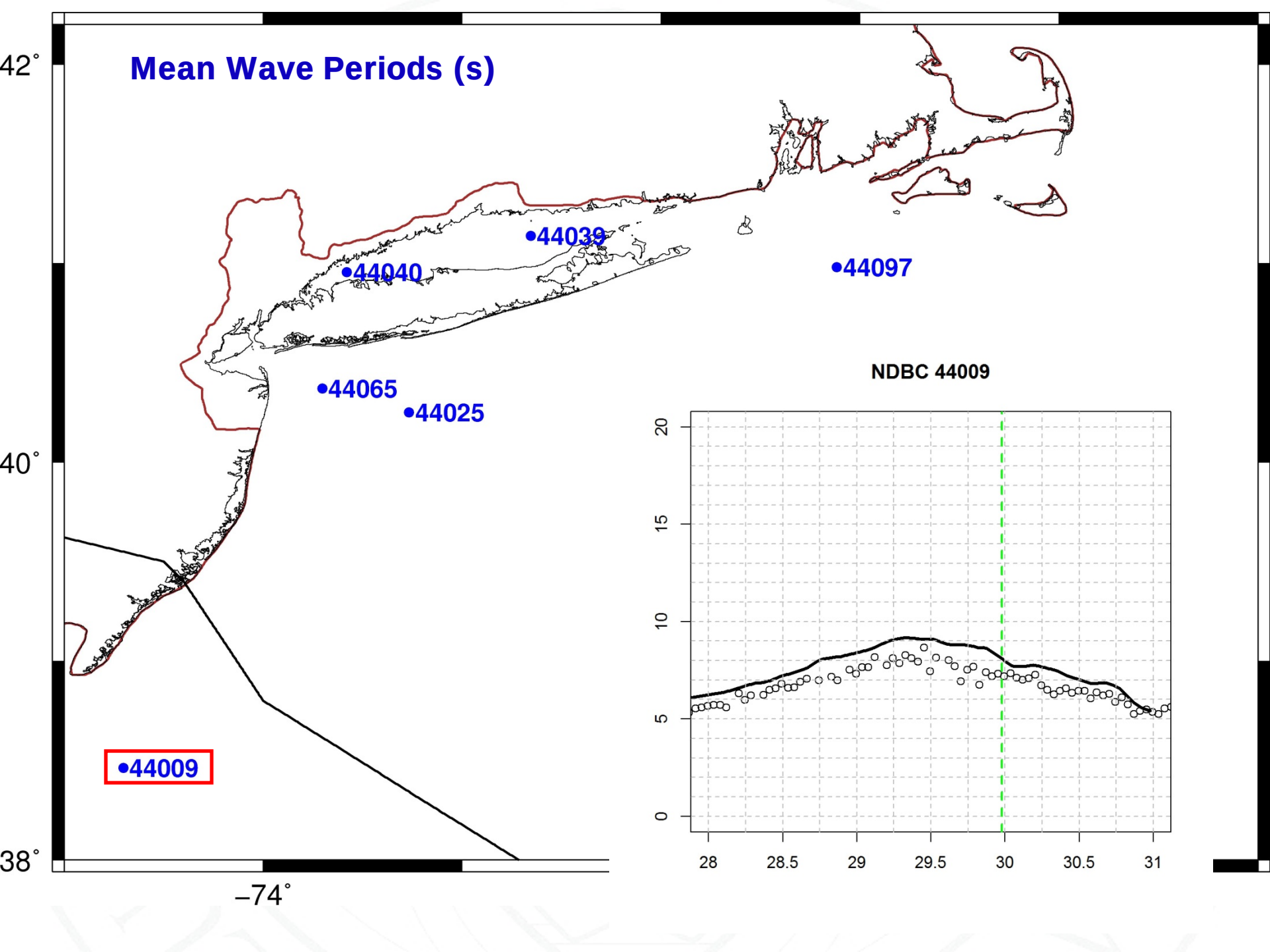
Peak Wave Periods (s)



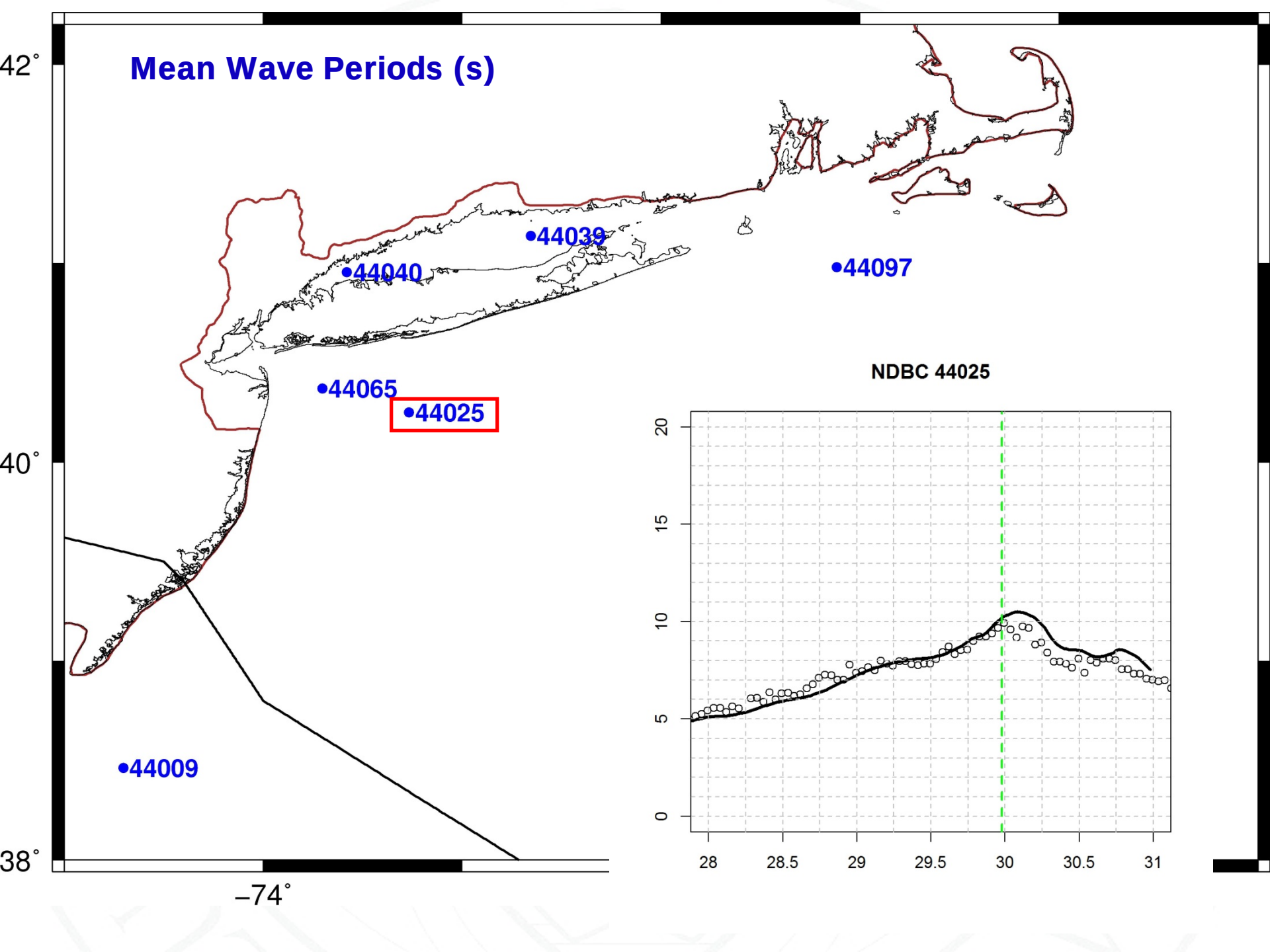
Peak Wave Periods (s)



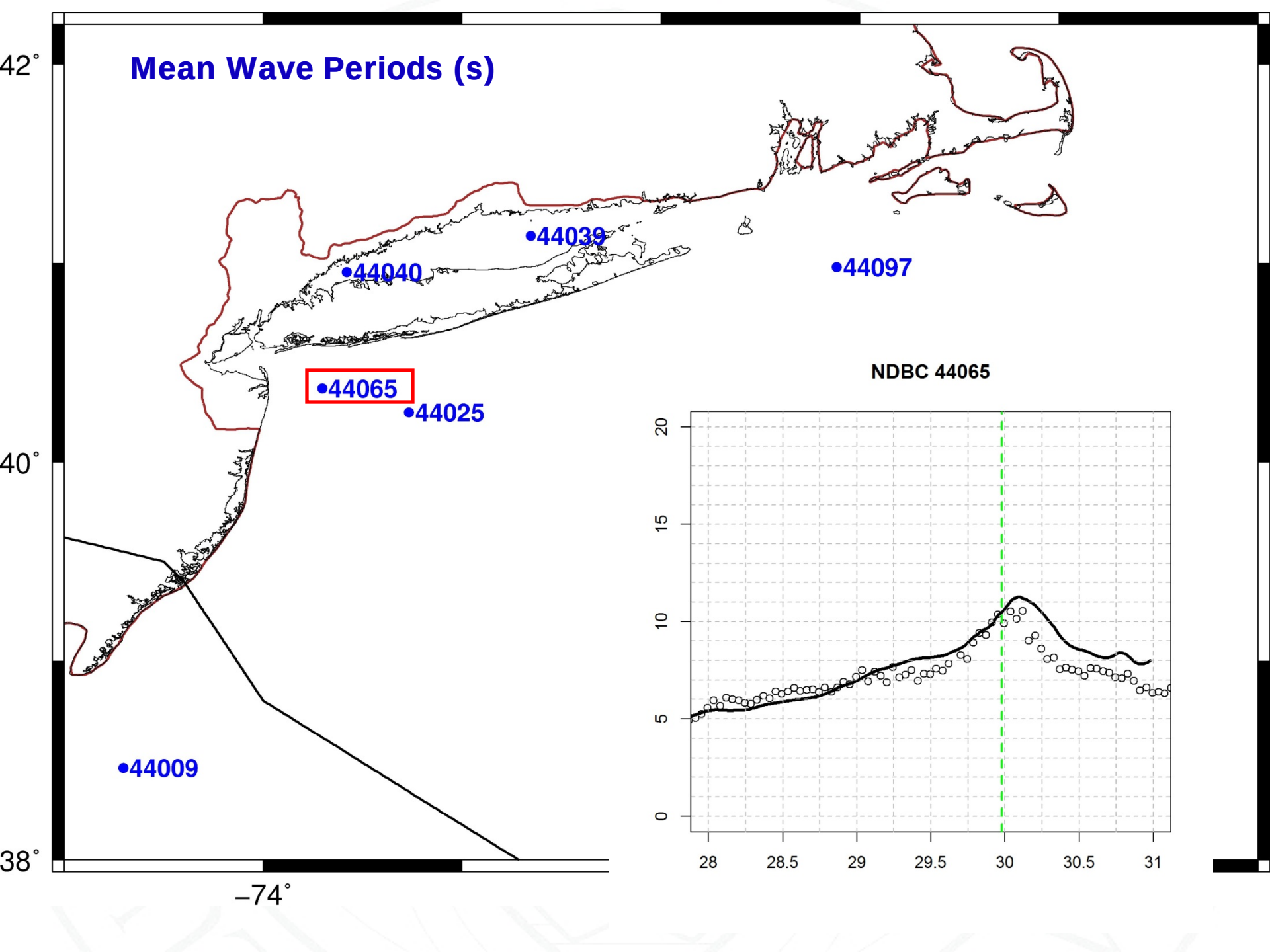
Mean Wave Periods (s)



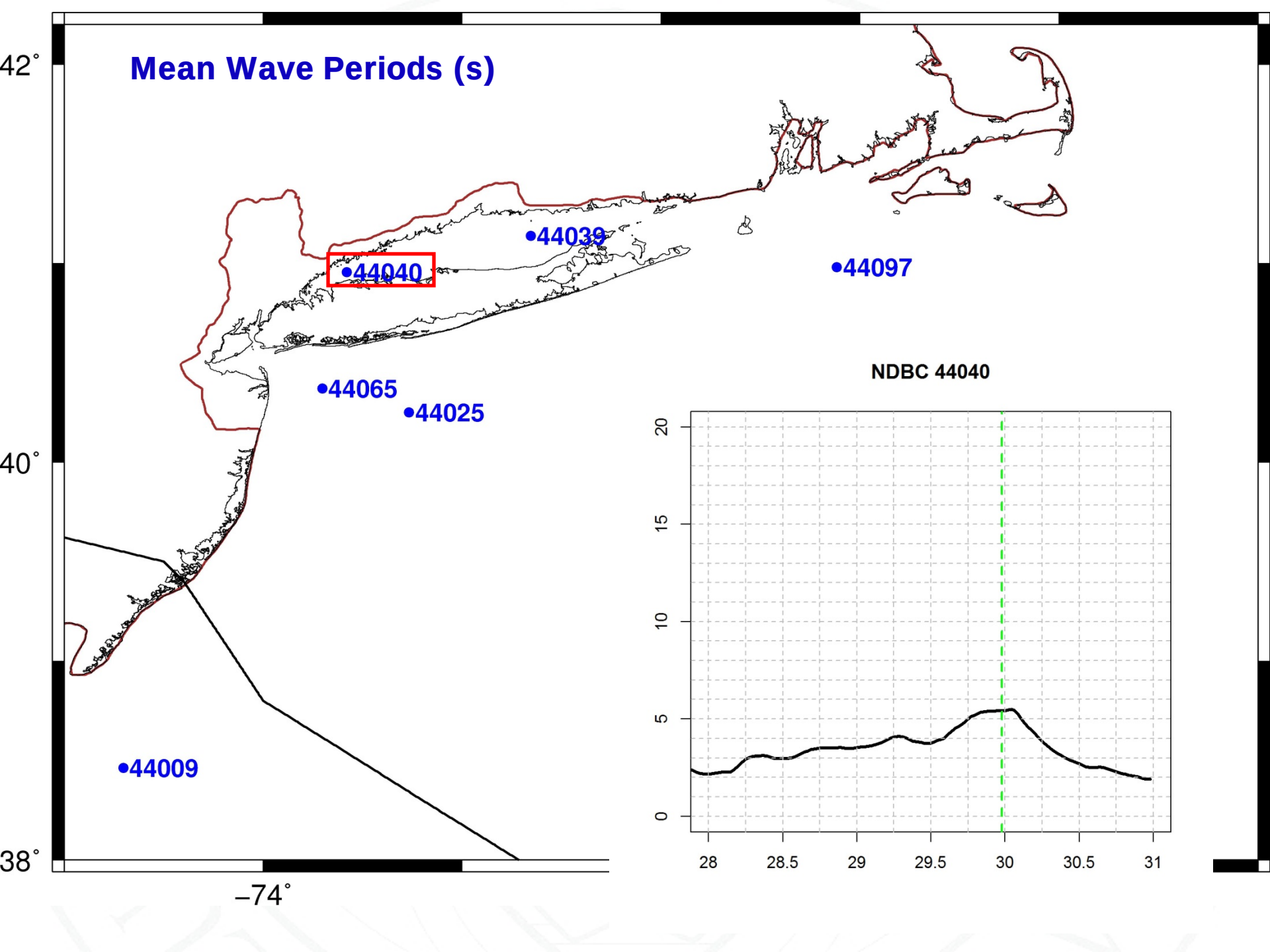
Mean Wave Periods (s)



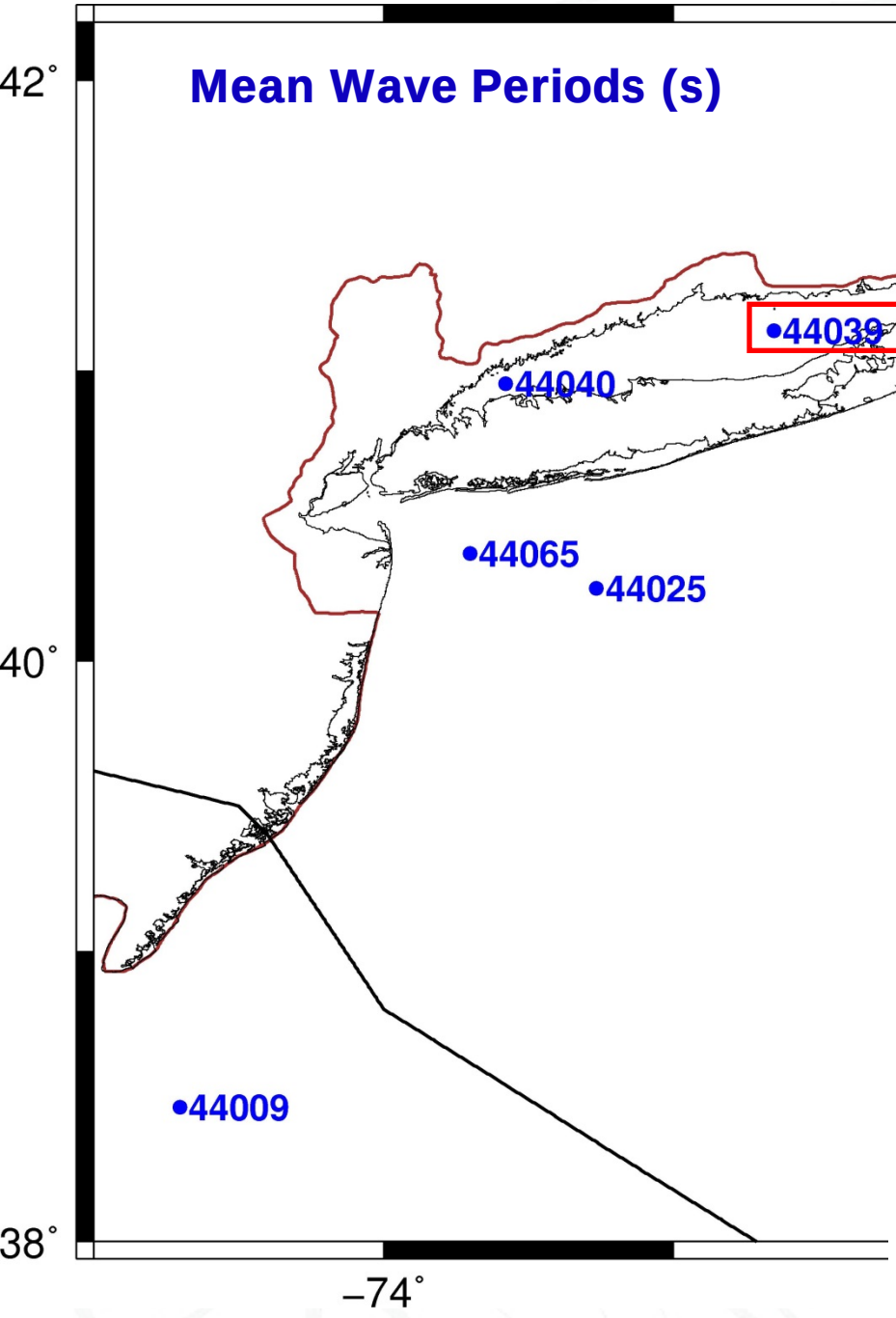
Mean Wave Periods (s)

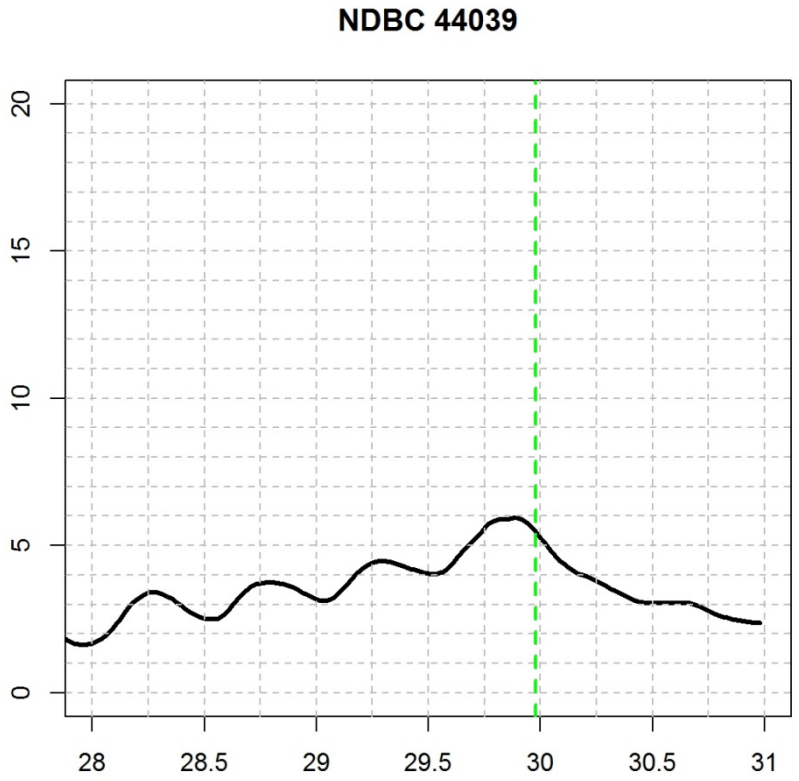


Mean Wave Periods (s)

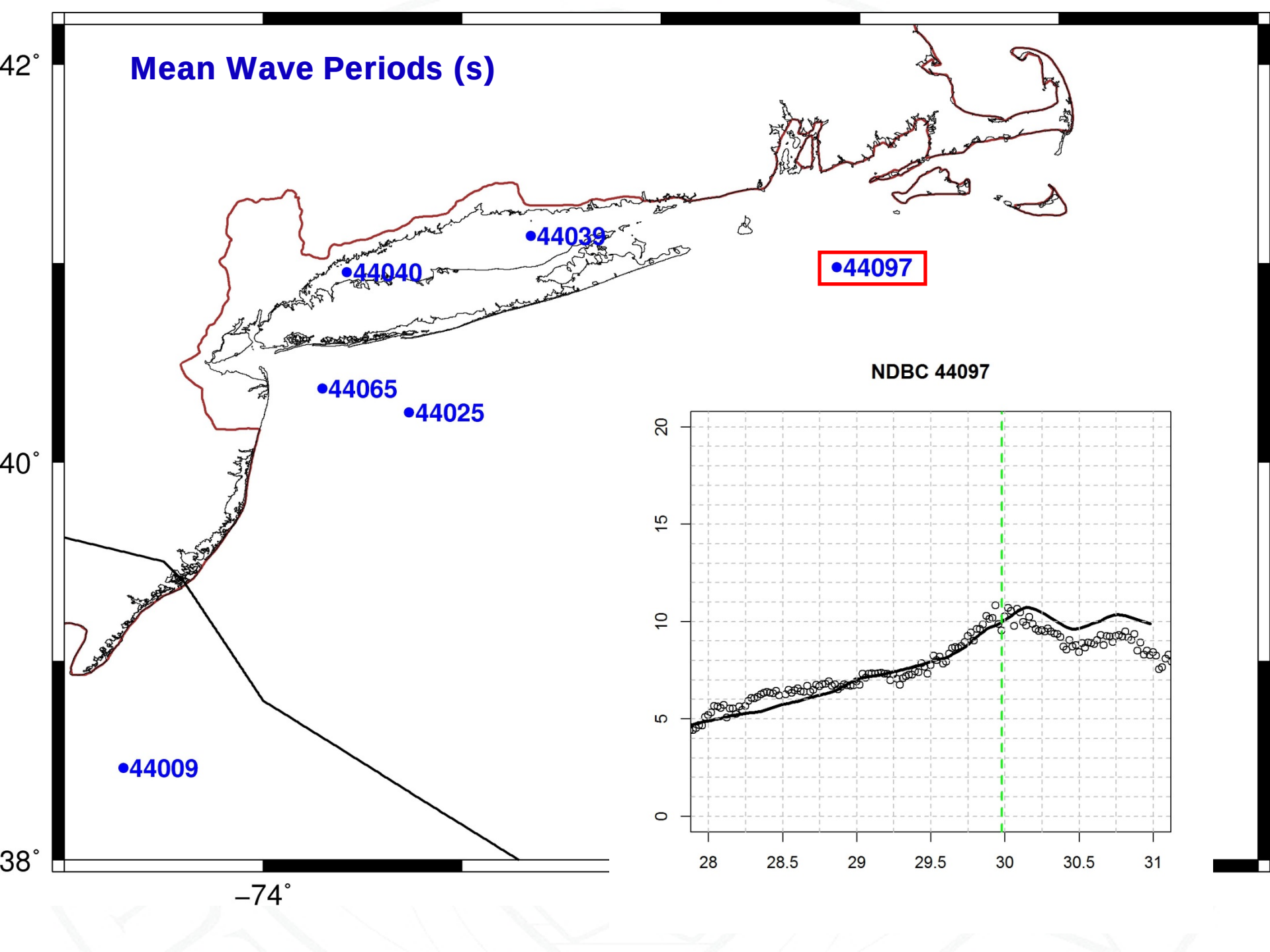


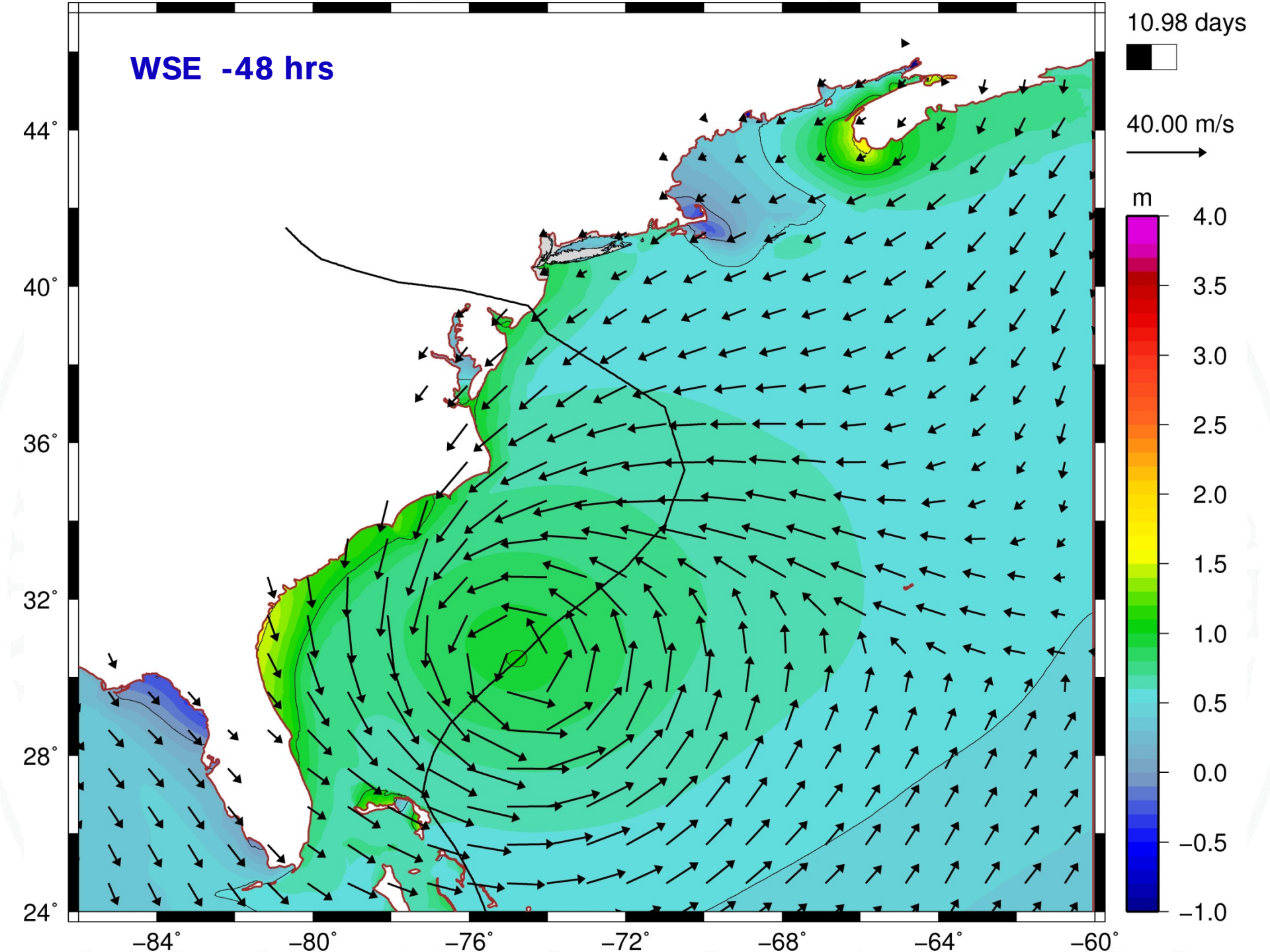
Mean Wave Periods (s)

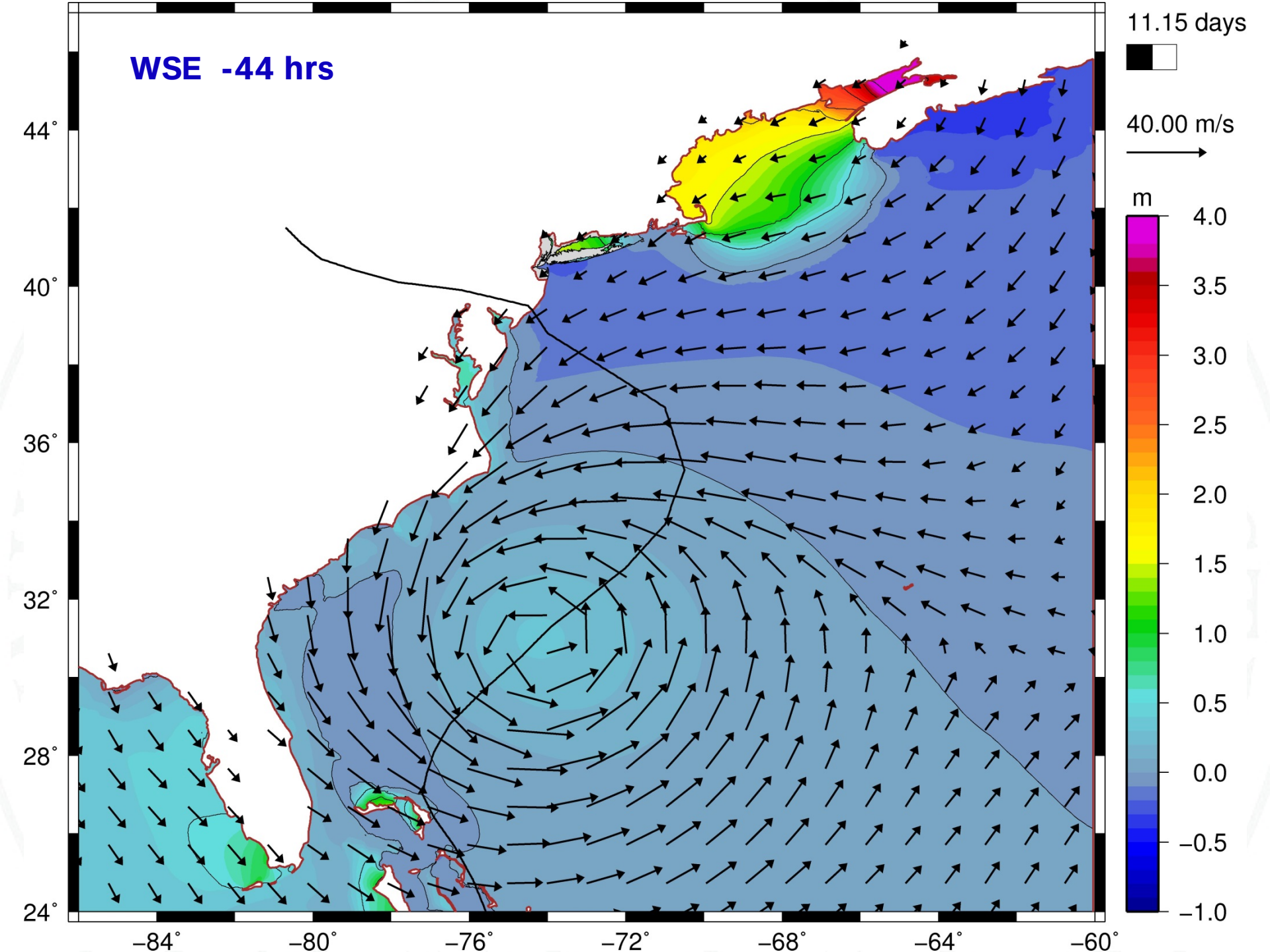


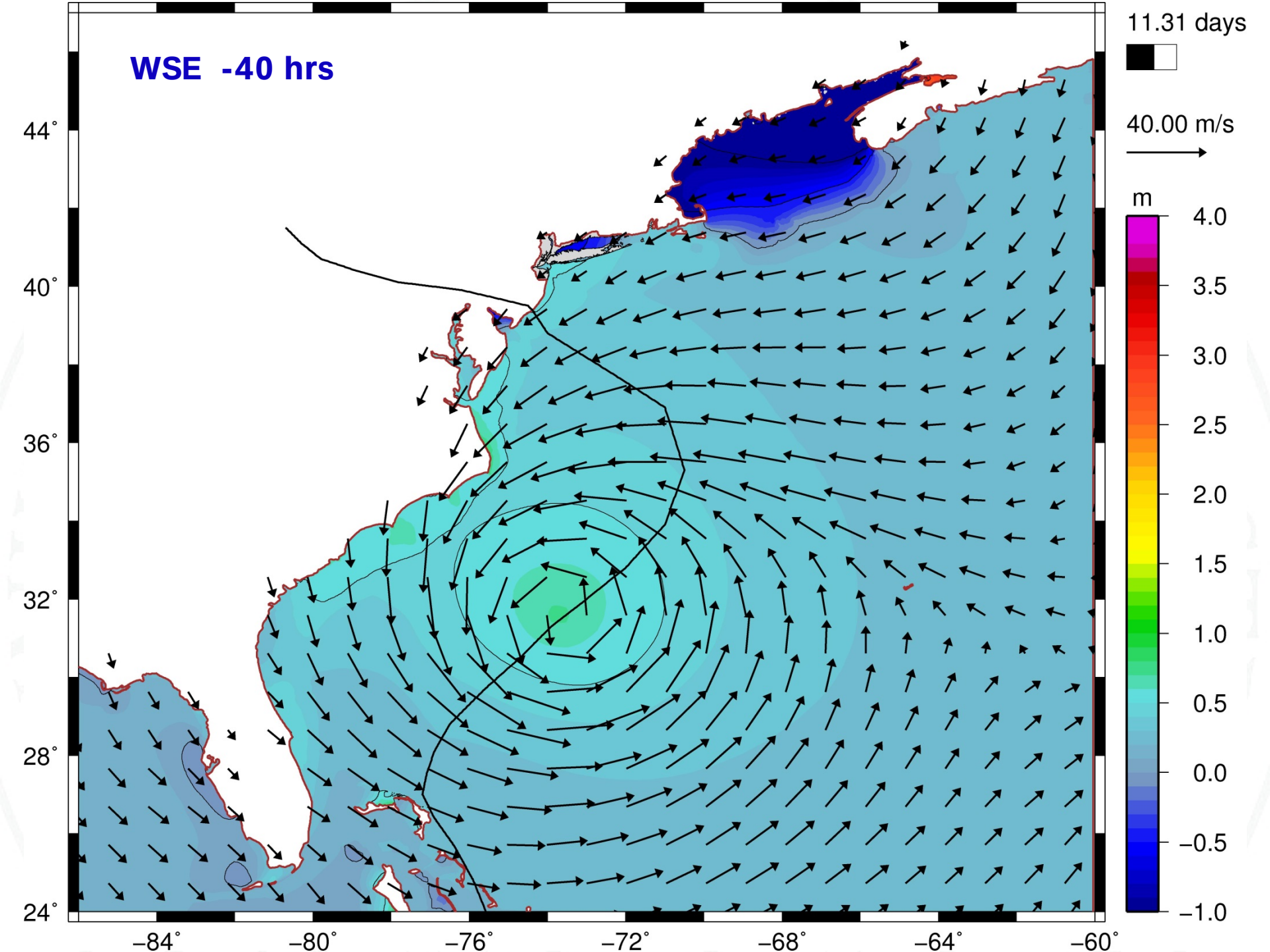


Mean Wave Periods (s)




WSE -48 hrs
10.98 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


WSE -44 hrs
11.15 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


WSE -40 hrs
11.31 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
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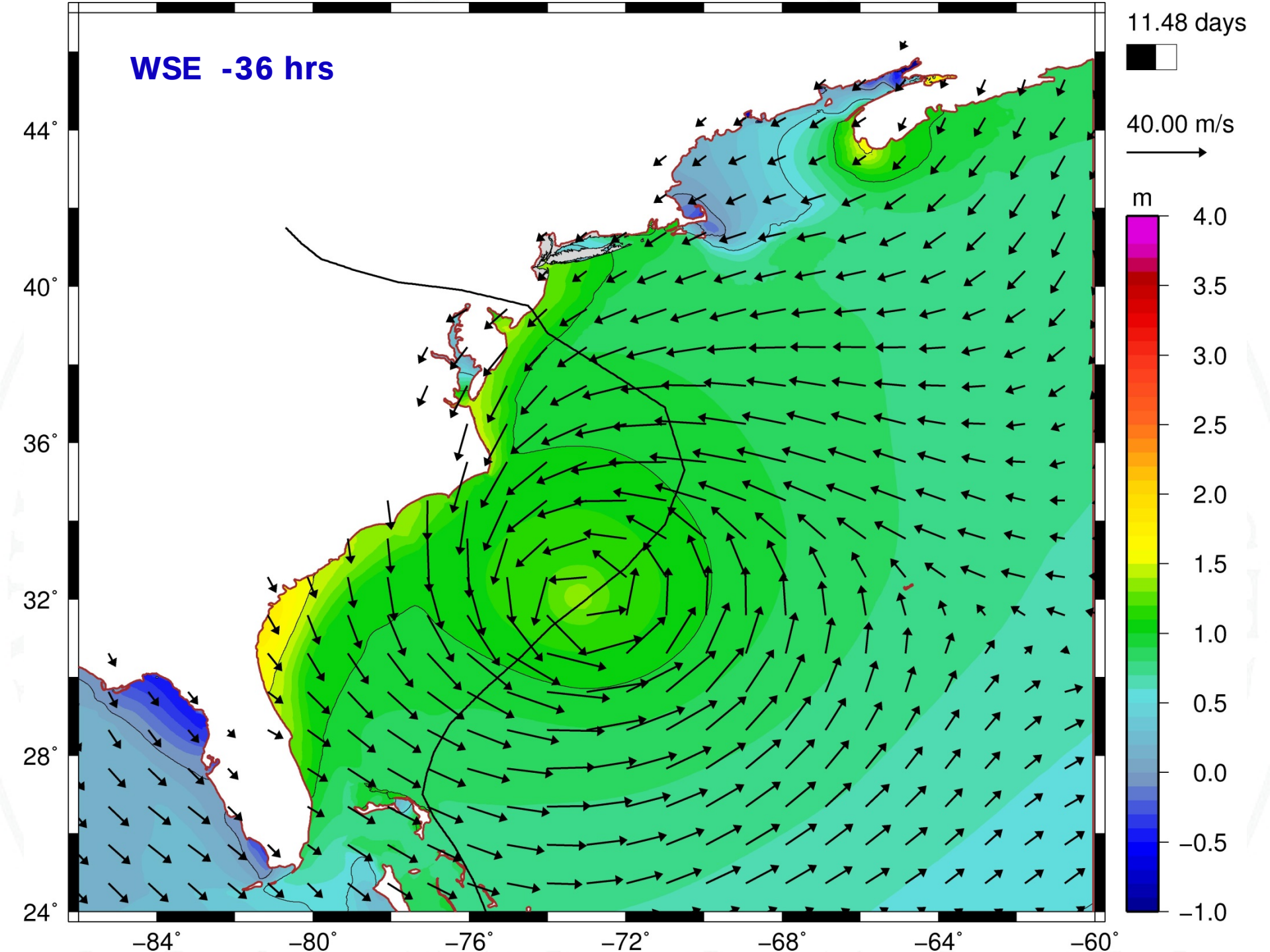
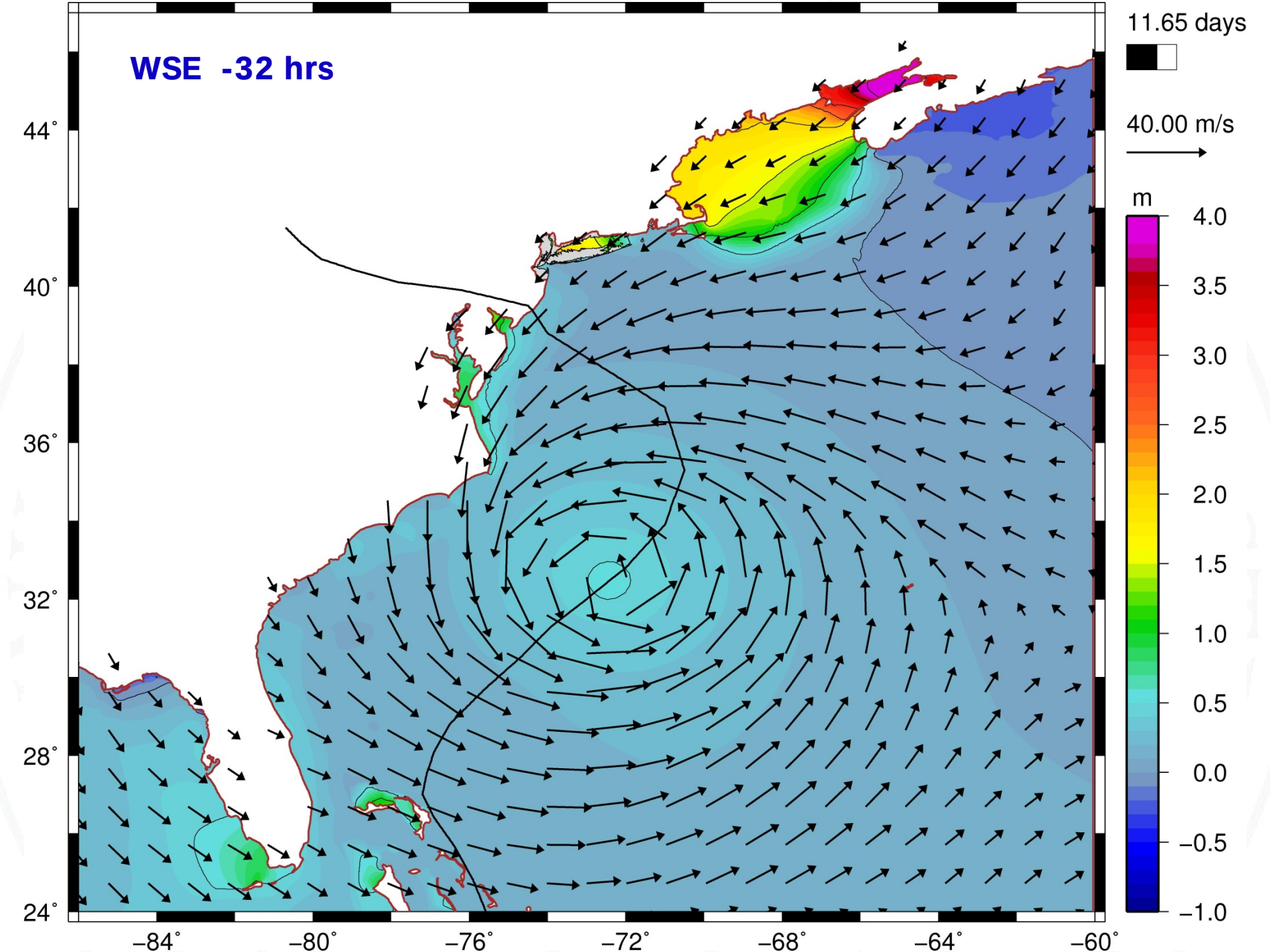
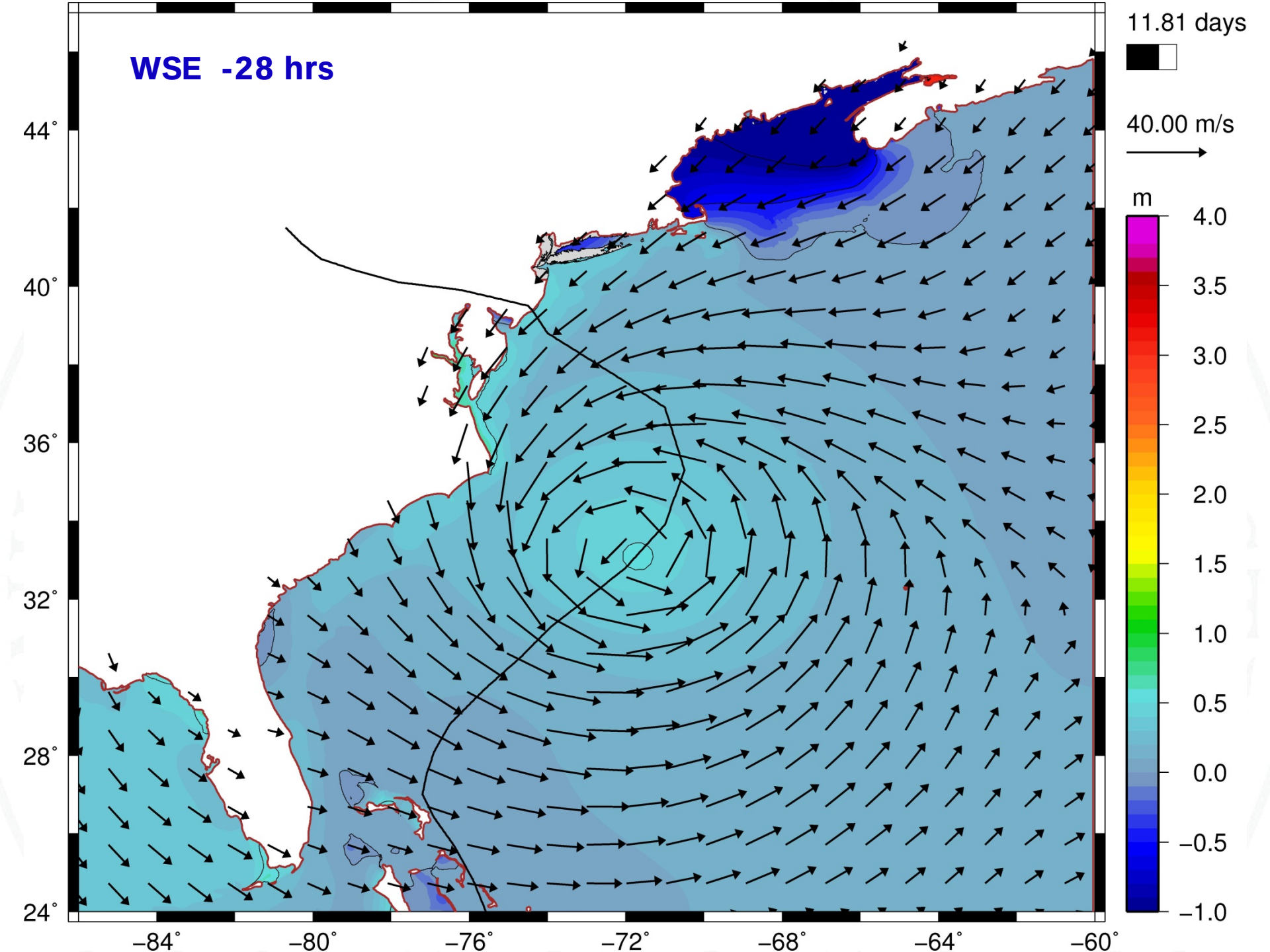
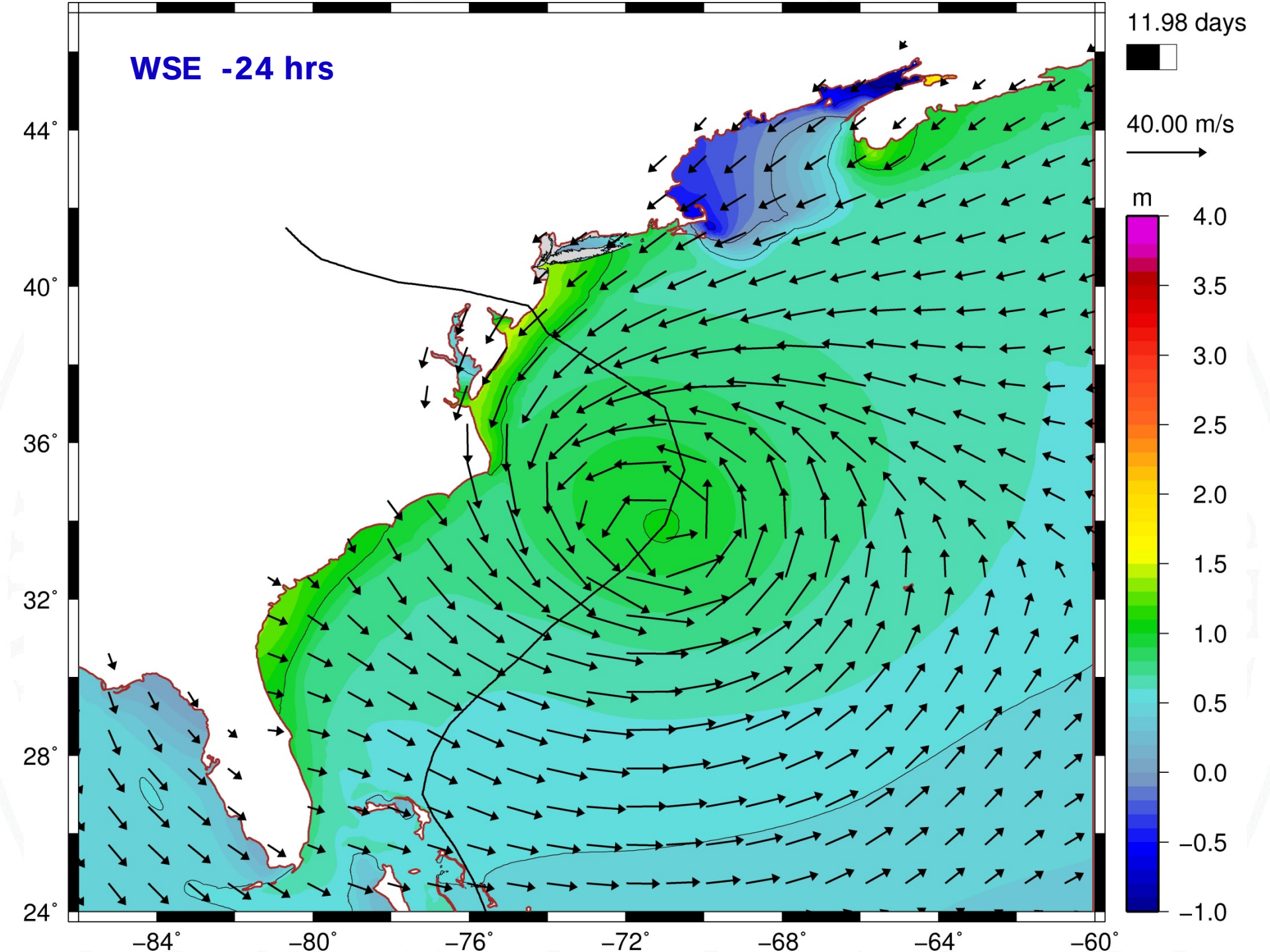
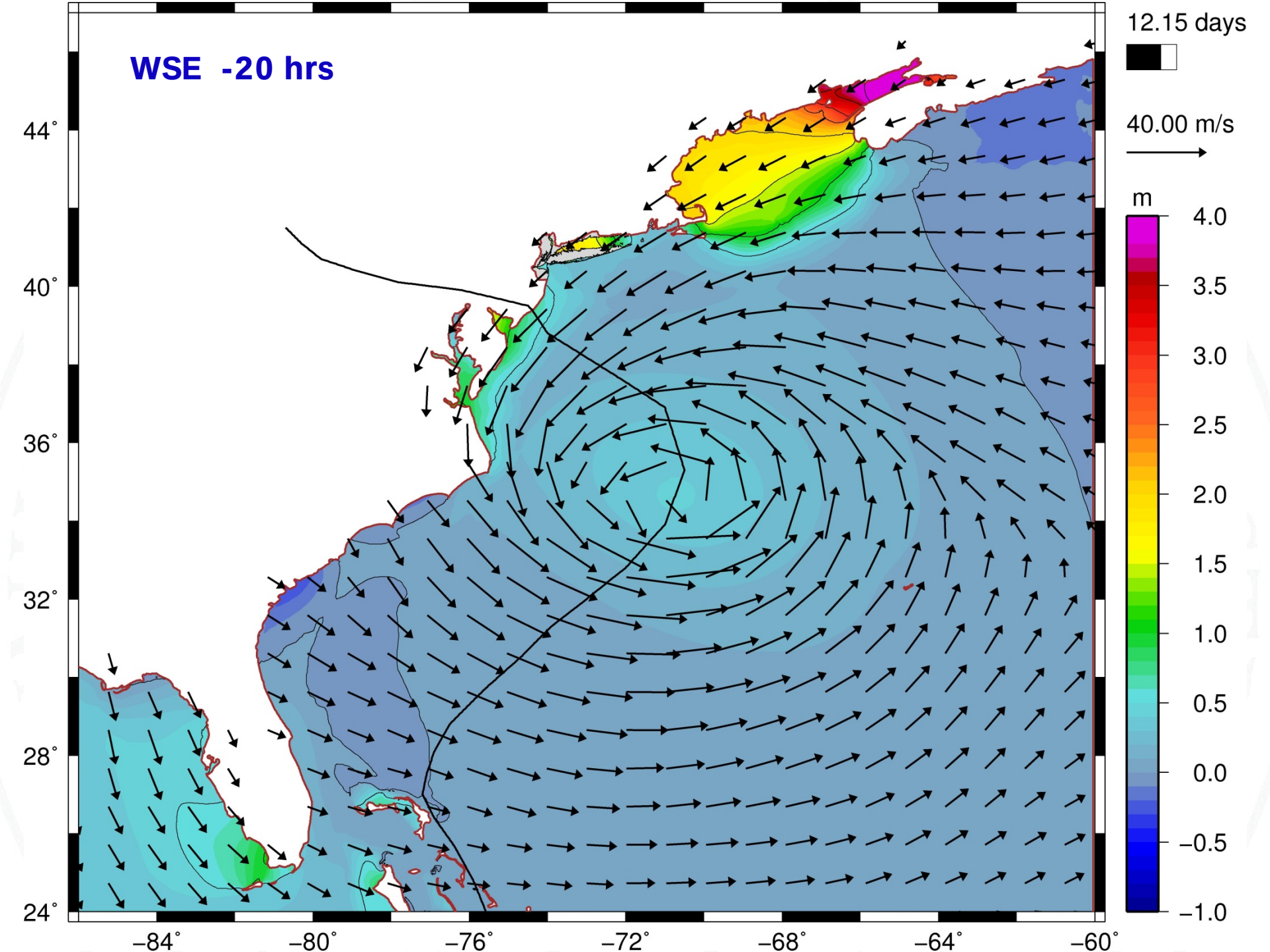
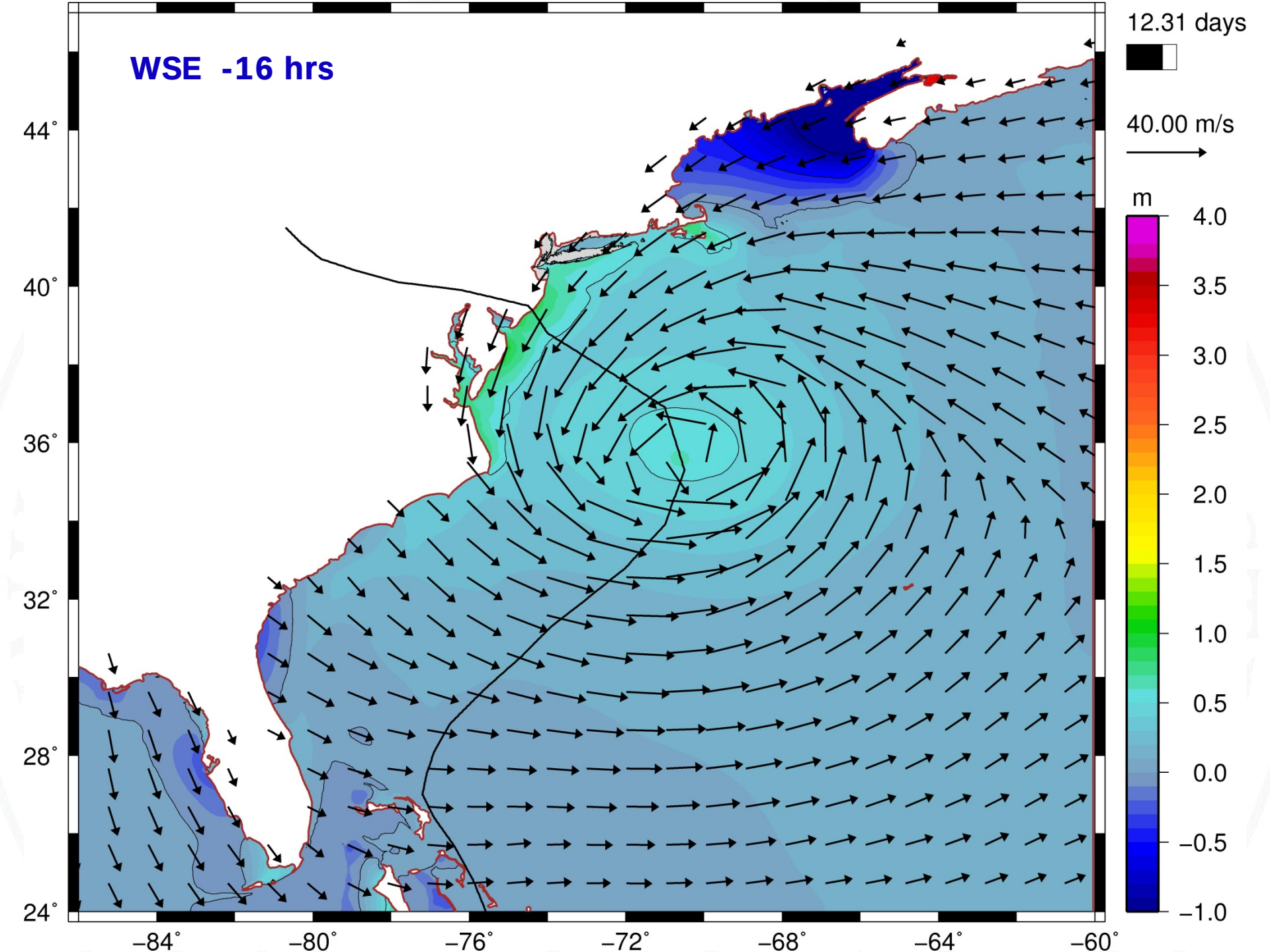

WSE -36 hrs
11.48 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

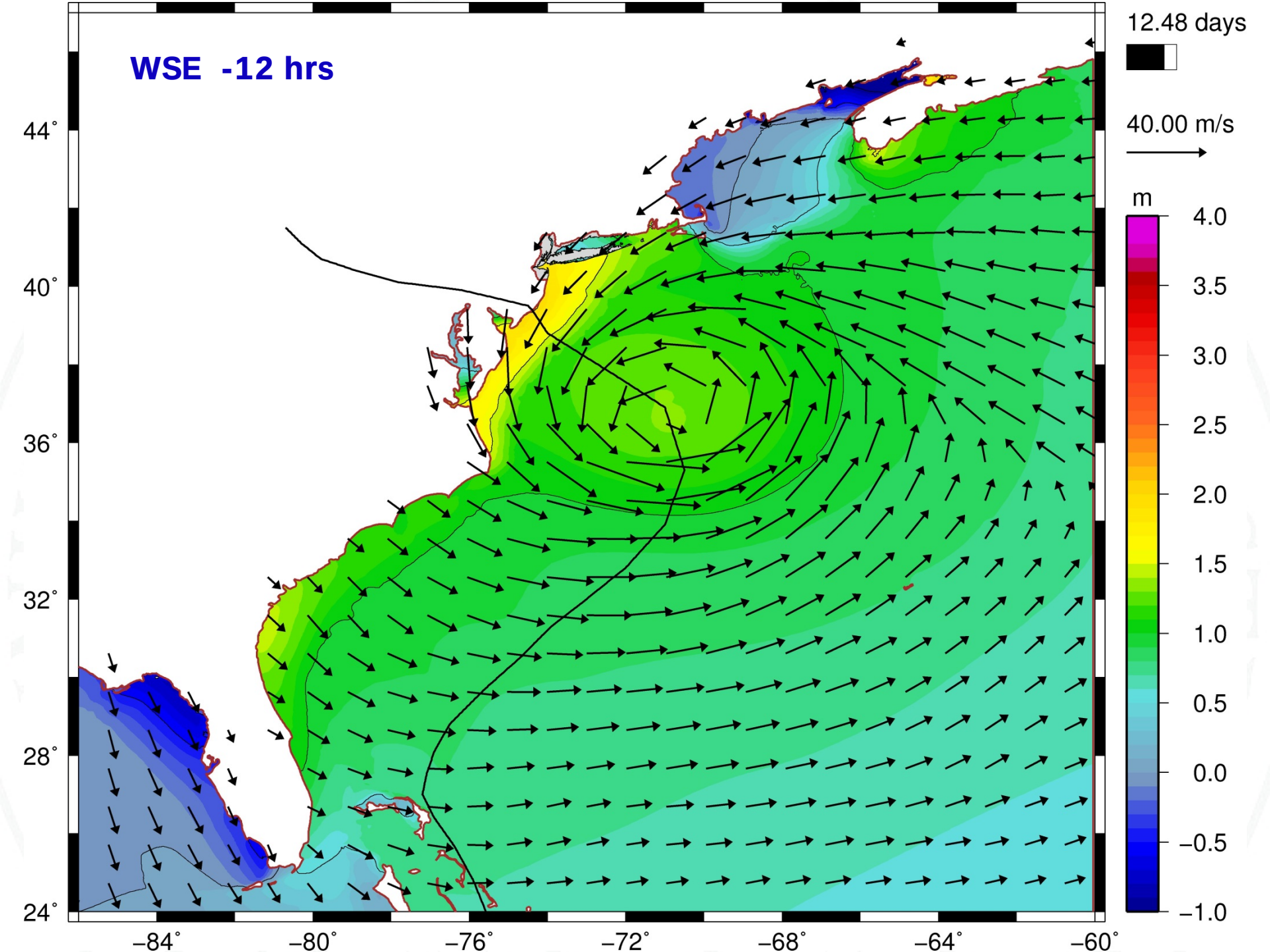

WSE -32 hrs
11.65 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

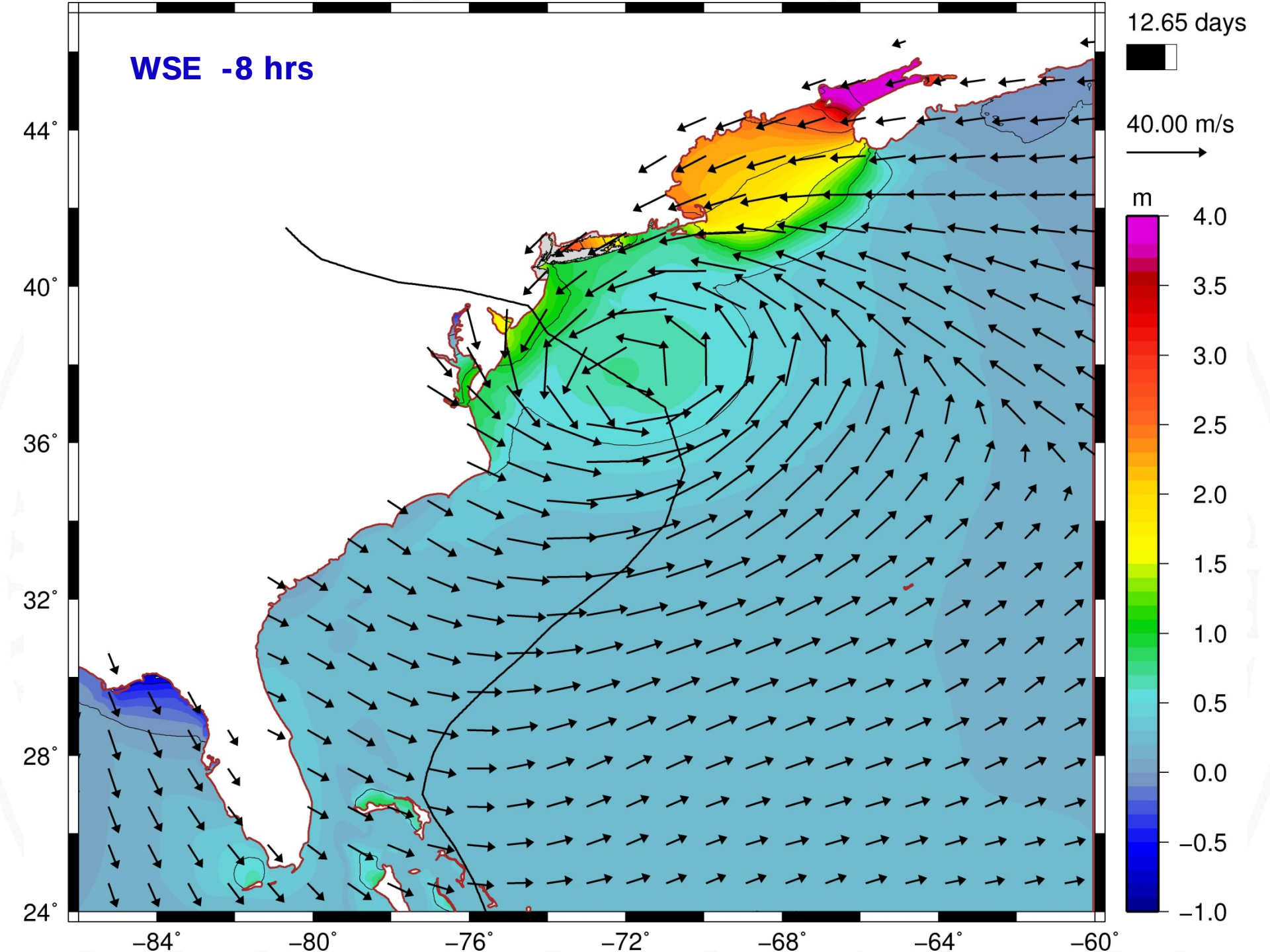

WSE -28 hrs
11.81 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

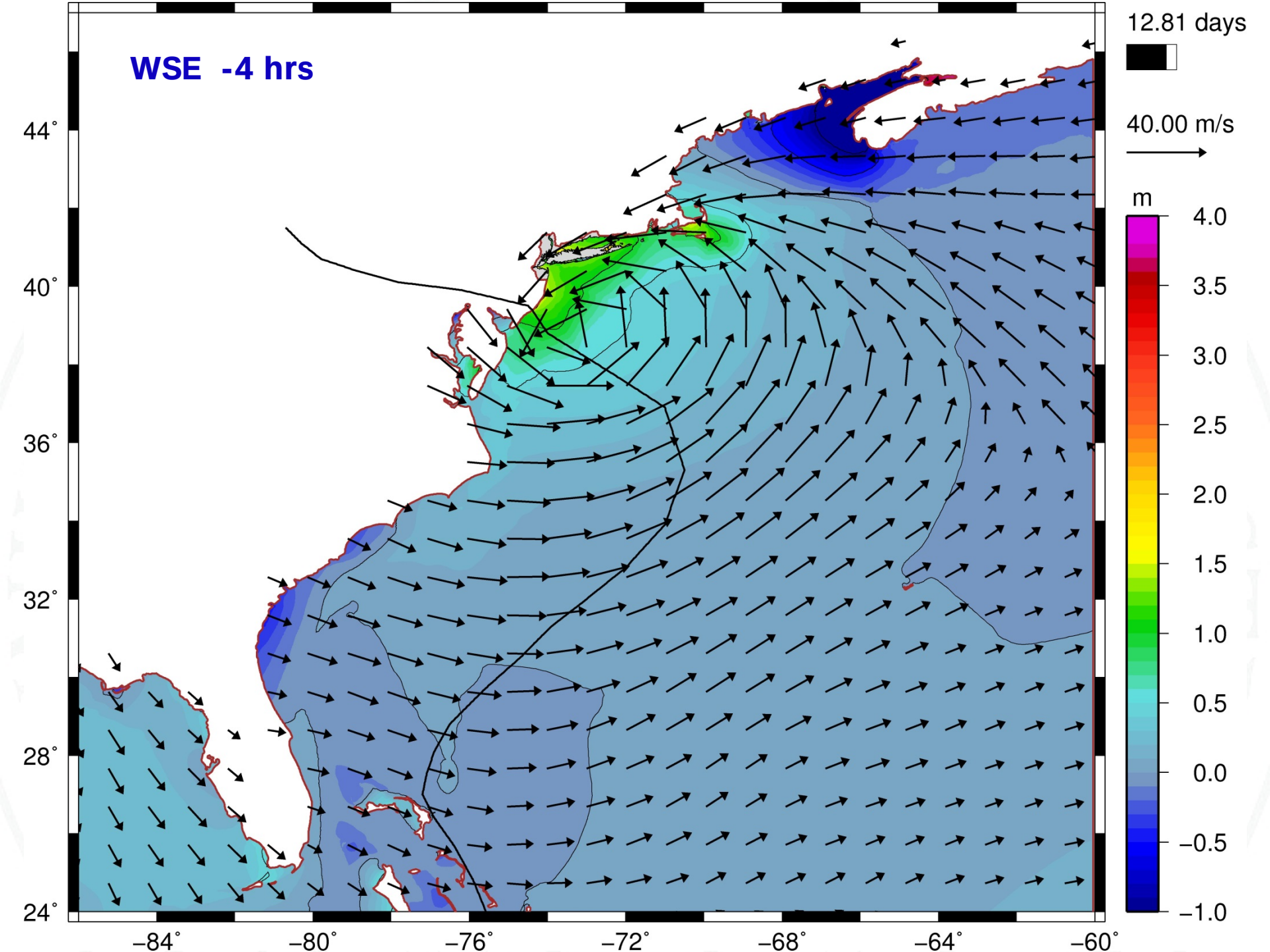

WSE -24 hrs
11.98 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

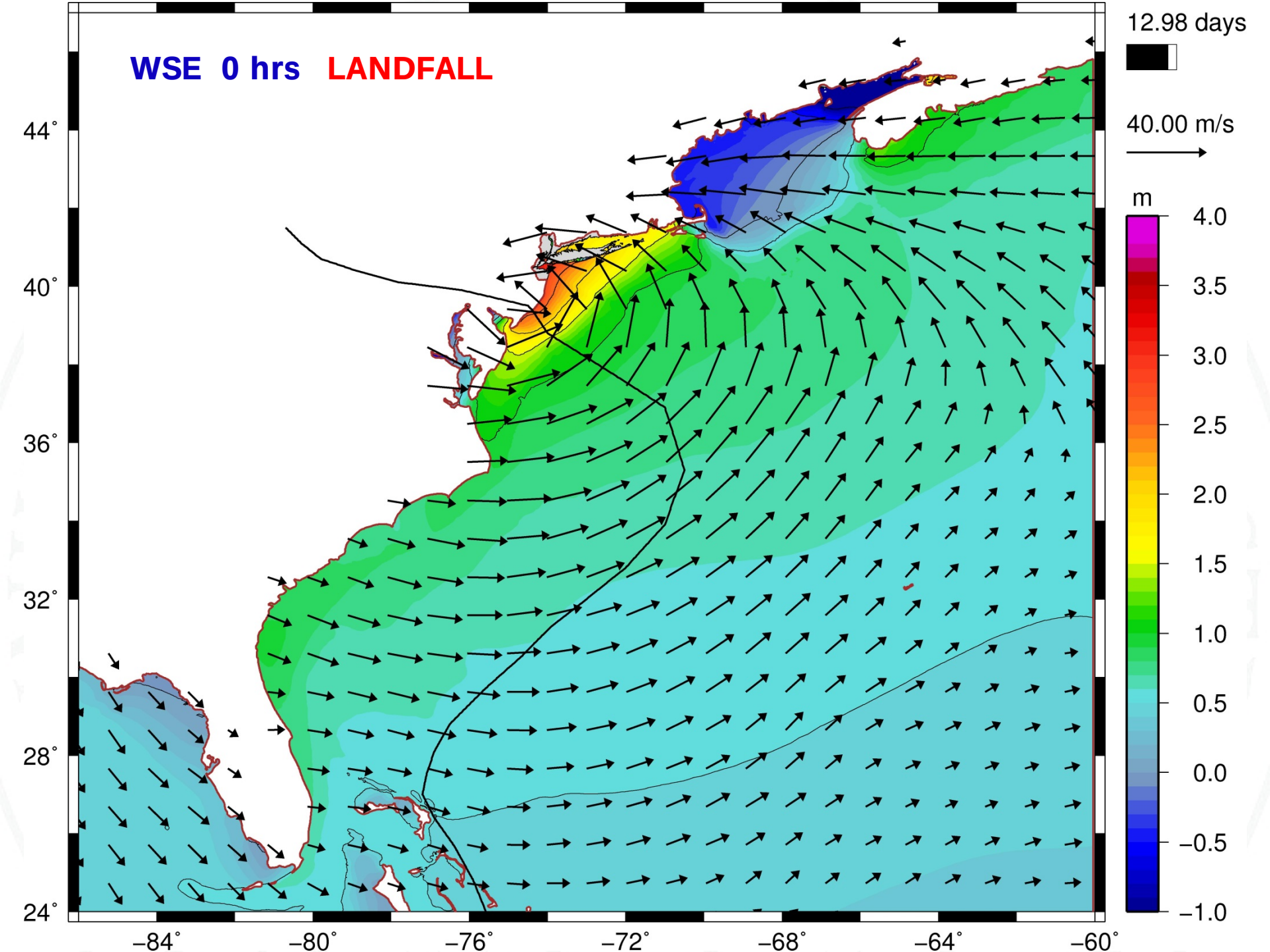

WSE -20 hrs
12.15 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

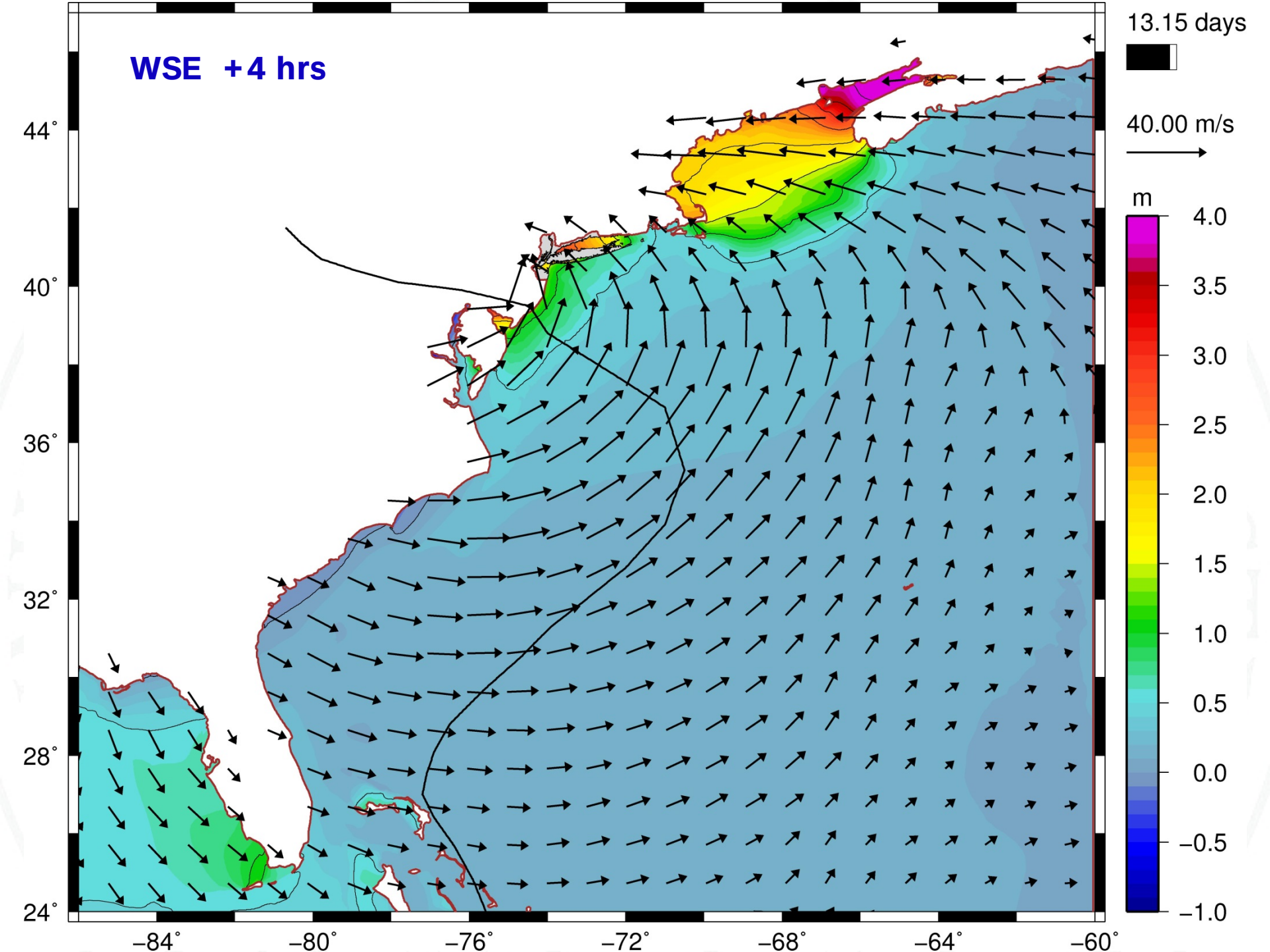

WSE -16 hrs
12.31 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

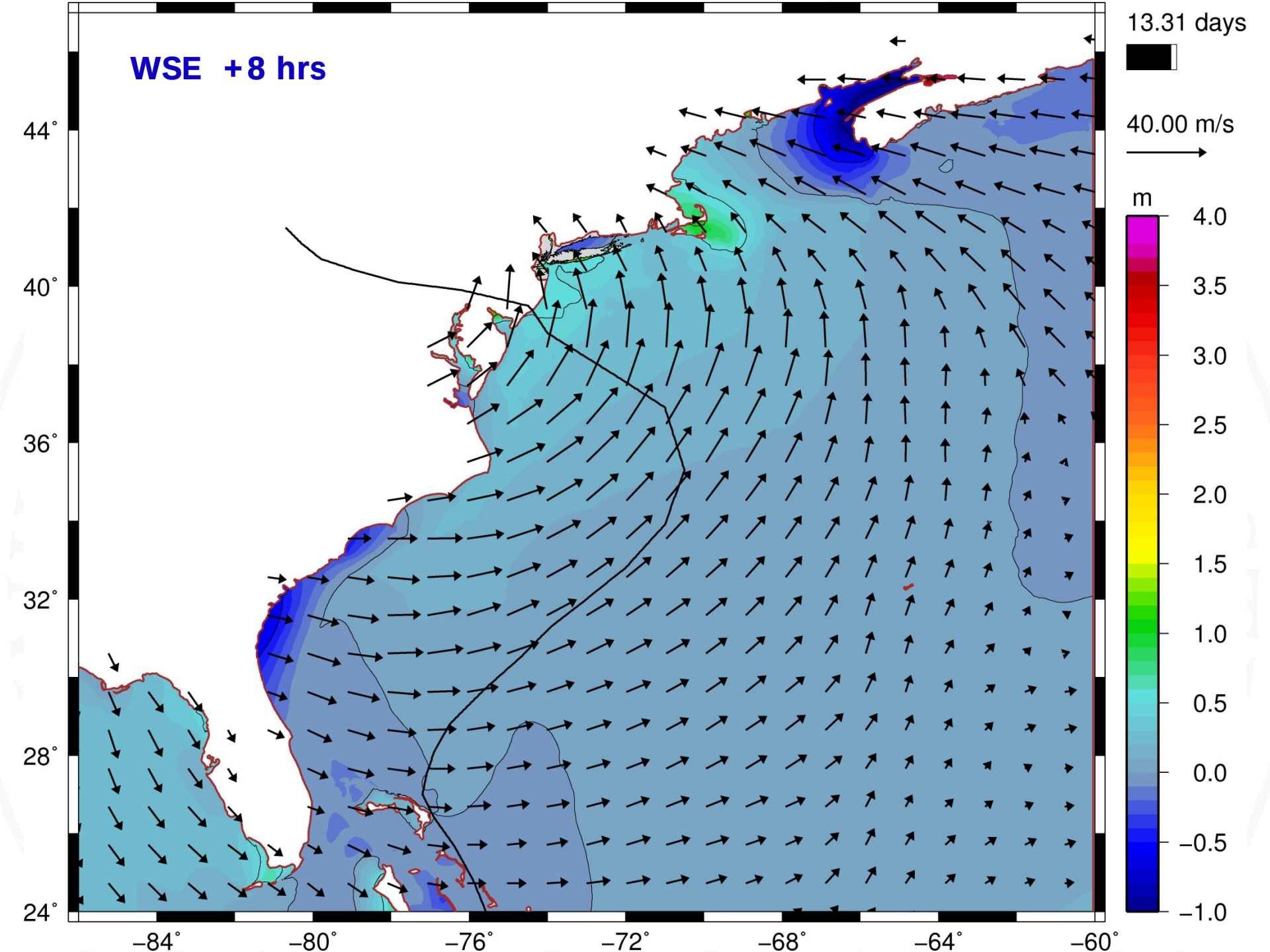

WSE -12 hrs
12.48 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

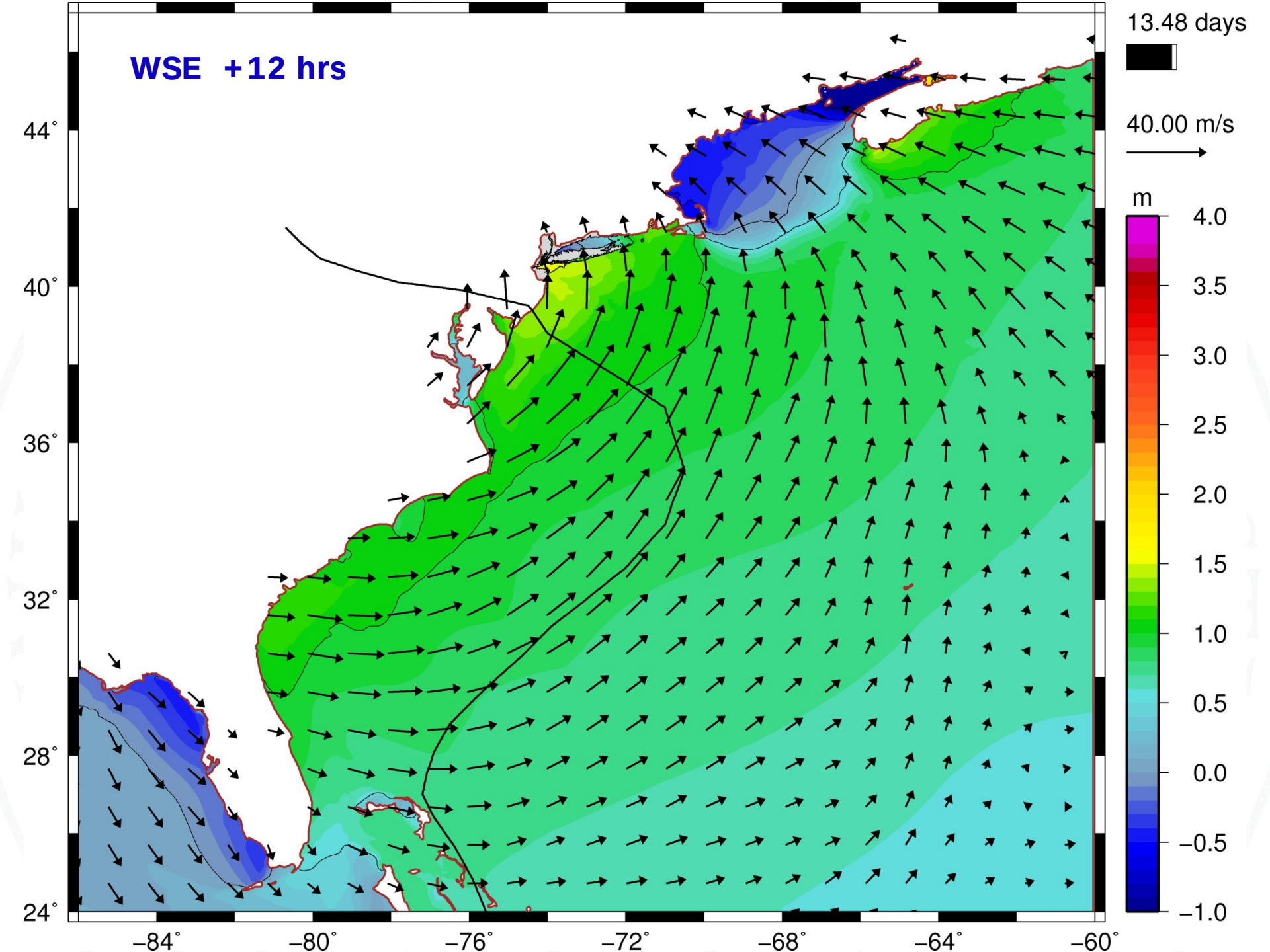

WSE -8 hrs
12.65 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

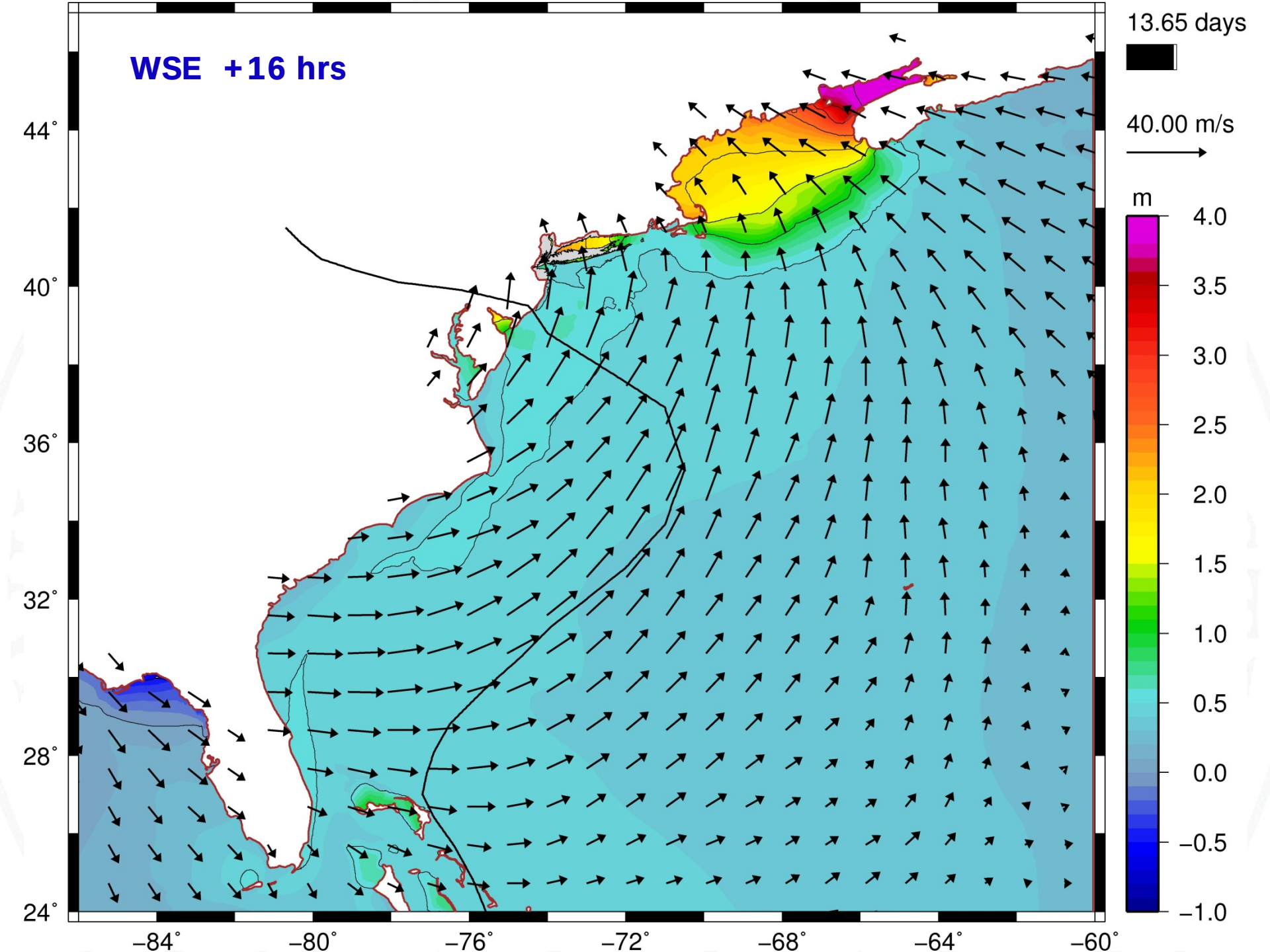

WSE -4 hrs
12.81 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

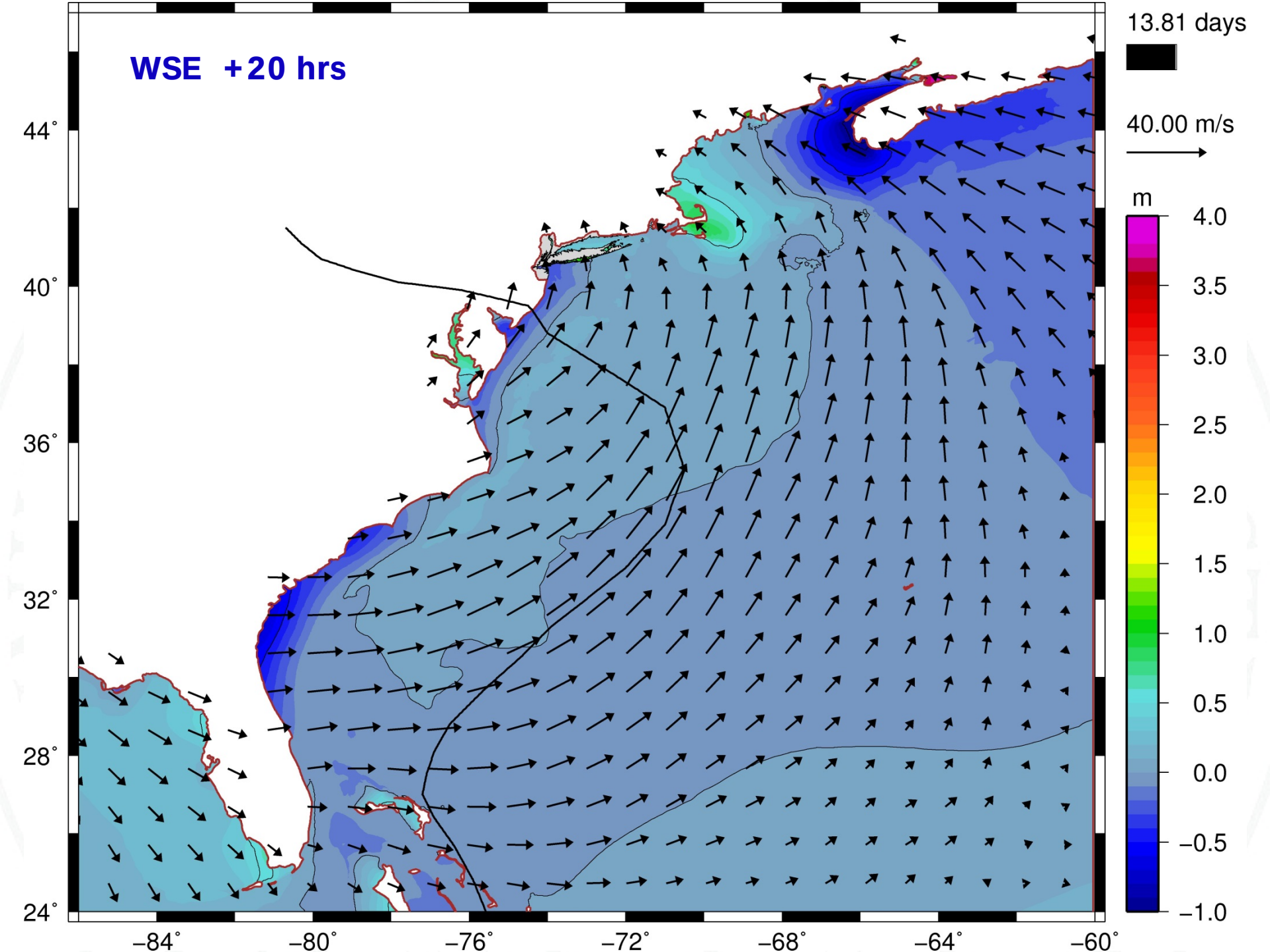

WSE 0 hrs LANDFALL
12.98 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


WSE +4 hrs
13.15 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

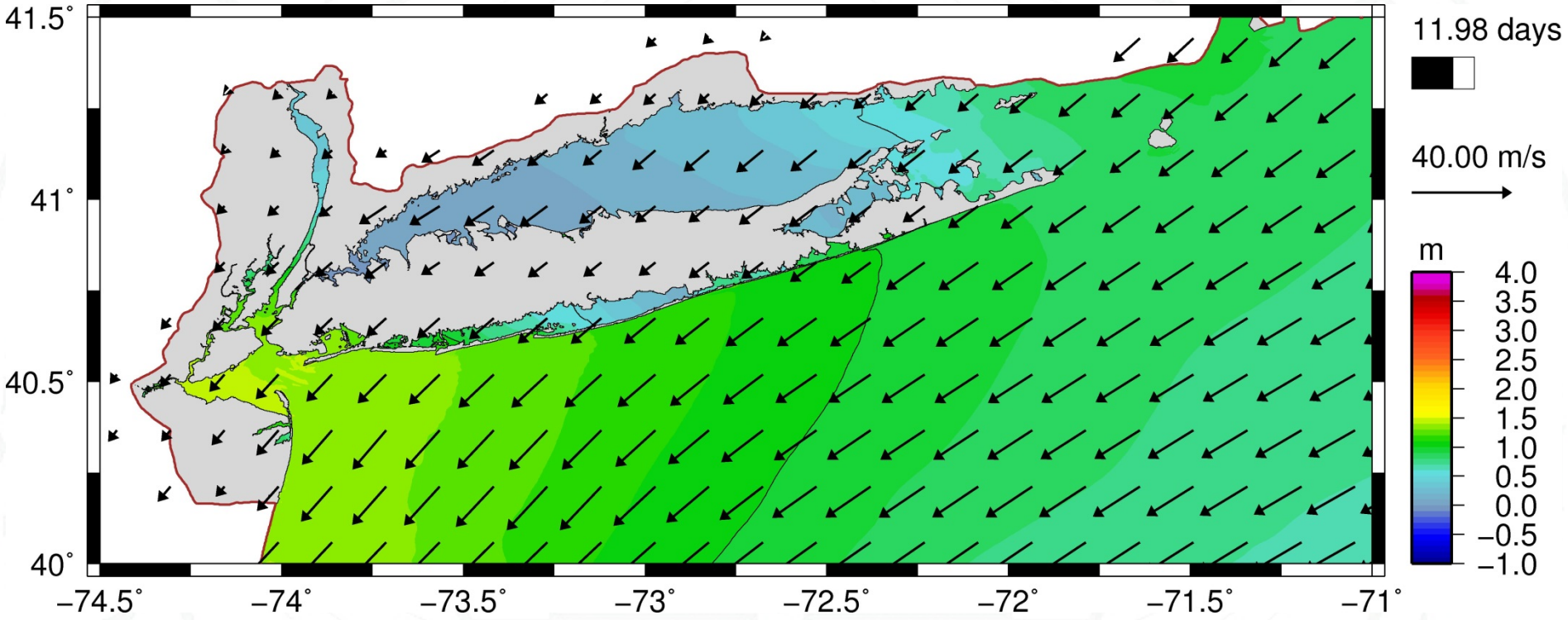

WSE +8 hrs
13.31 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


WSE +12 hrs
13.48 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

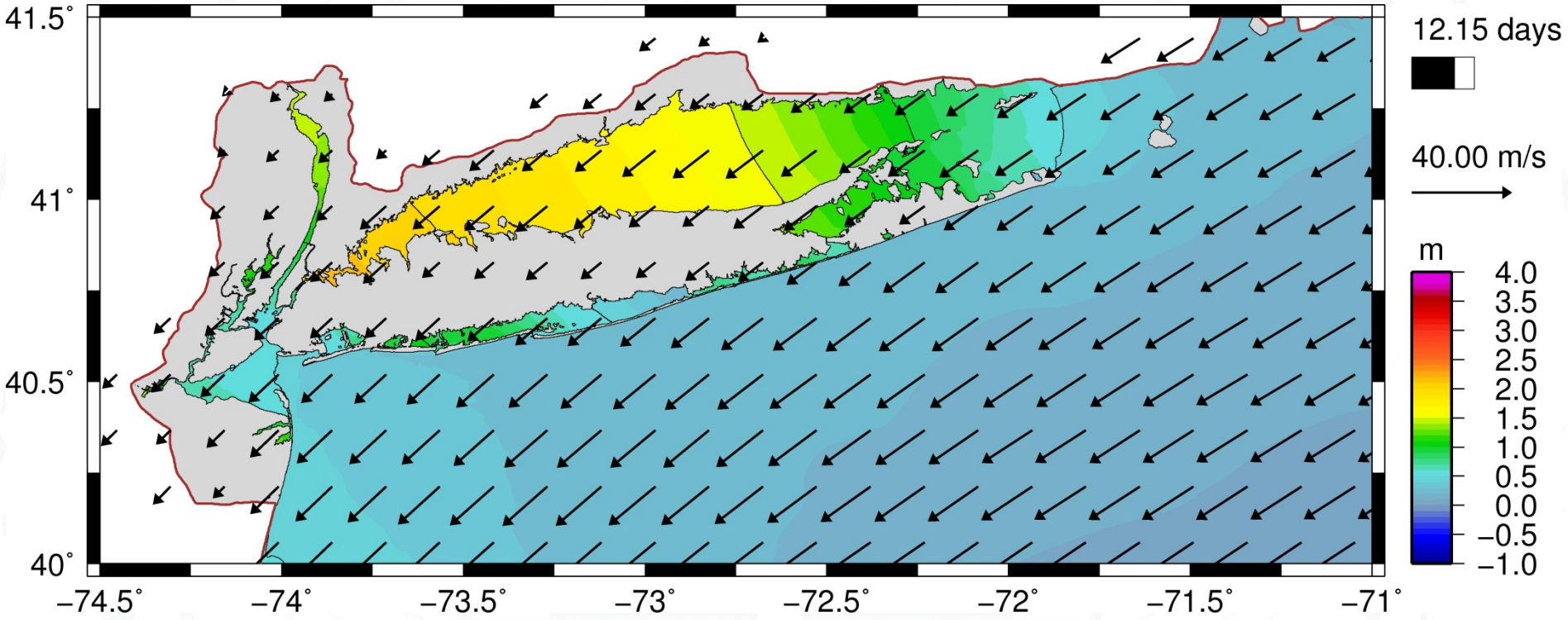

WSE +16 hrs
13.65 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚


WSE +20 hrs
13.81 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
44˚
40˚
36˚
32˚
28˚
24˚
−84˚
−80˚
−76˚
−72˚
−68˚
−64˚
−60˚

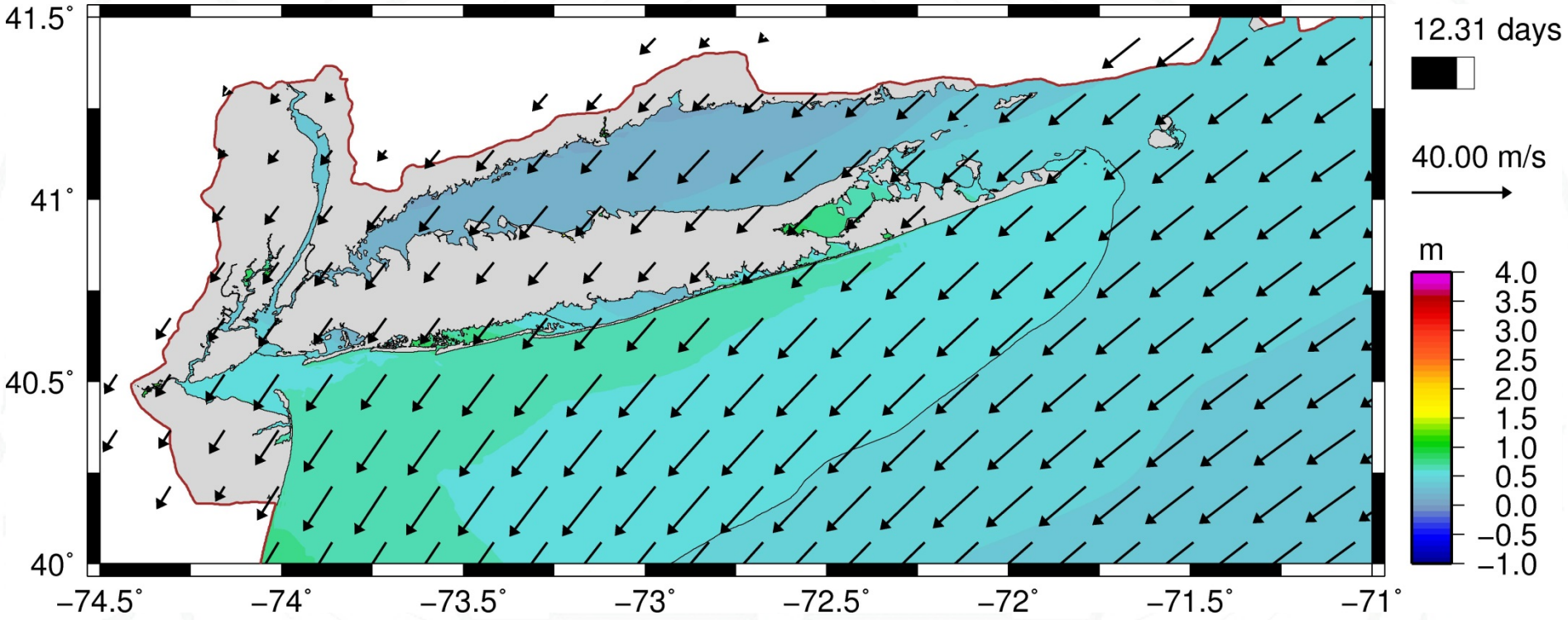
WSE -24 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
11.98 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

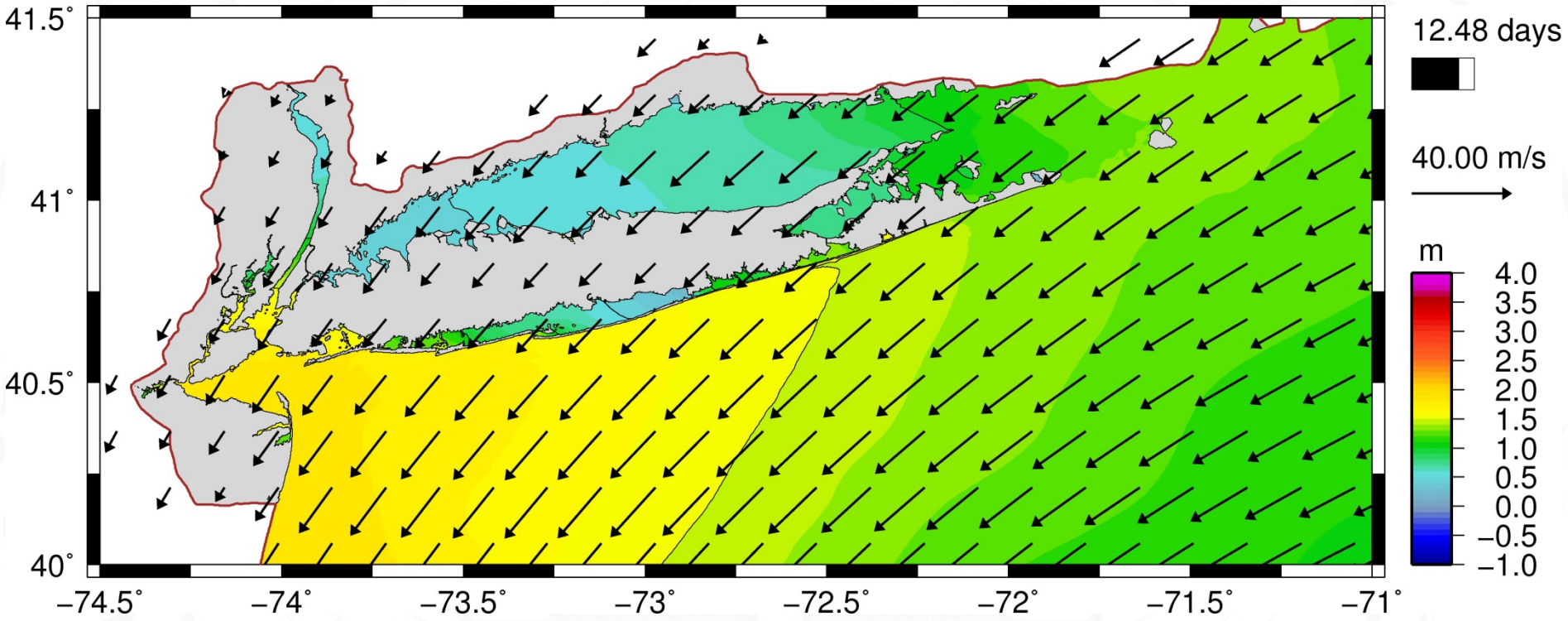
WSE -20 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.15 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

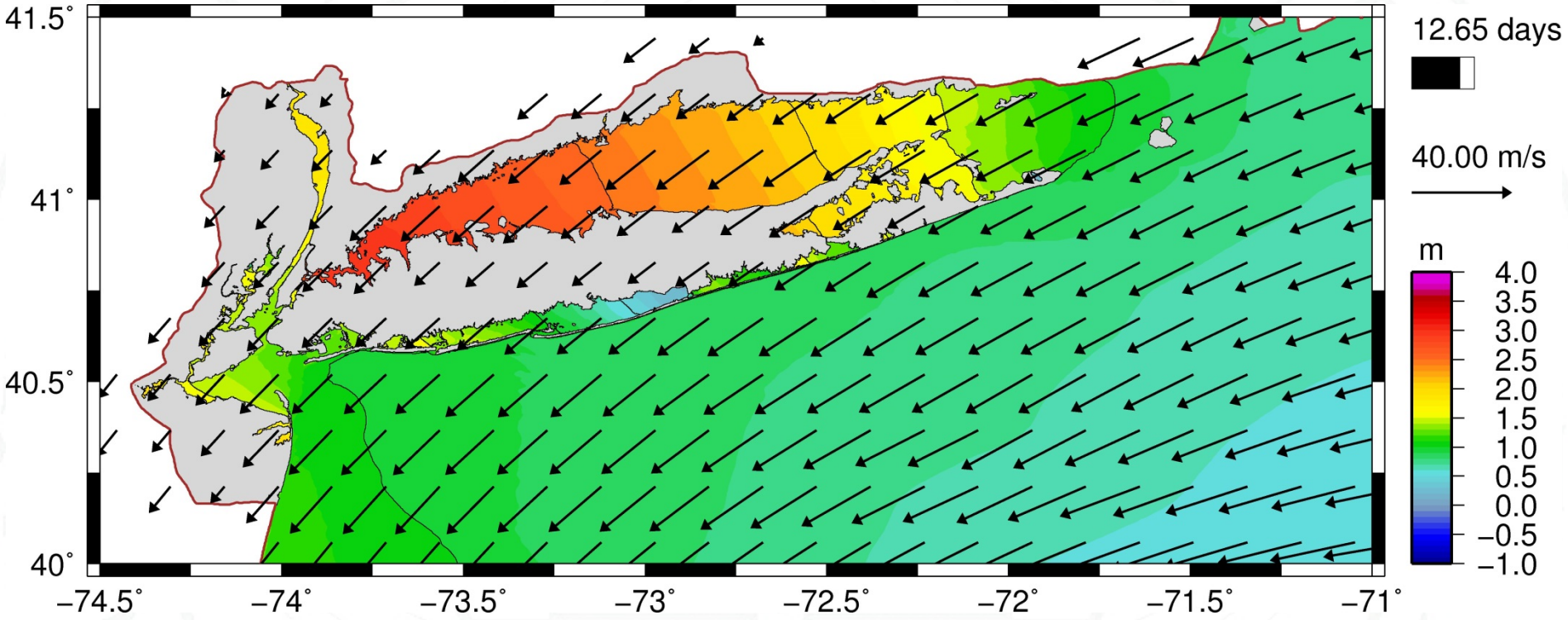
WSE -16 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.31 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

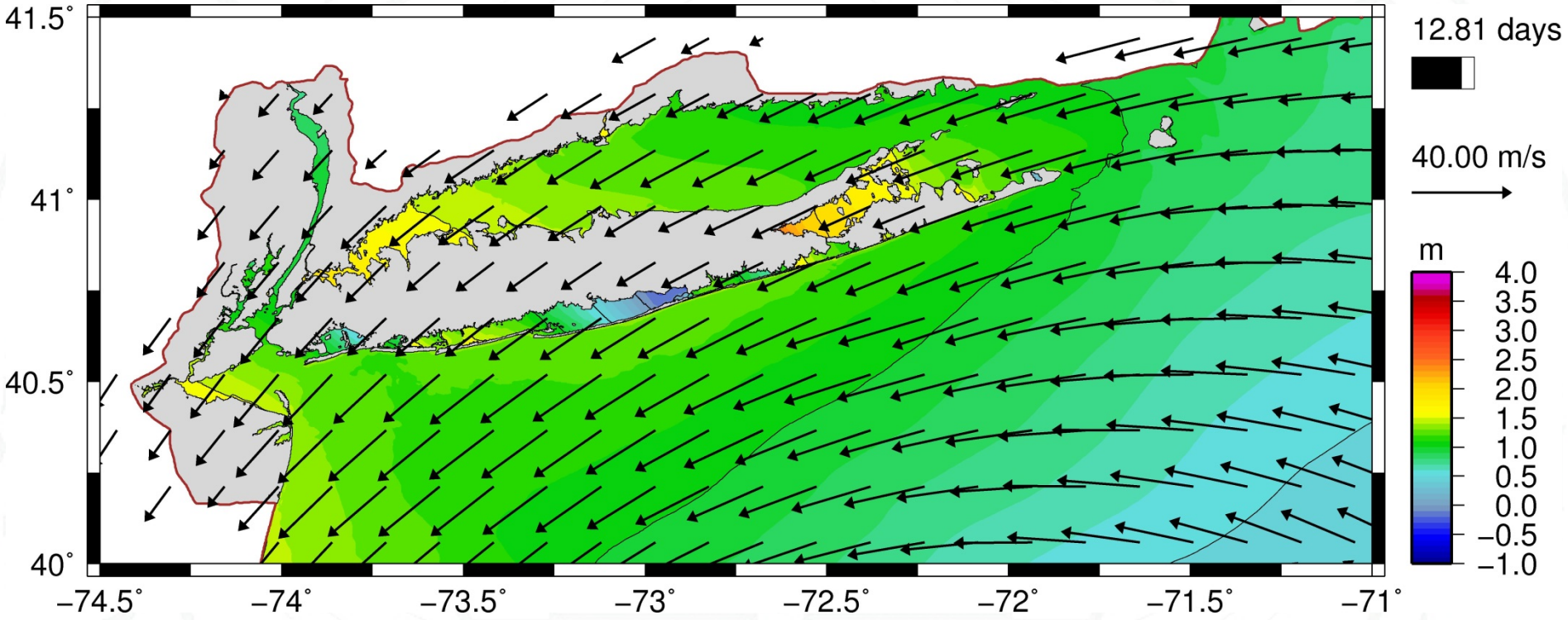
WSE -12 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.48 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

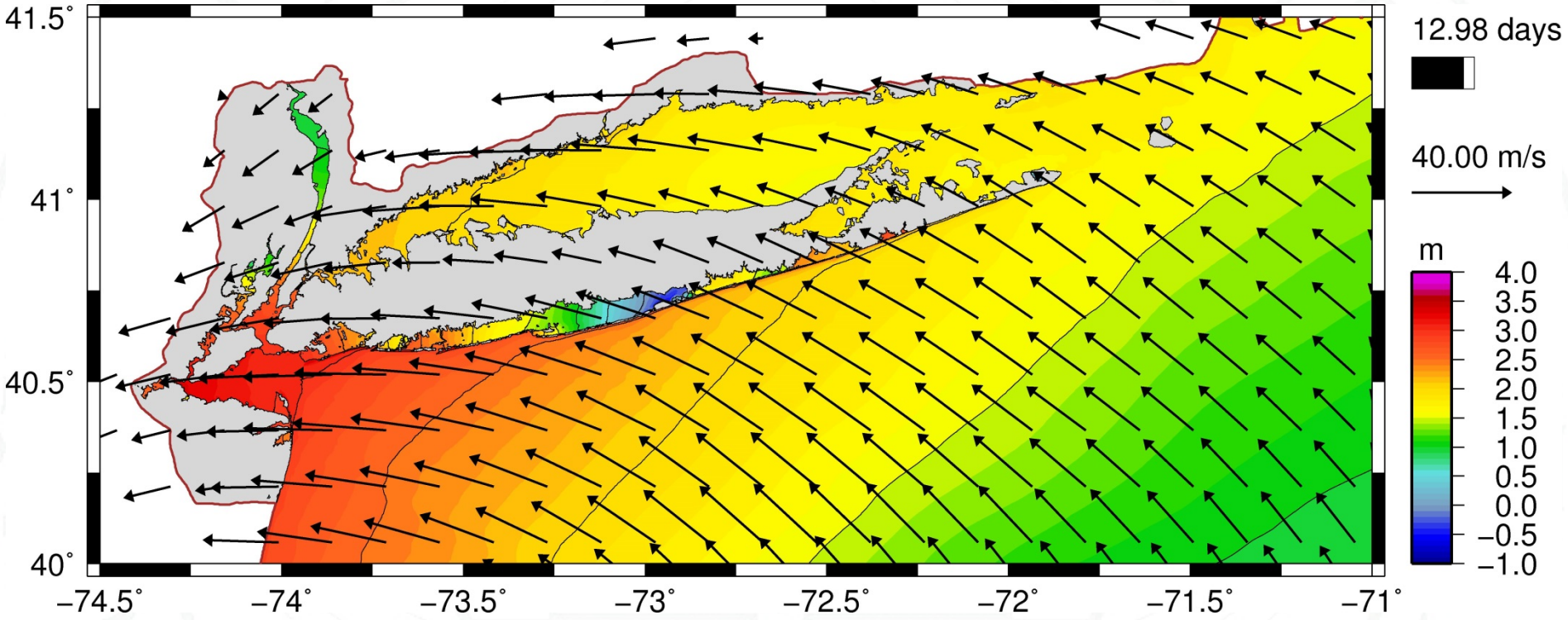
WSE -8 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.65 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

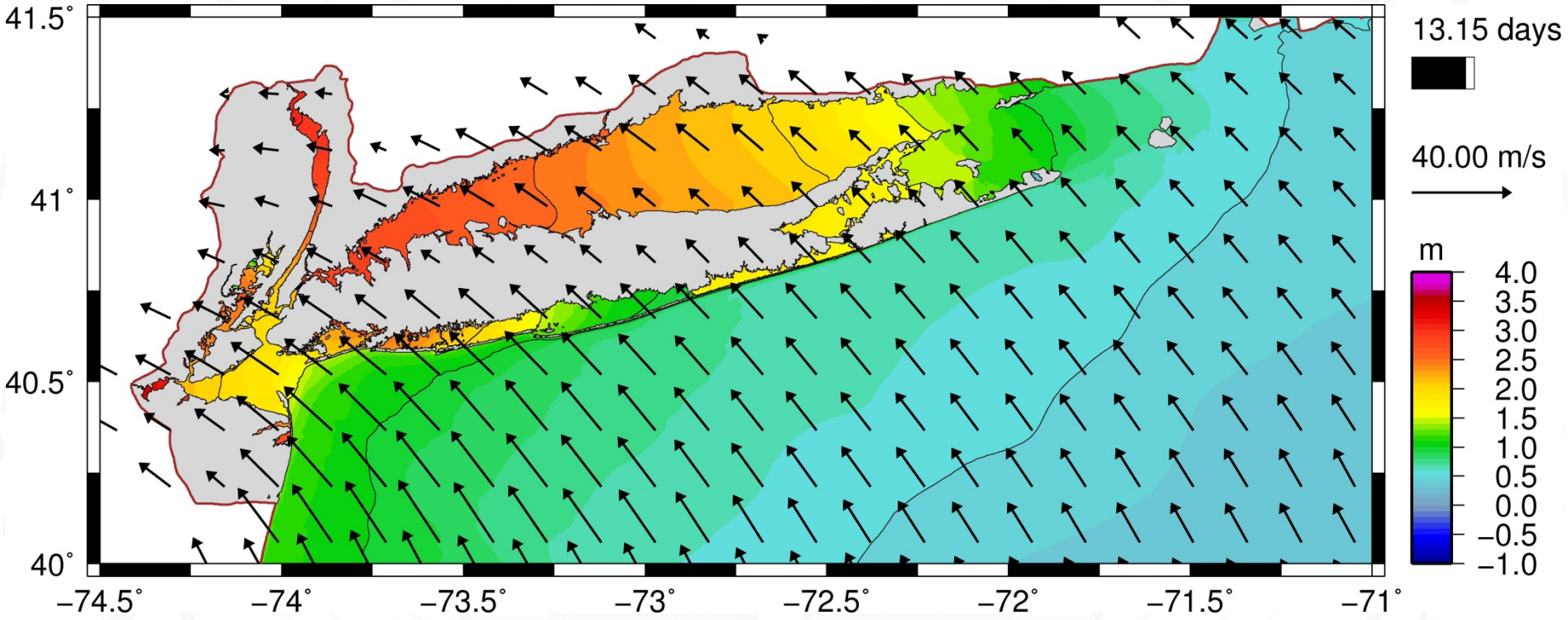
WSE -4 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
12.81 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

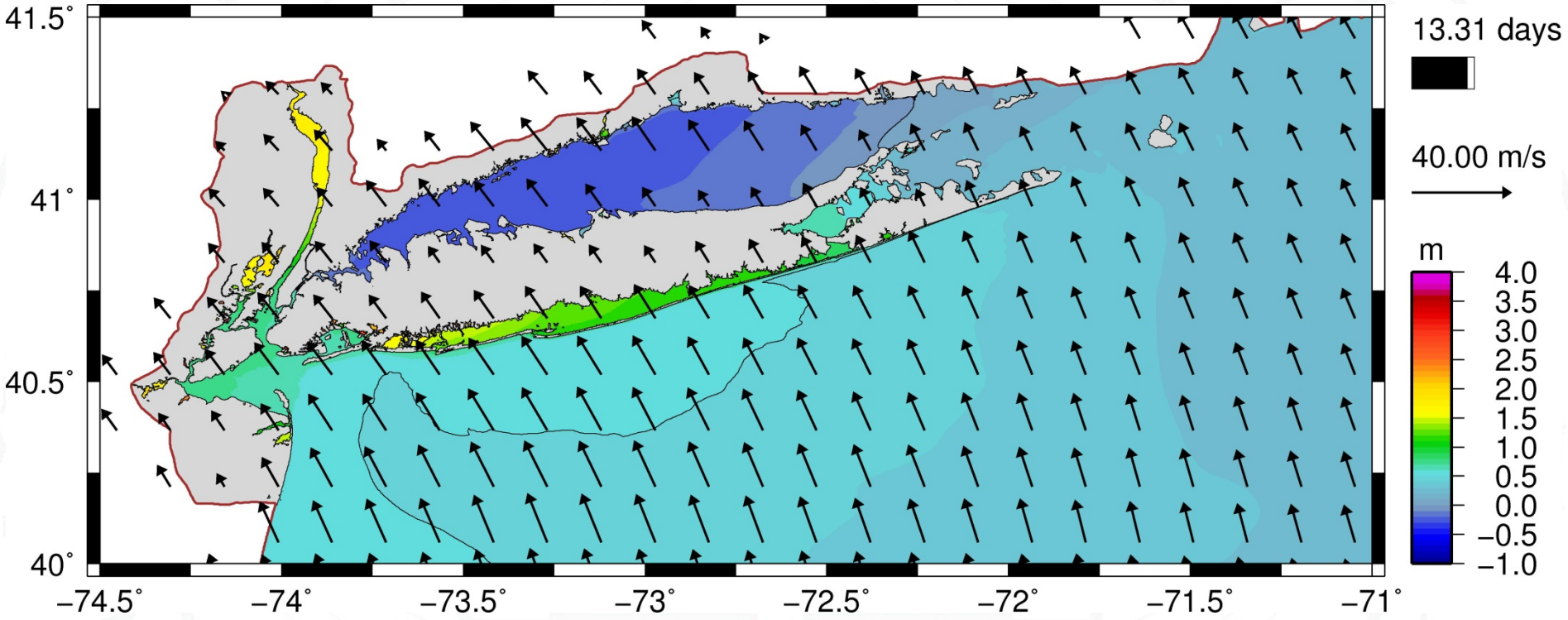
WSE 0 hrs LANDFALL



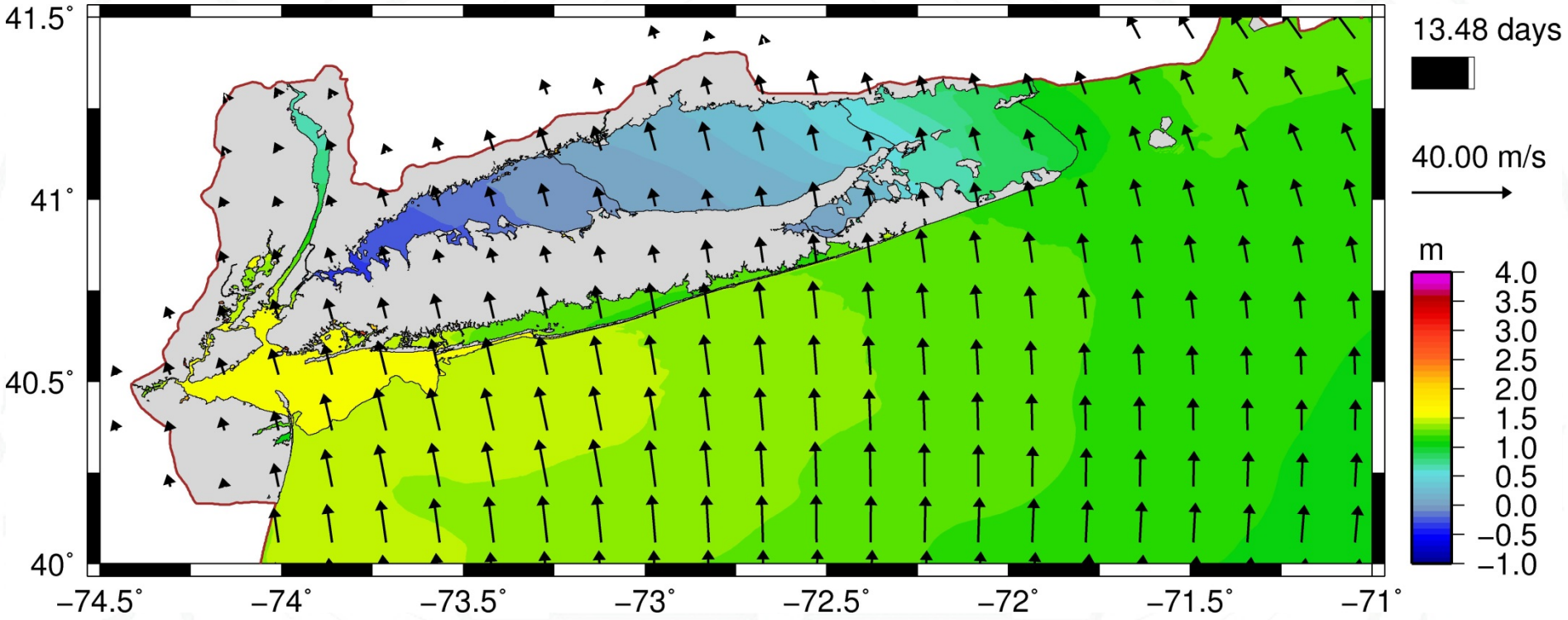
WSE +4 hrs

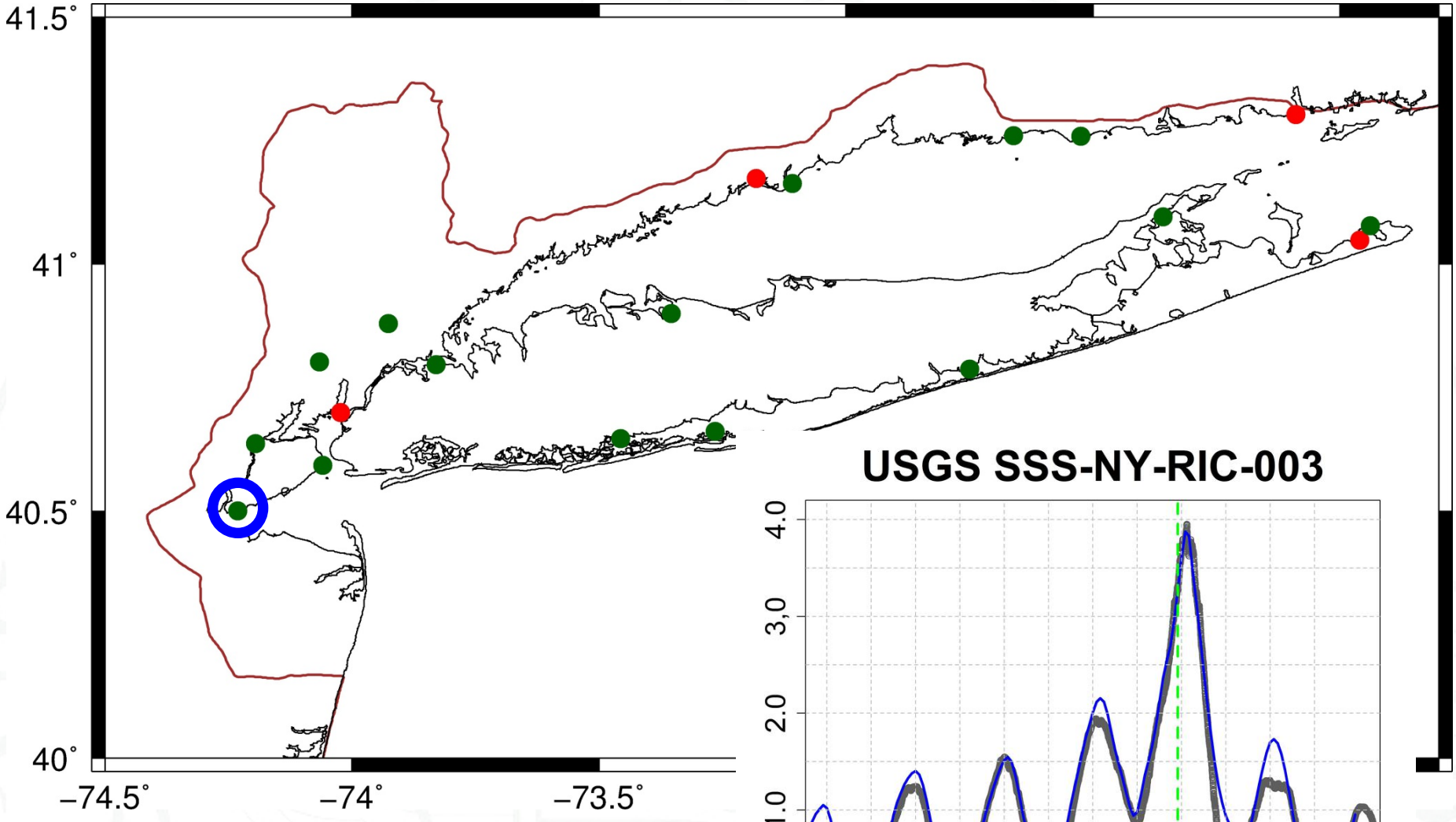

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
13.15 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

WSE +8 hrs

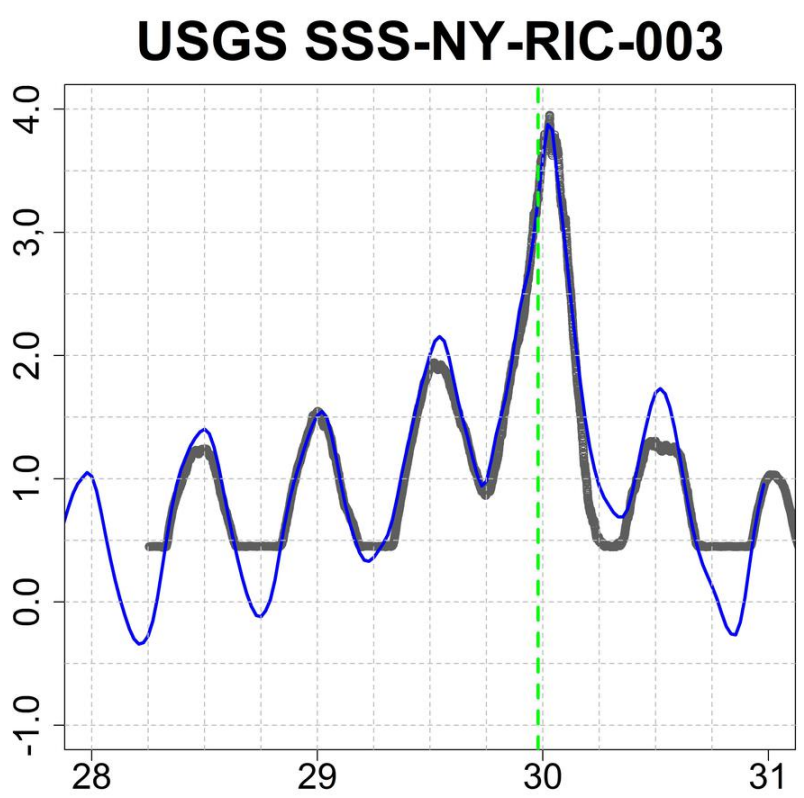

41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
13.31 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

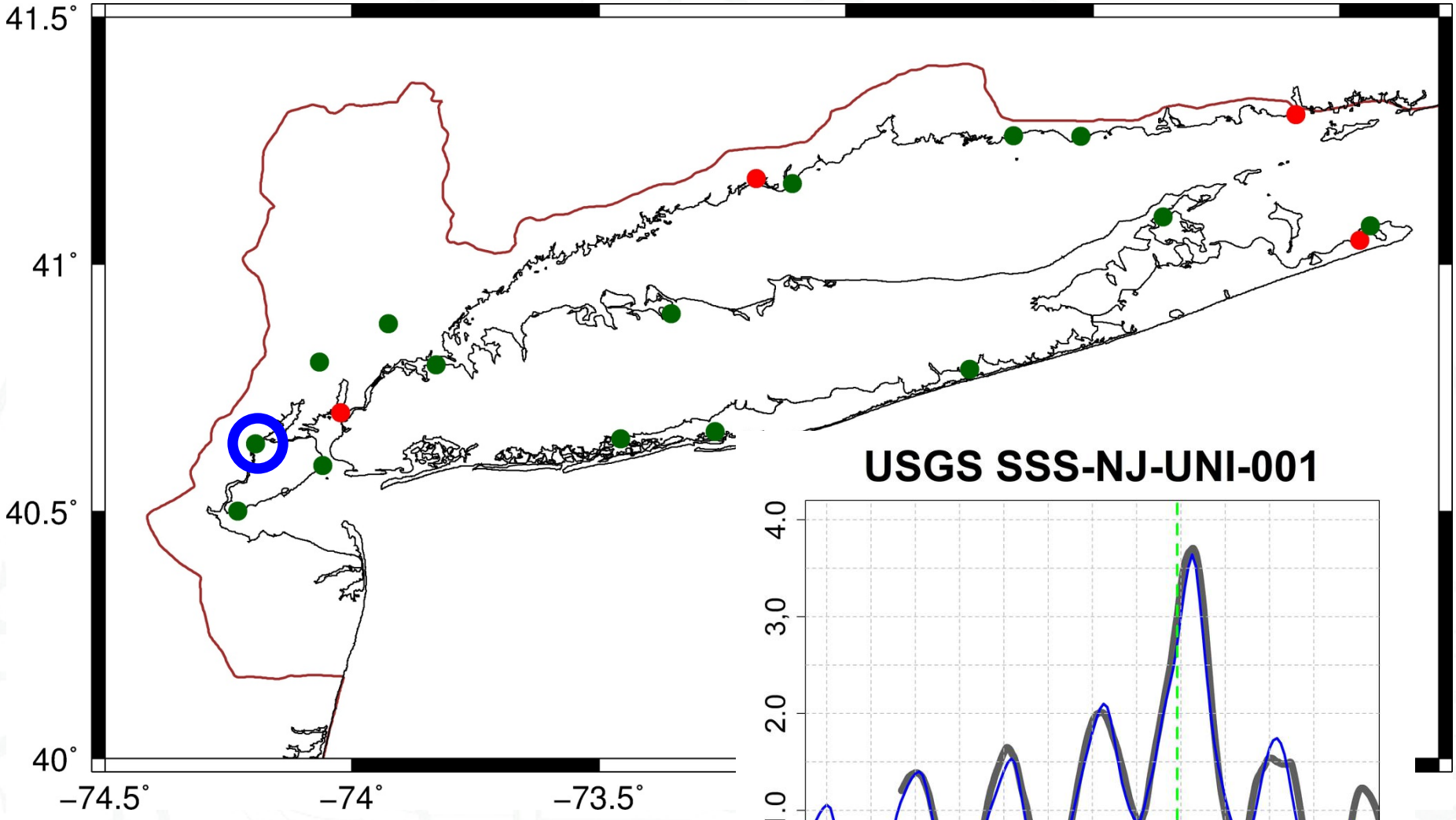
WSE +12 hrs


41.5˚
41˚
40.5˚
40˚
−74.5˚
−74˚
−73.5˚
−73˚
−72.5˚
−72˚
−71.5˚
−71˚
13.48 days
40.00 m/s
m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

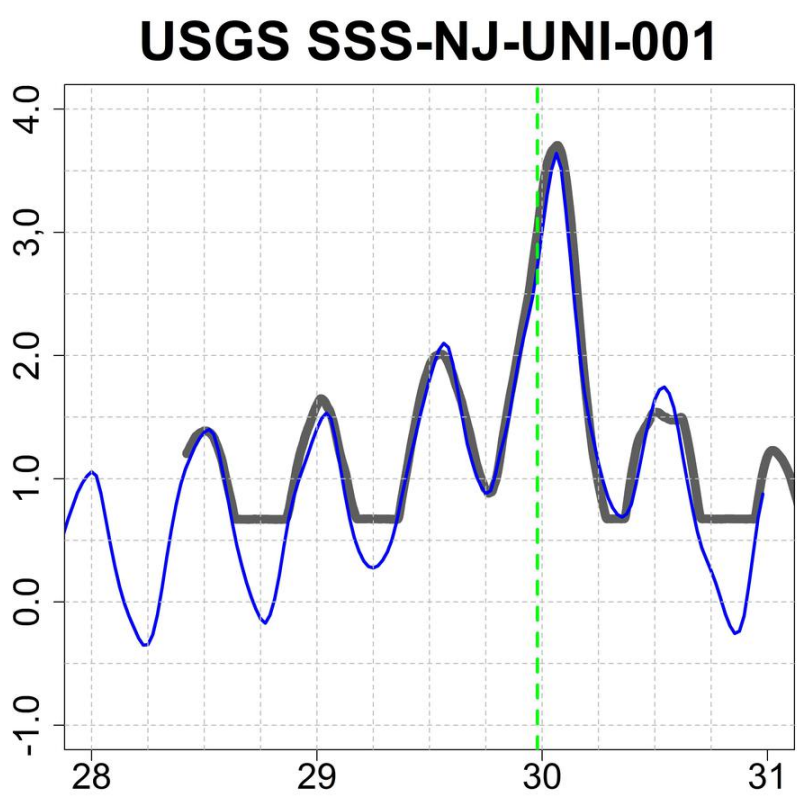


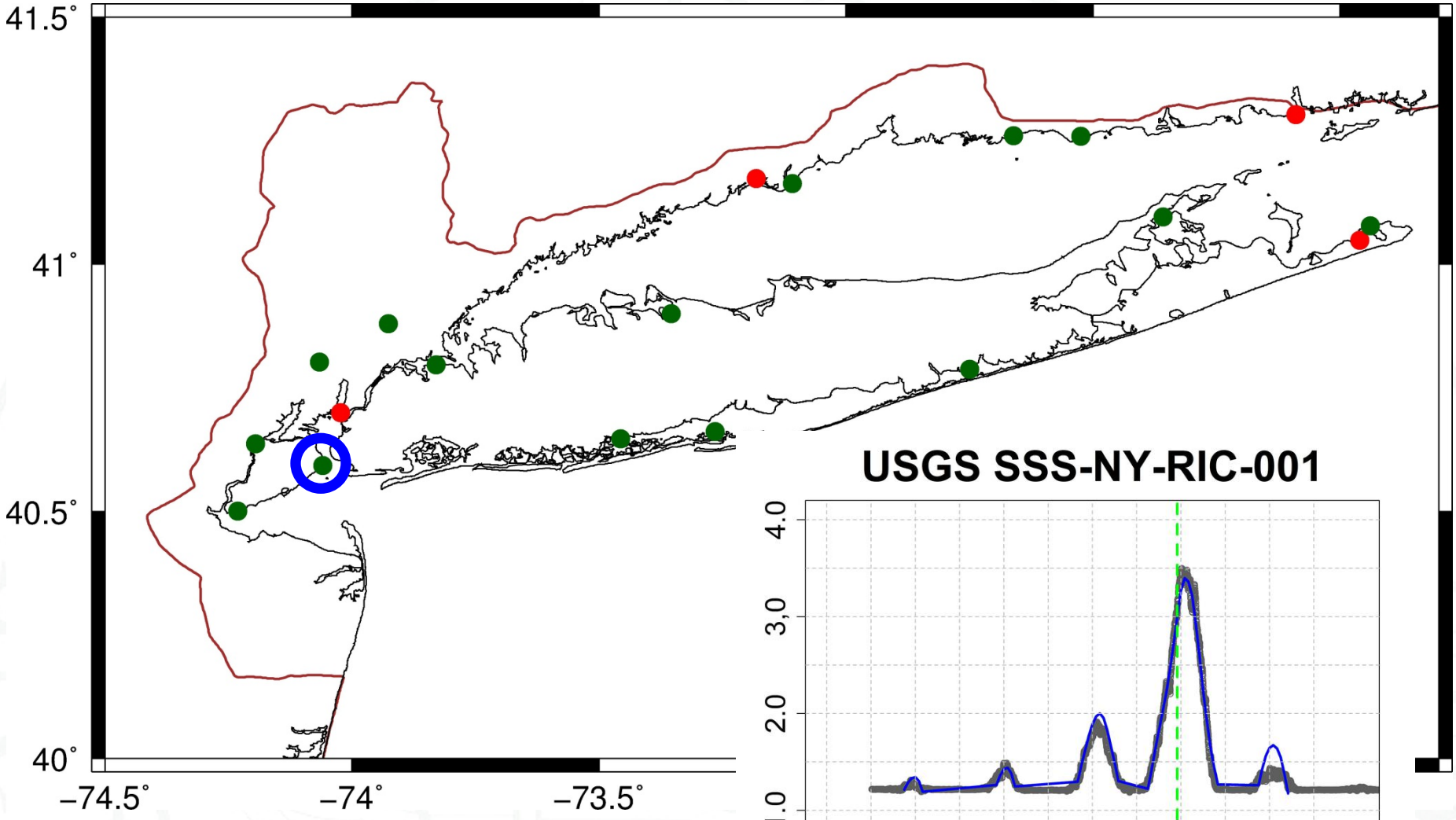
NOAA & USGS Water level comparisons

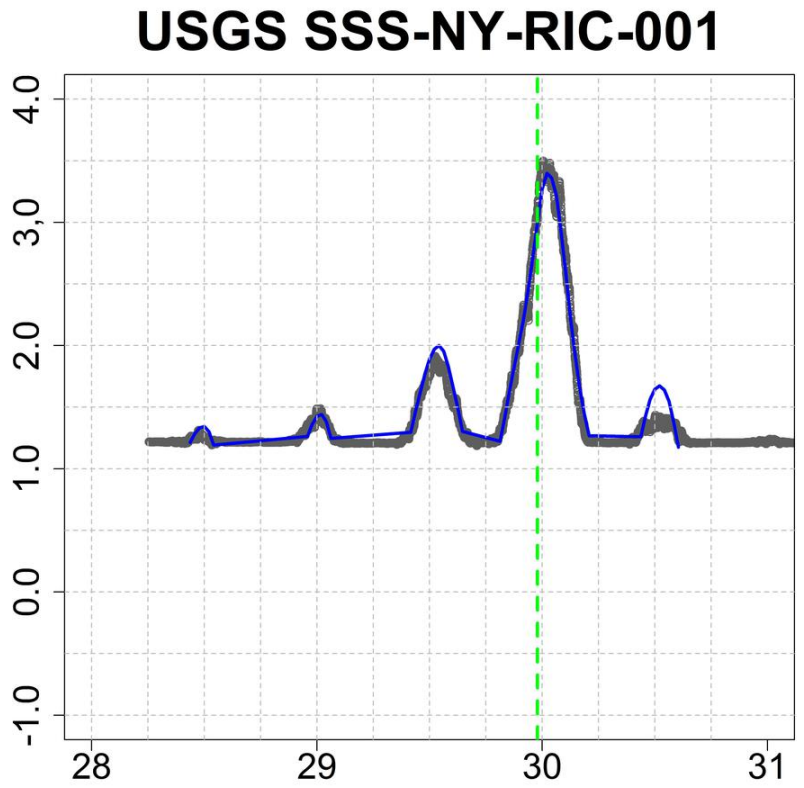




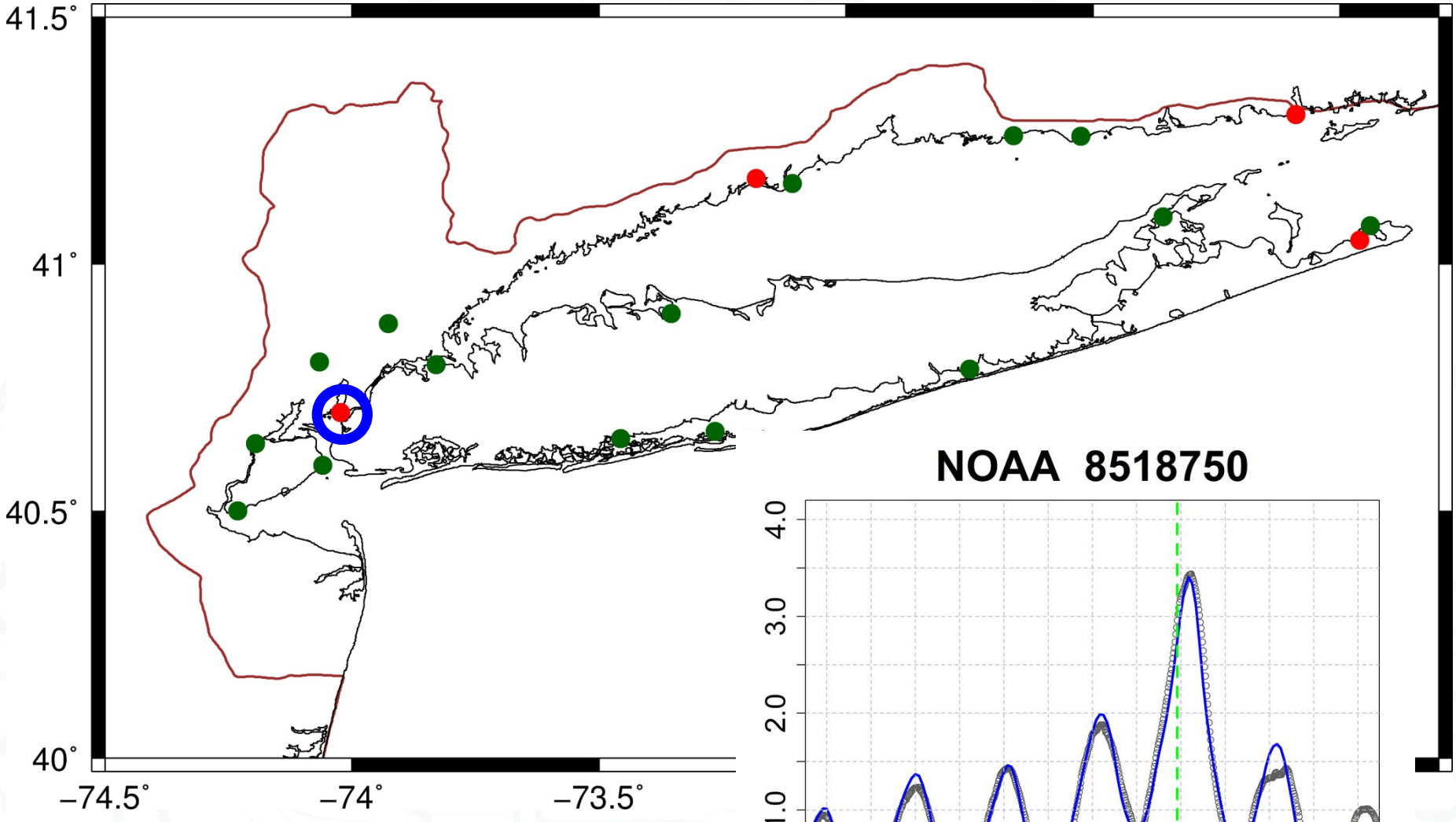
NOAA & USGS Water level comparisons



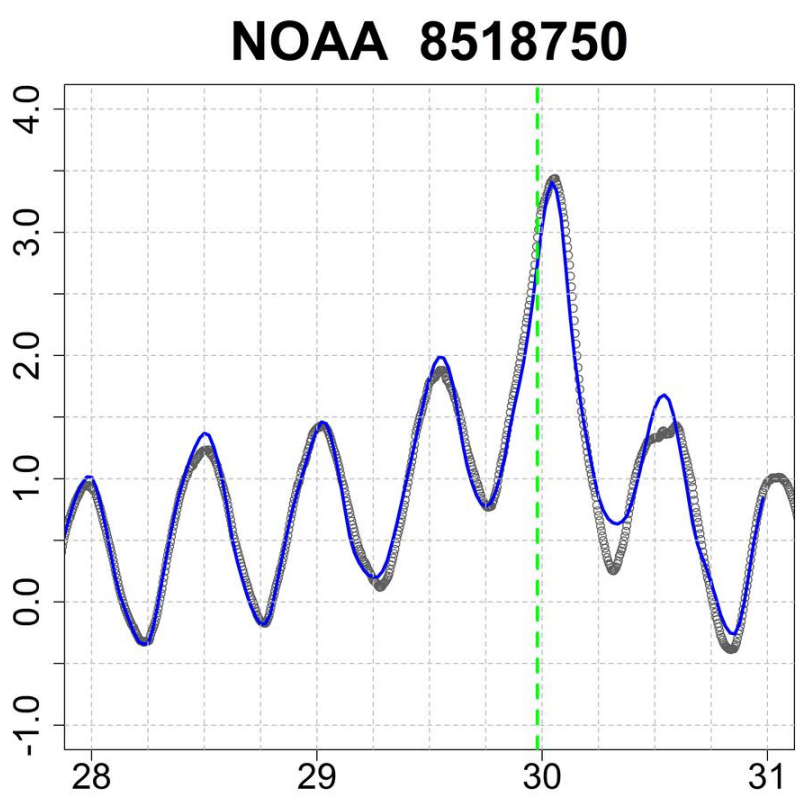


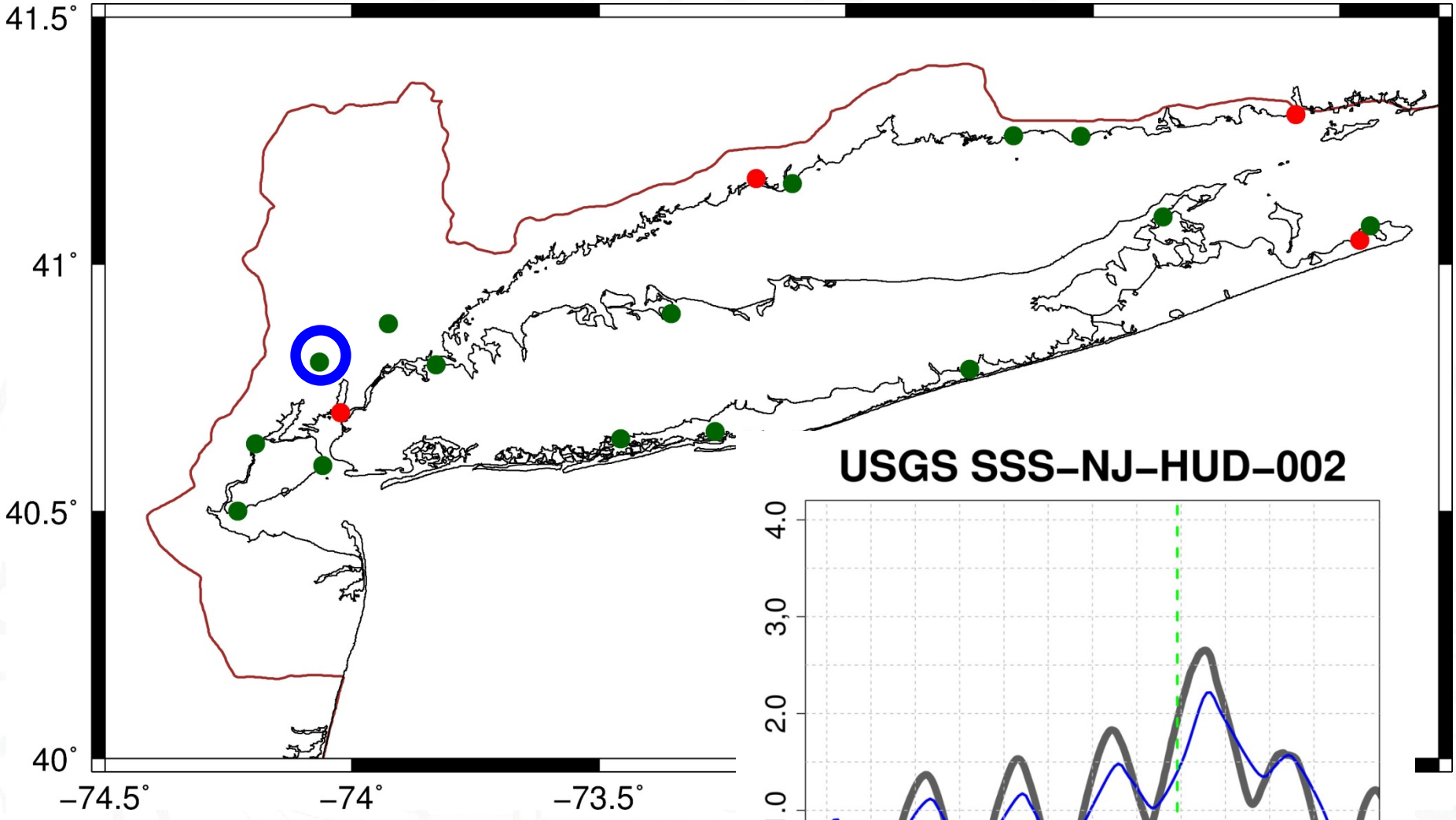


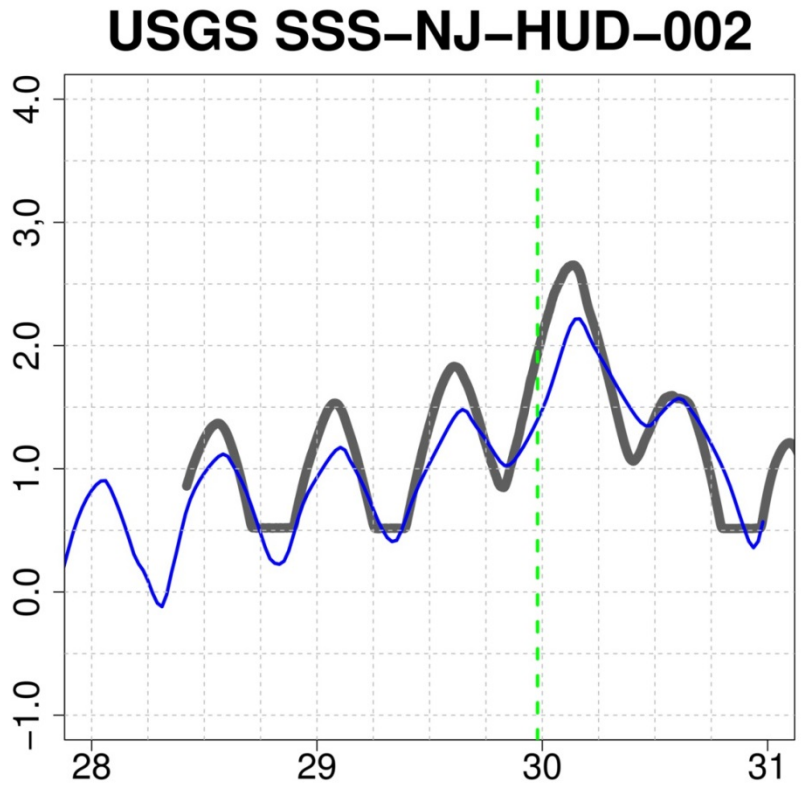
NOAA & USGS Water level comparisons



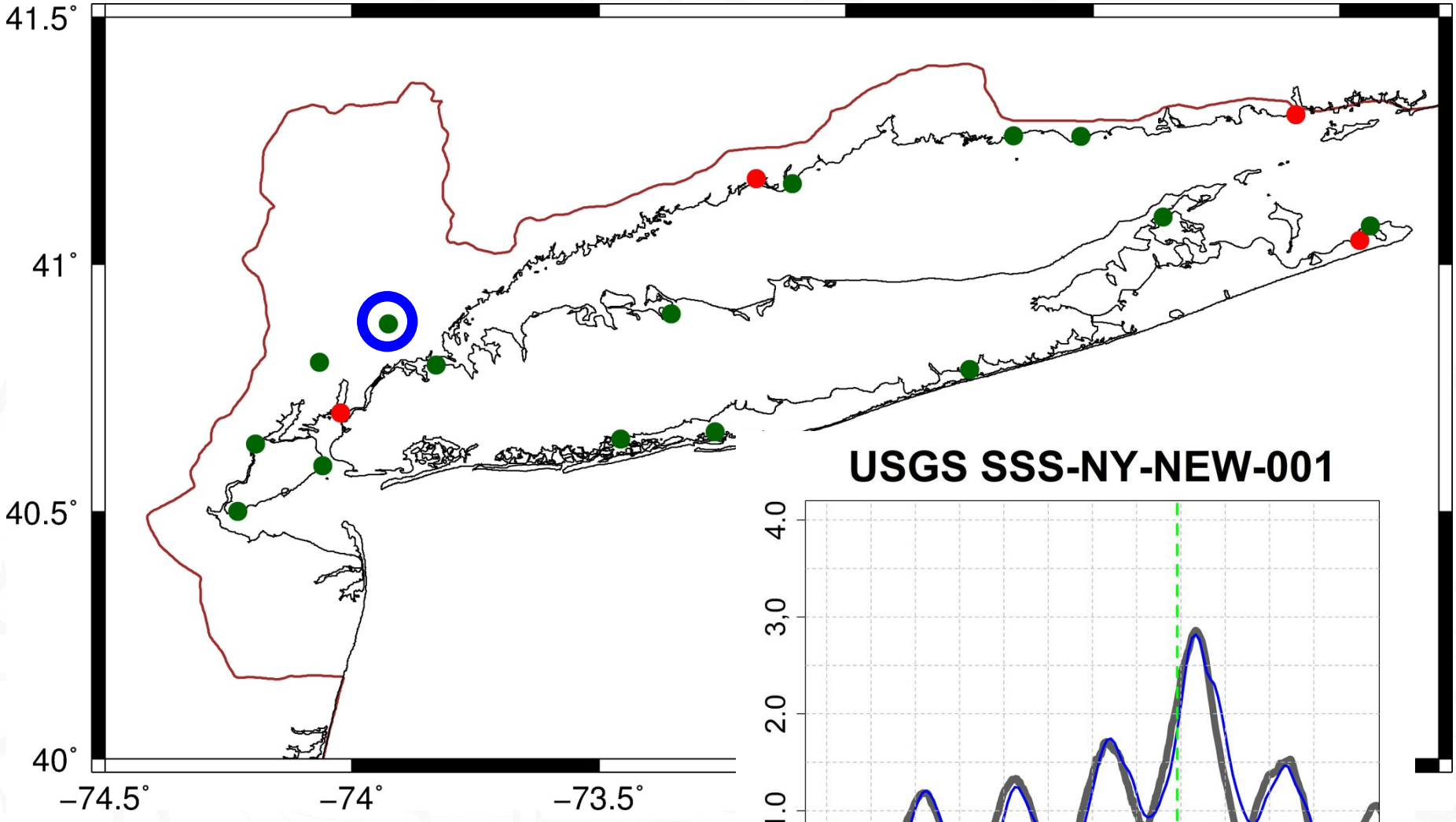
NOAA & USGS Water level comparisons



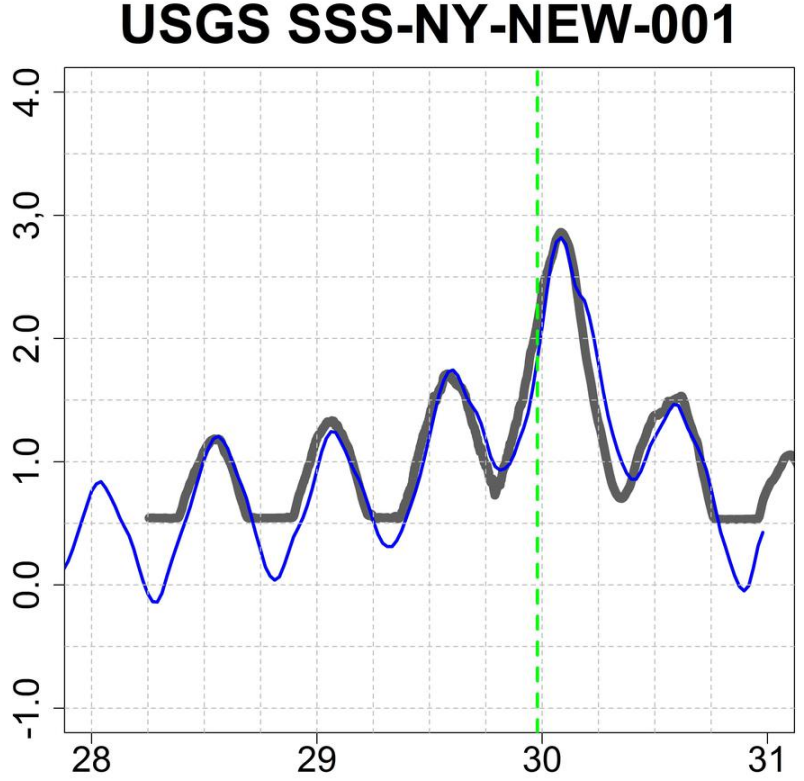


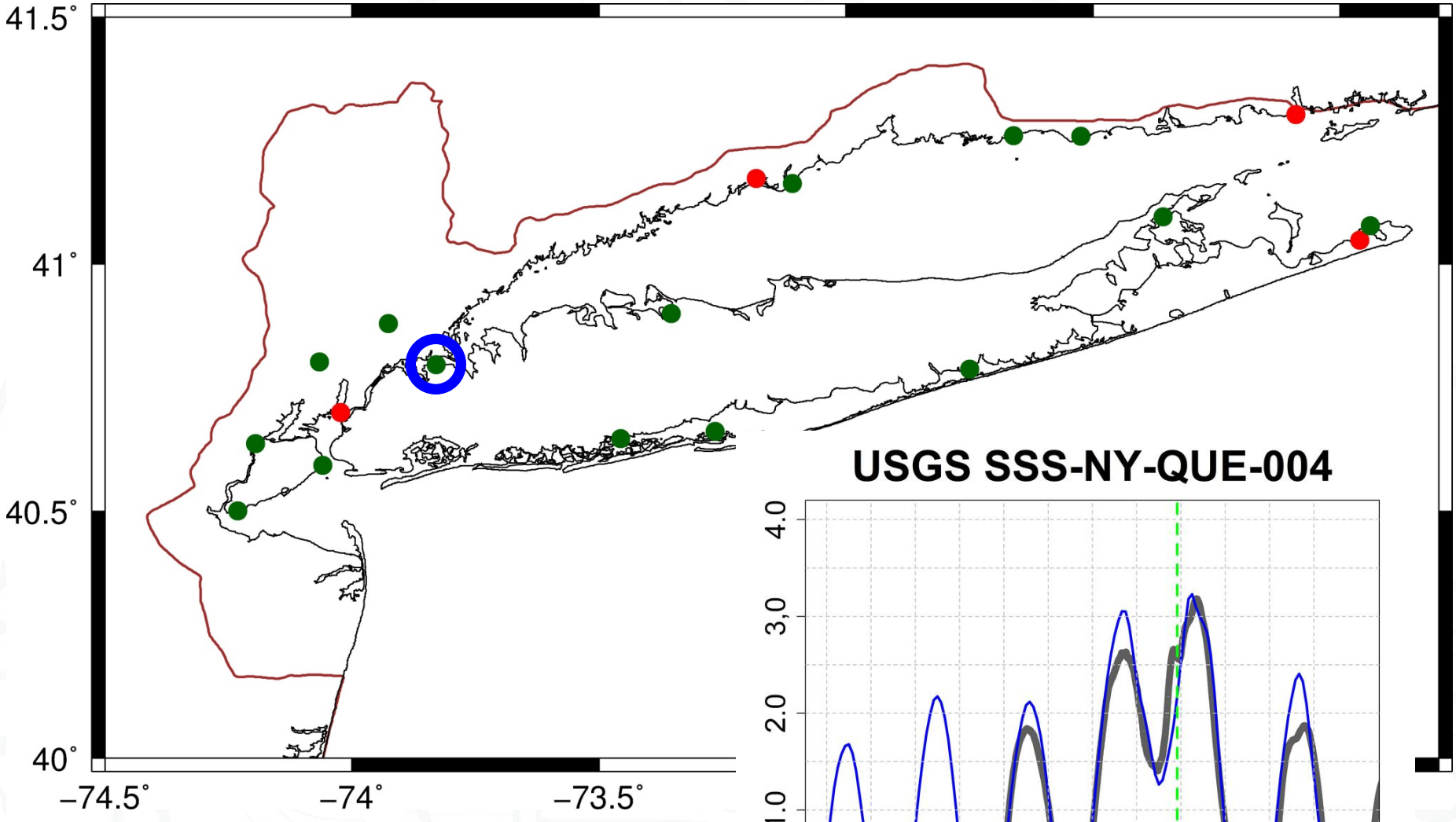


NOAA & USGS Water level comparisons

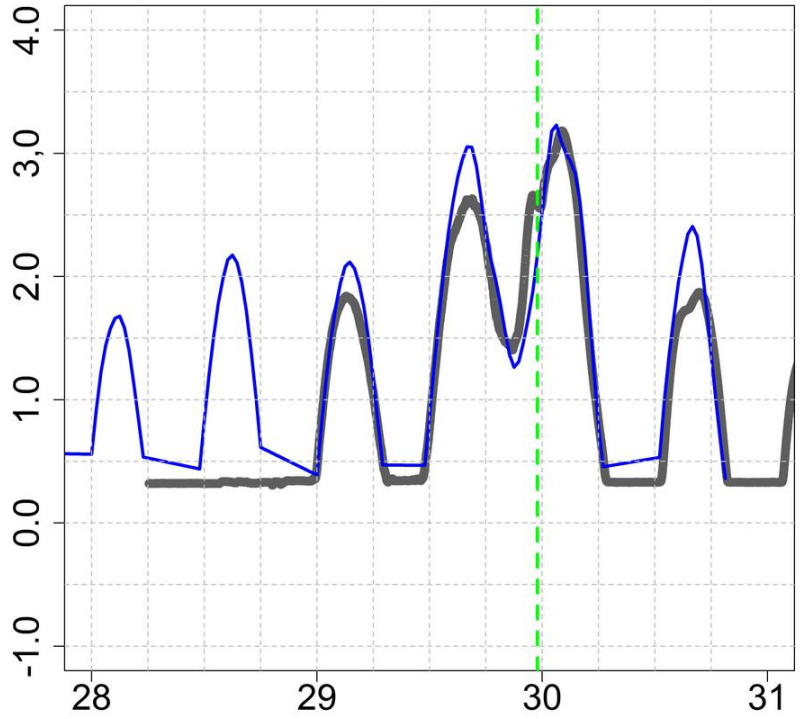


NOAA & USGS Water level comparisons

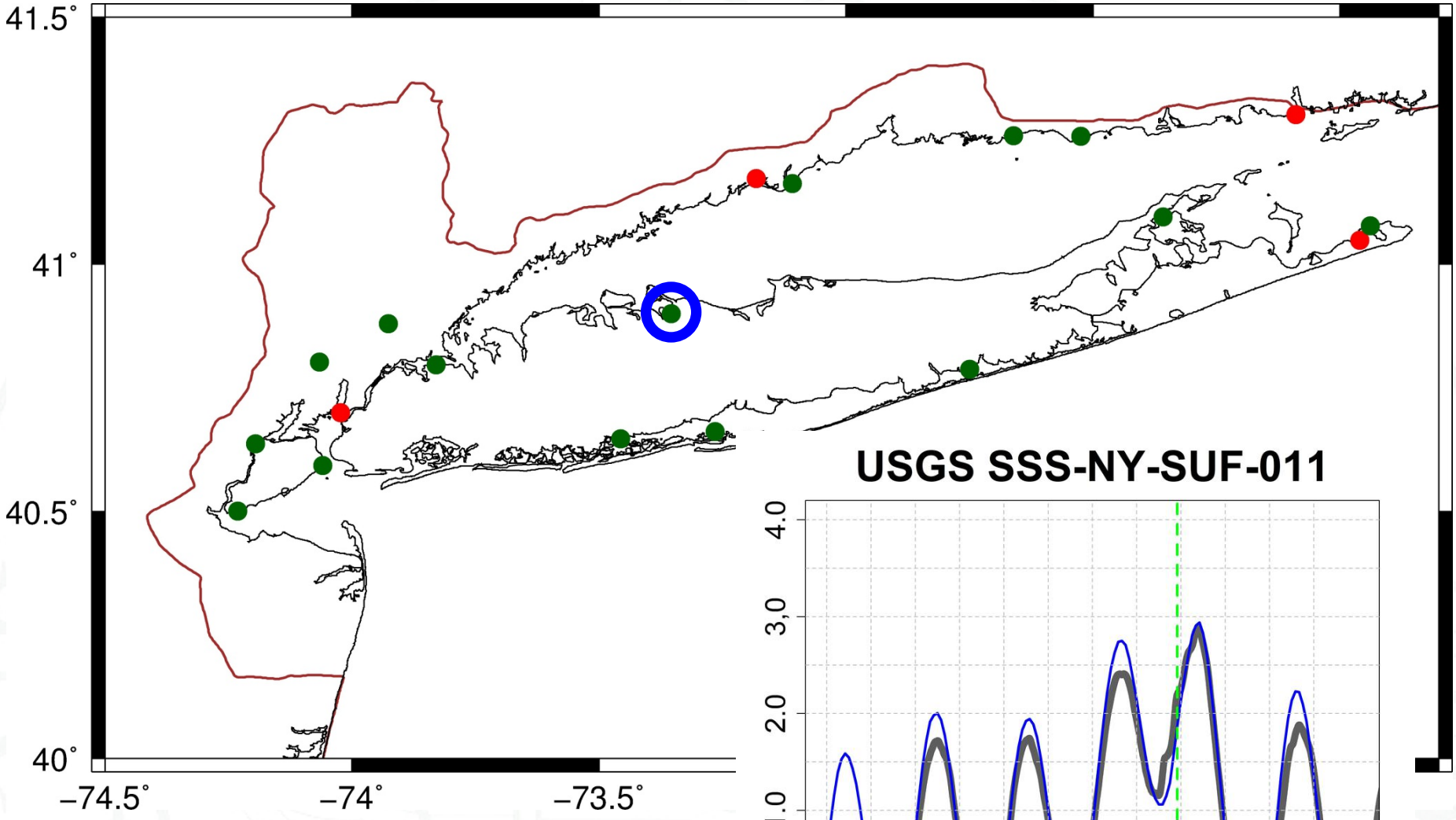




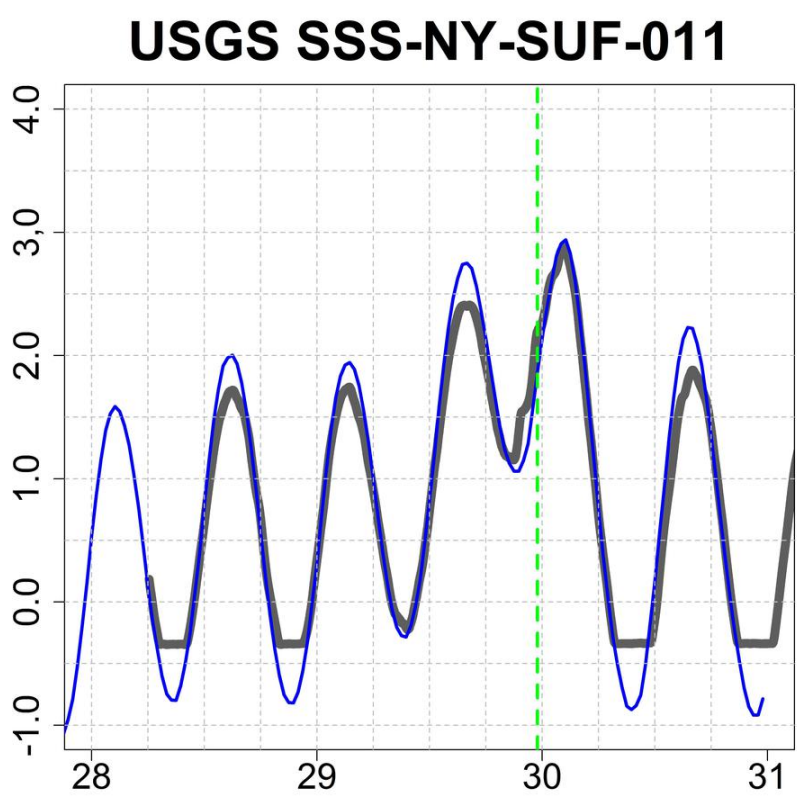
USGS SSS-NY-QUE-004

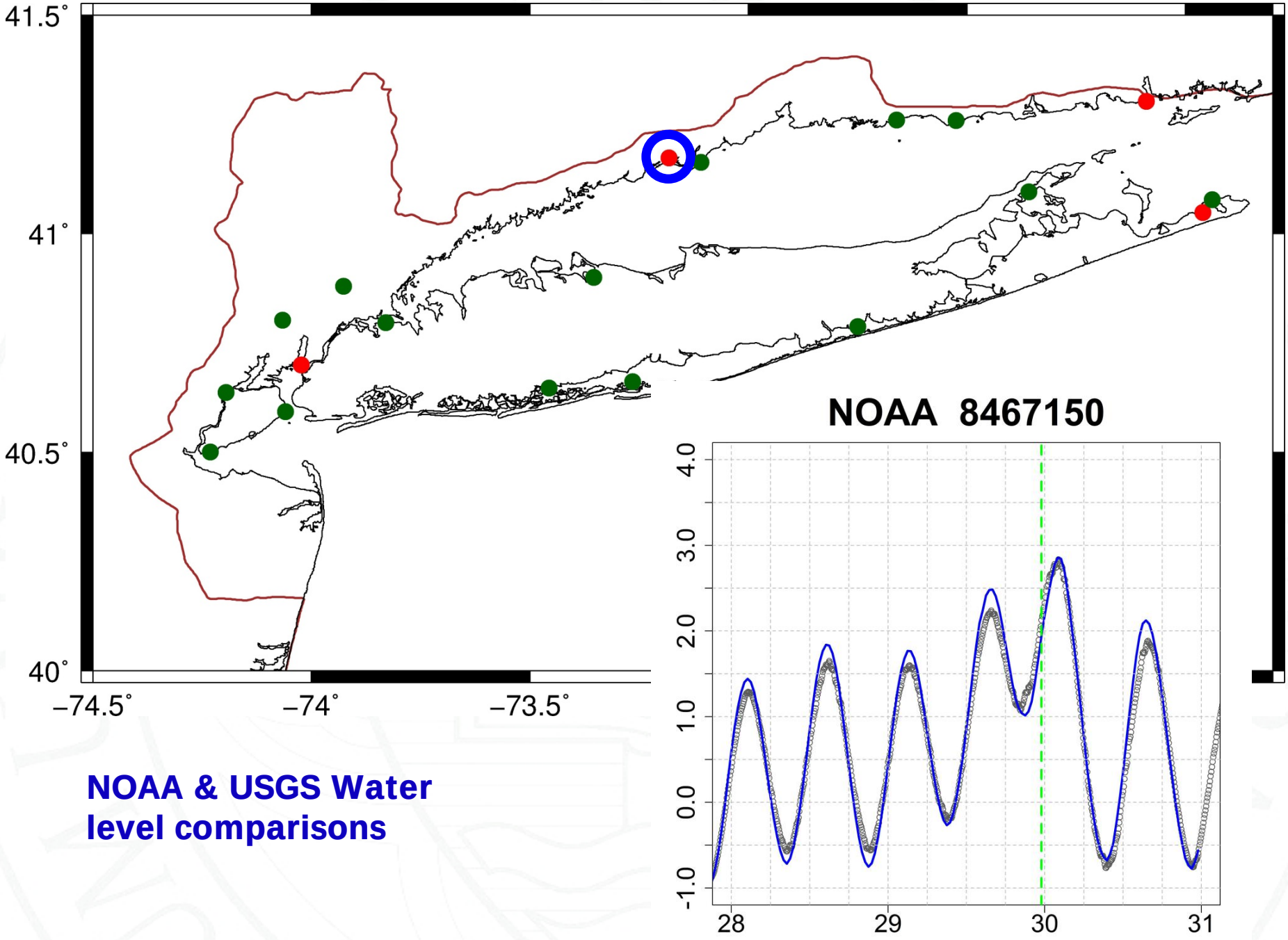


NOAA & USGS Water level comparisons

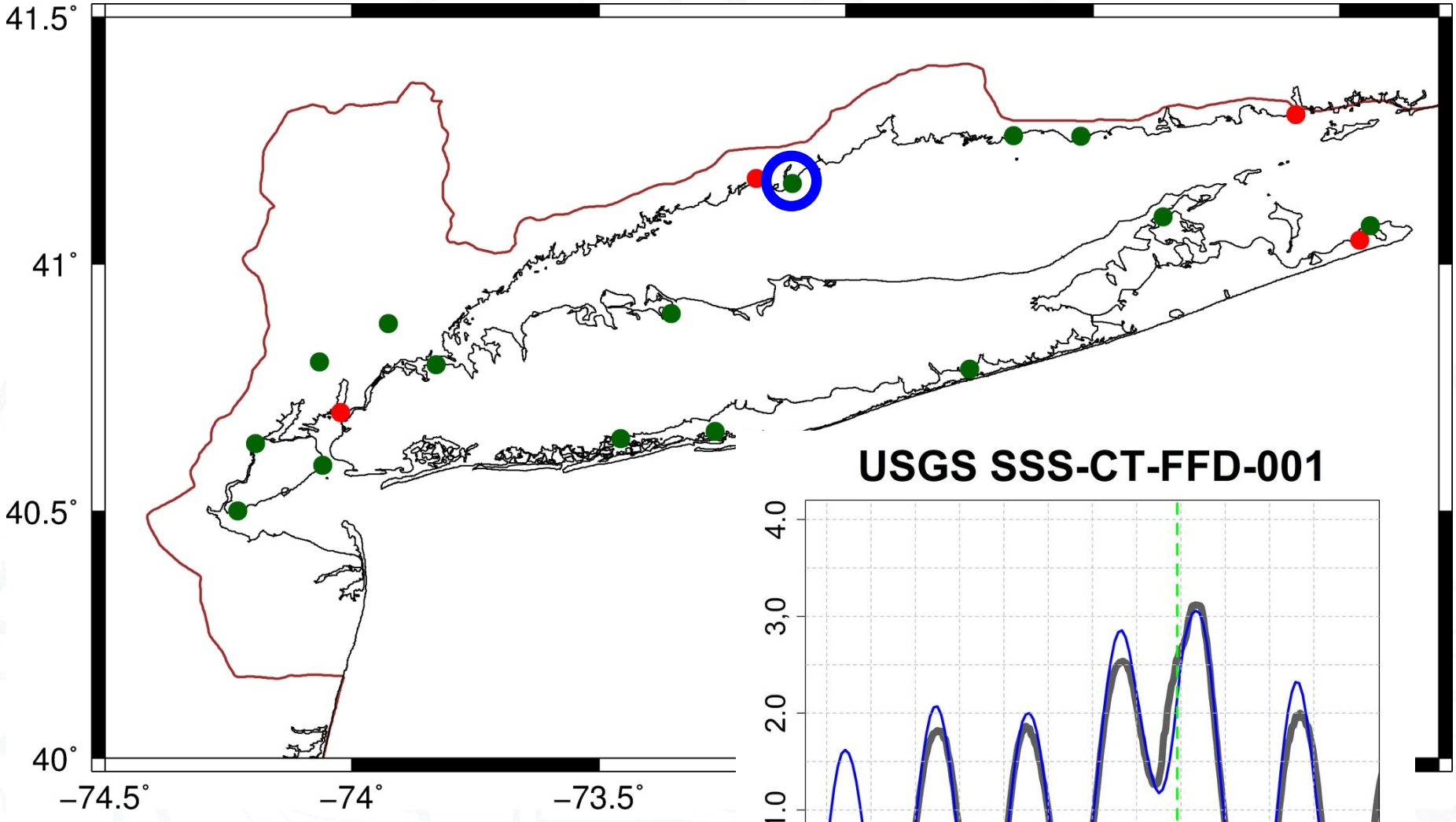


NOAA & USGS Water level comparisons

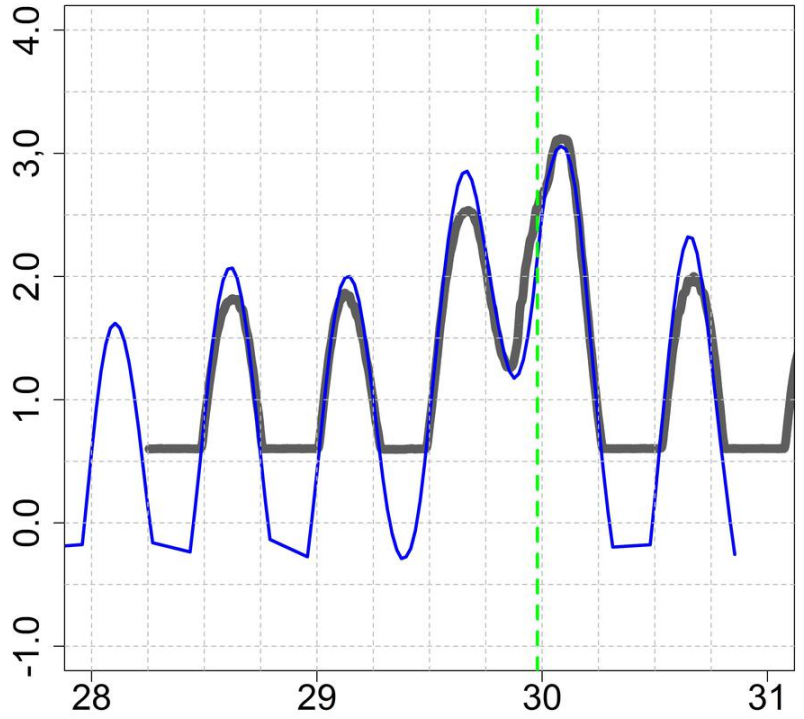




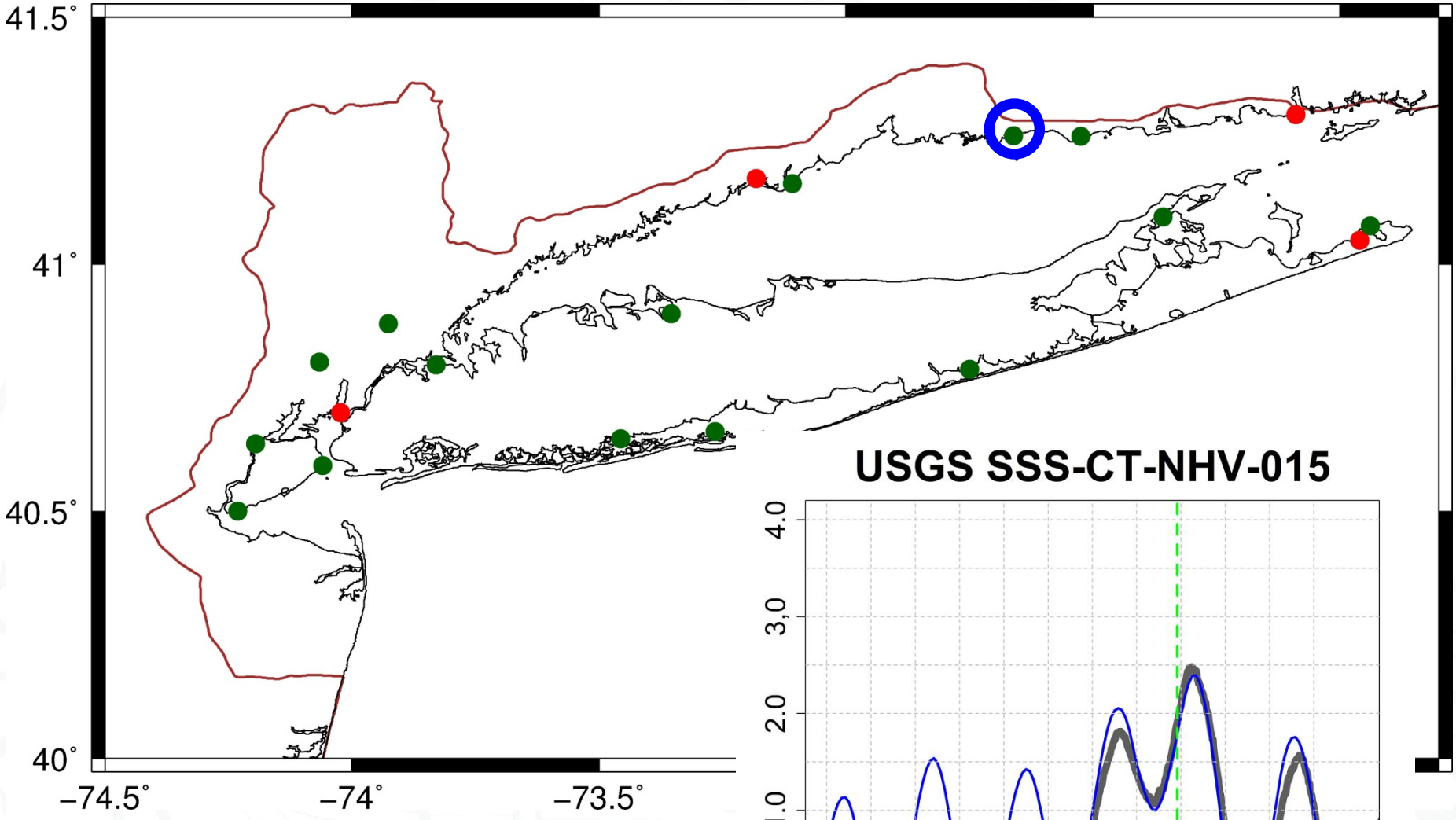
NOAA & USGS Water level comparisons



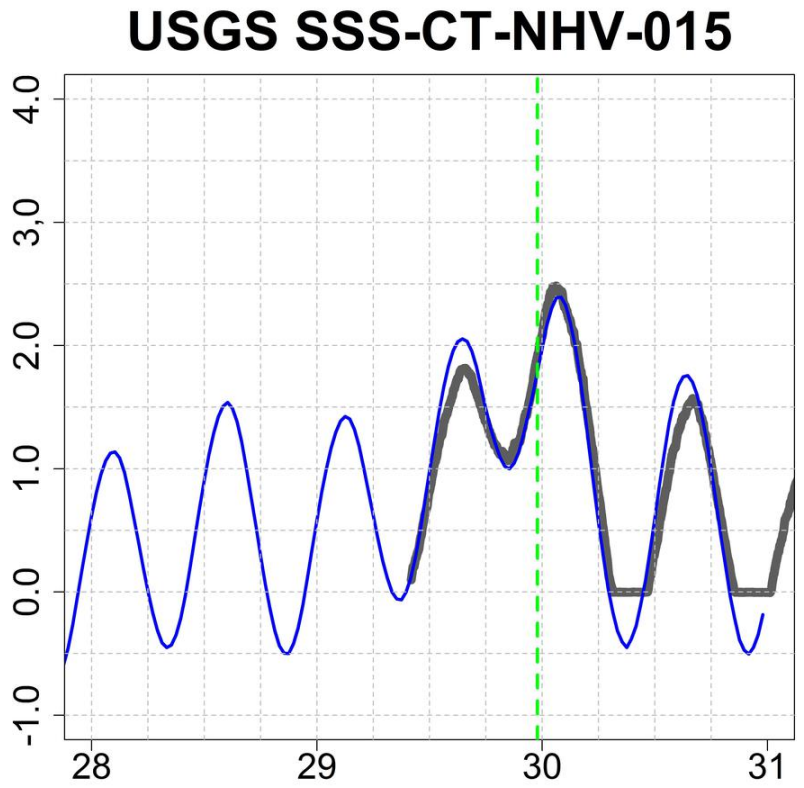
USGS SSS-CT-FFD-001

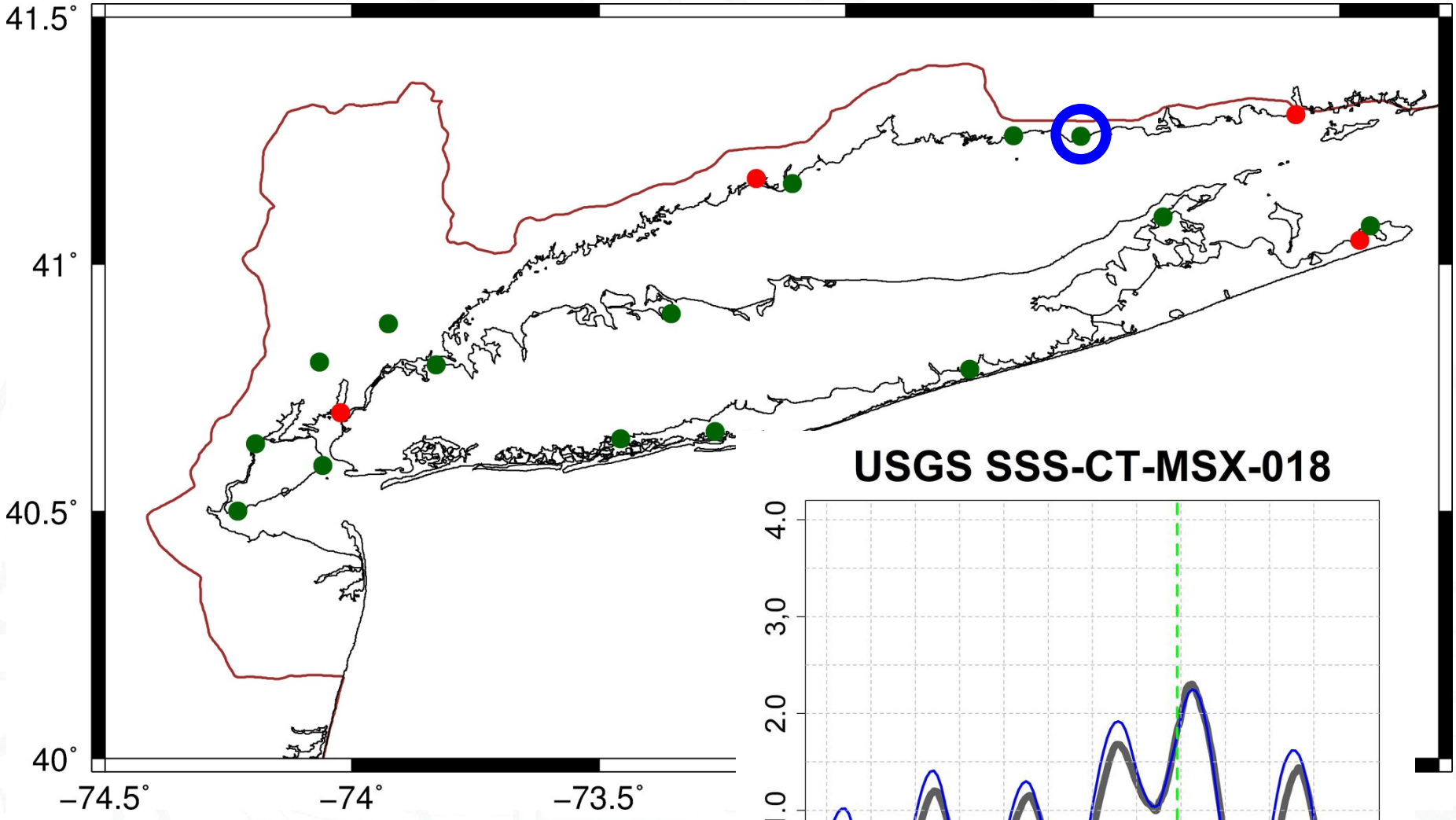


NOAA & USGS Water level comparisons



NOAA & USGS Water level comparisons





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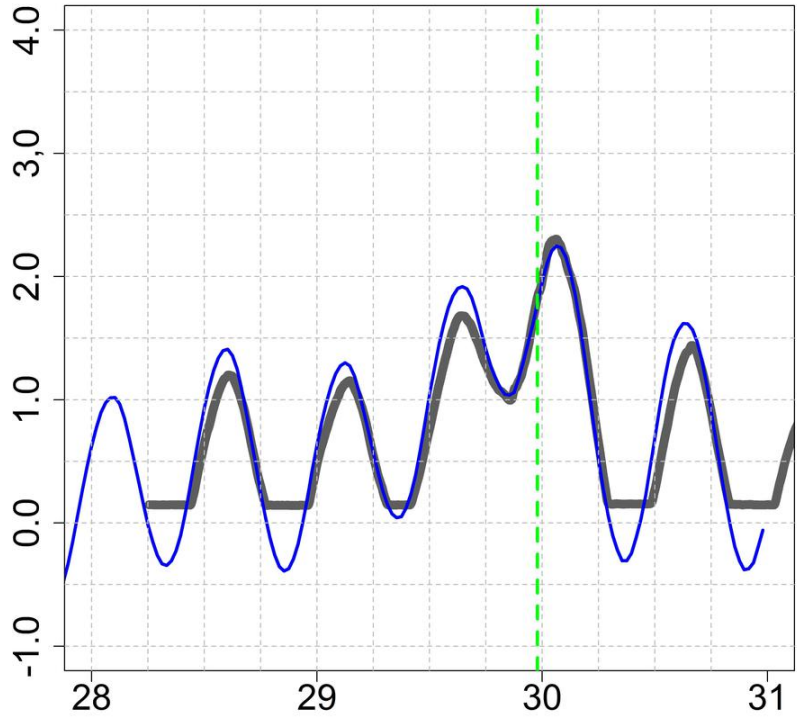
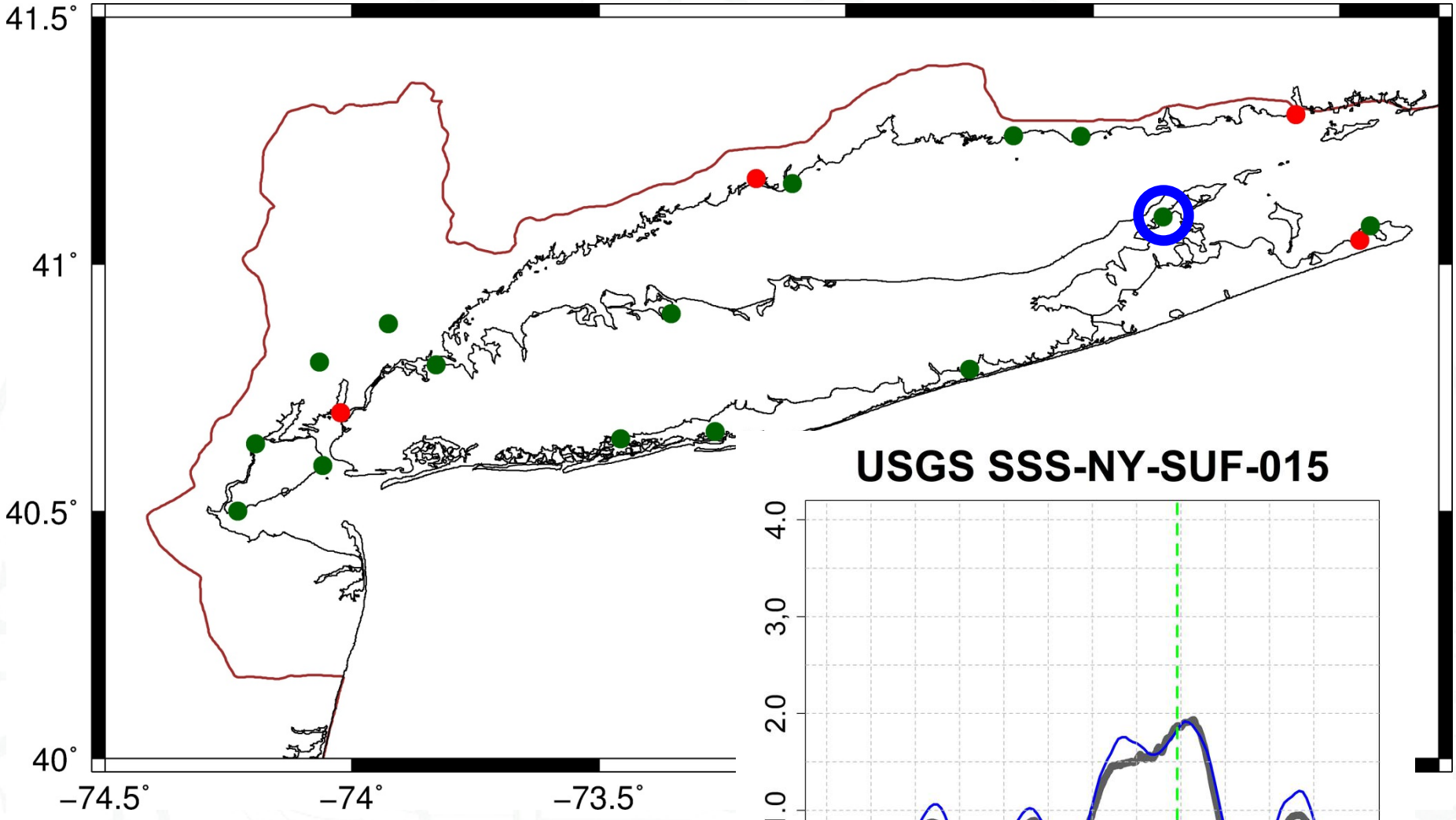
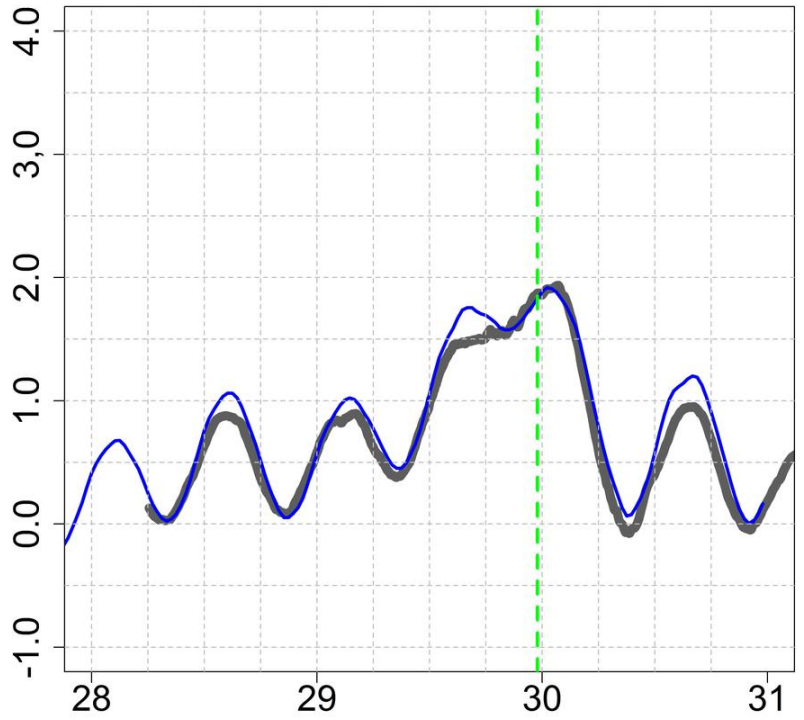
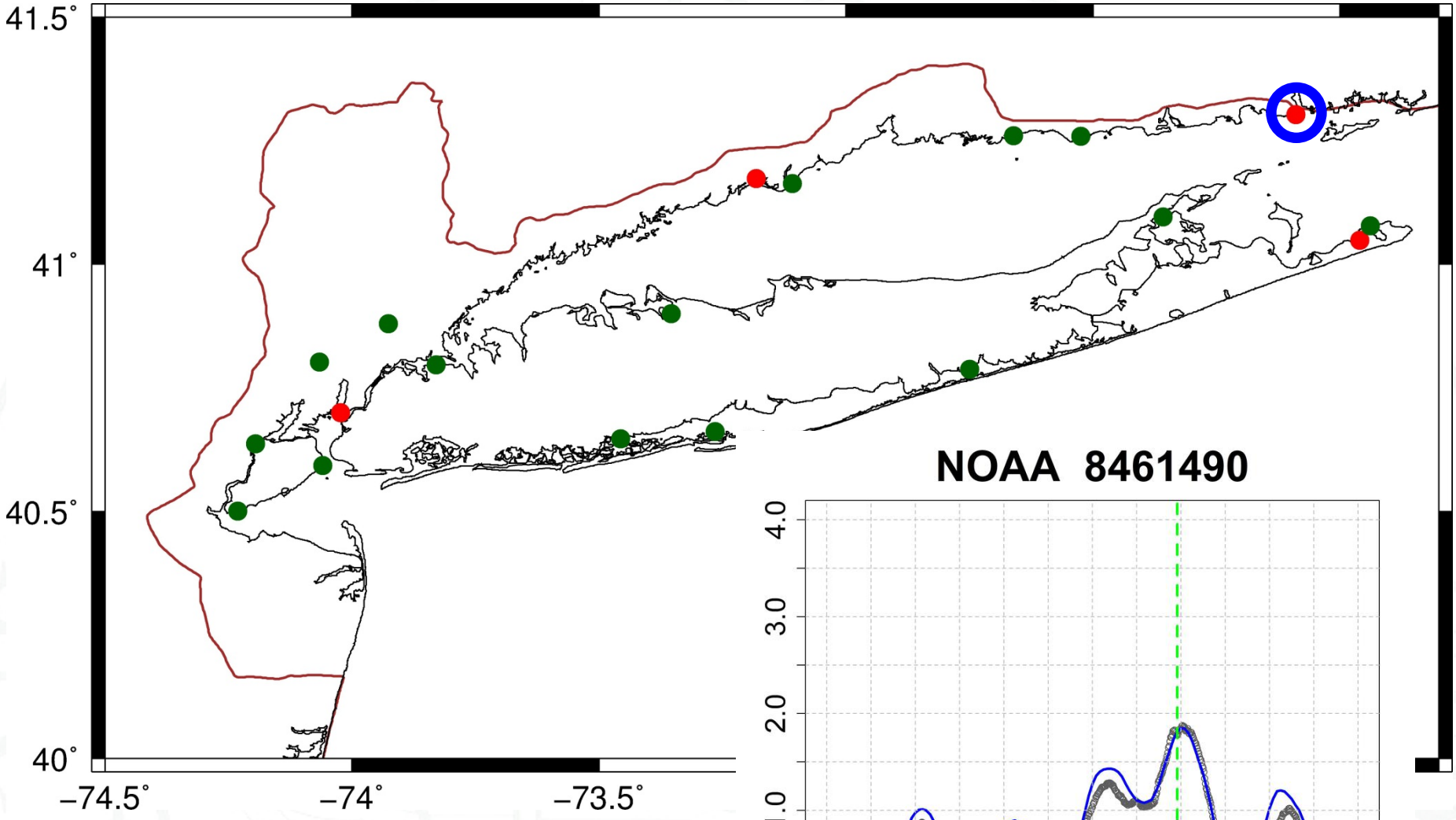


NOAA & USGS Water level comparisons

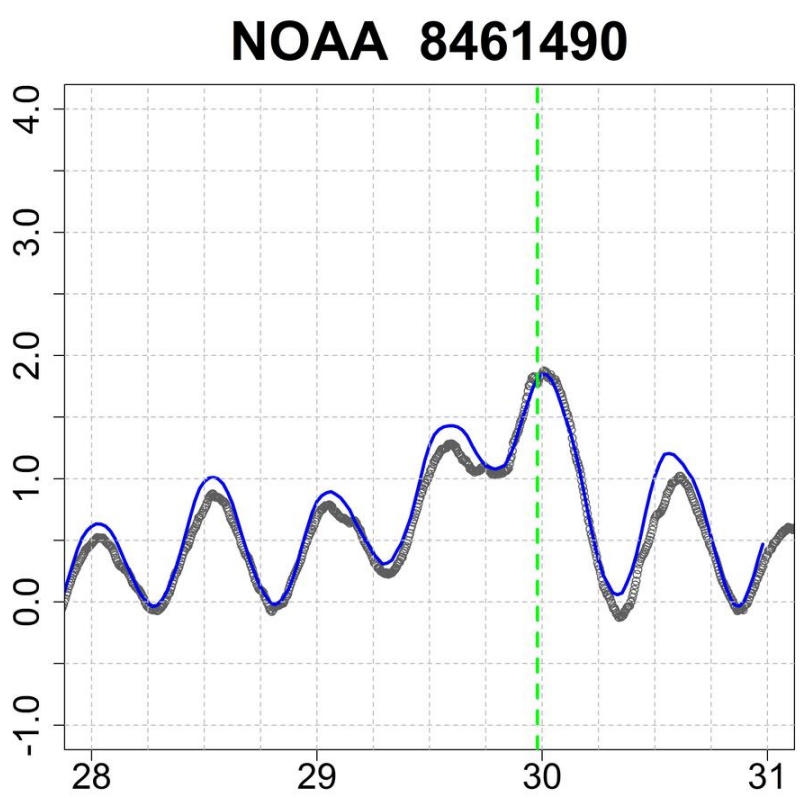


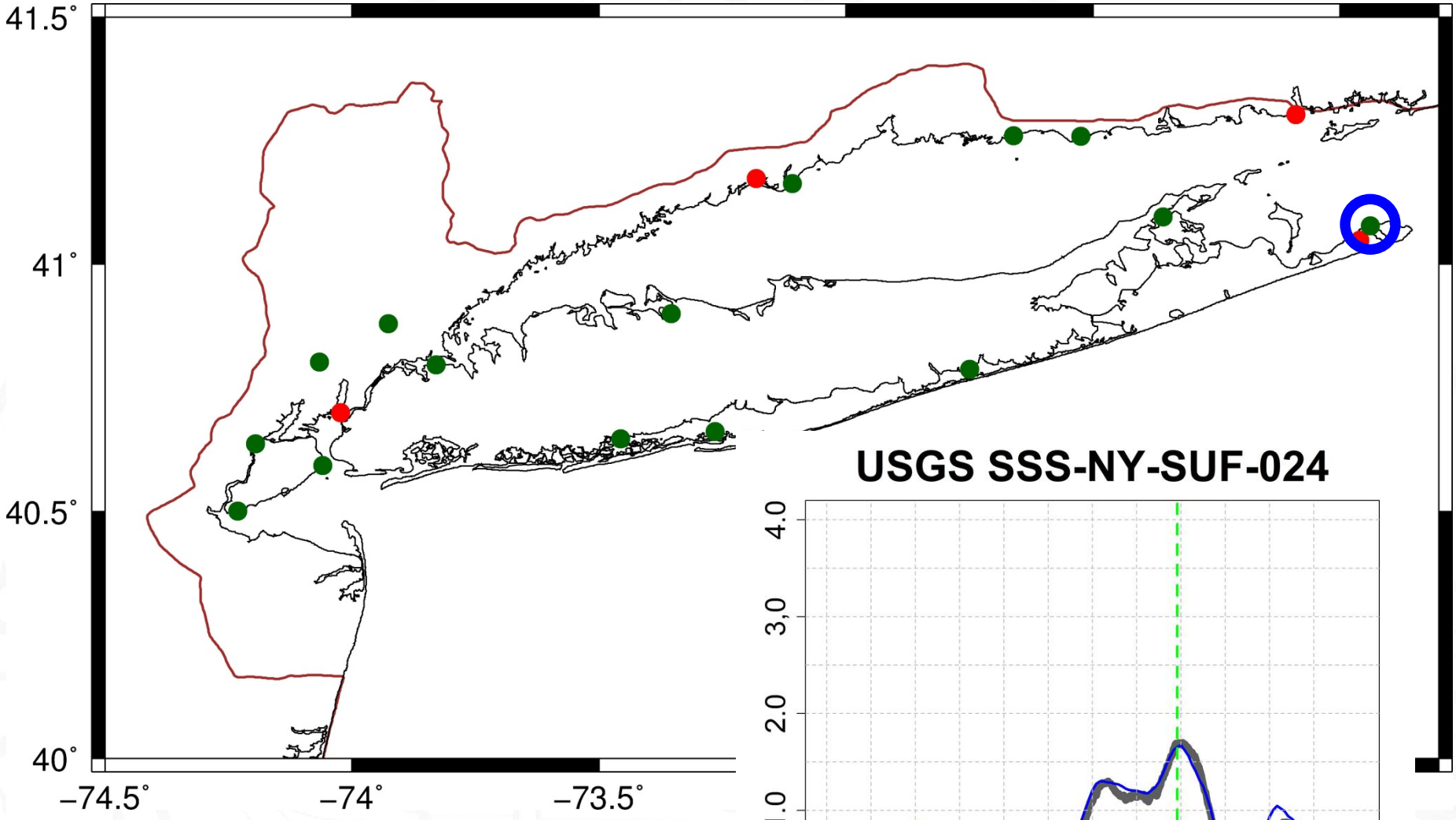
NOAA & USGS Water level comparisons

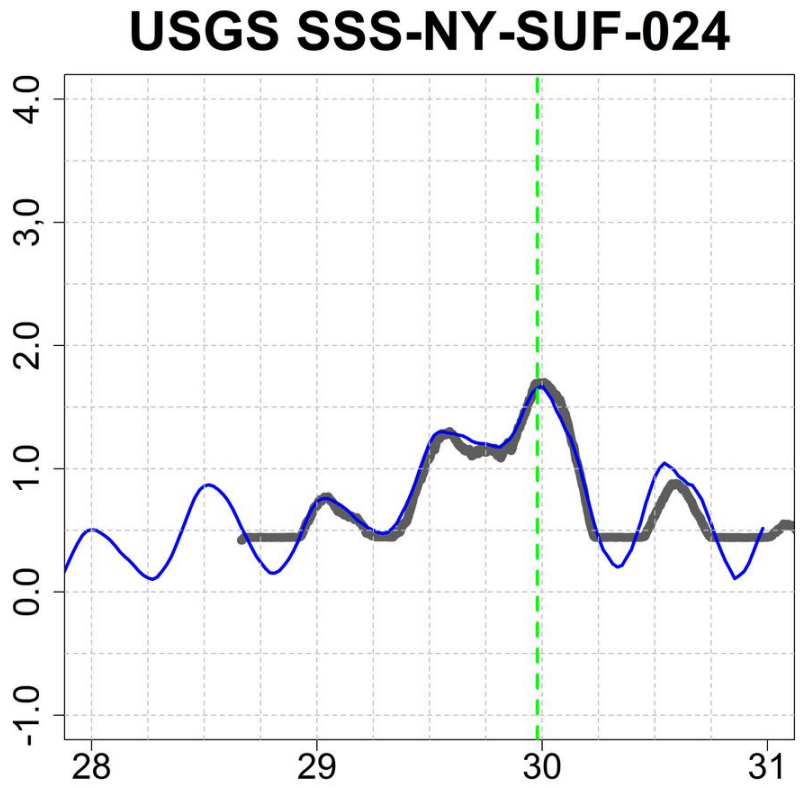




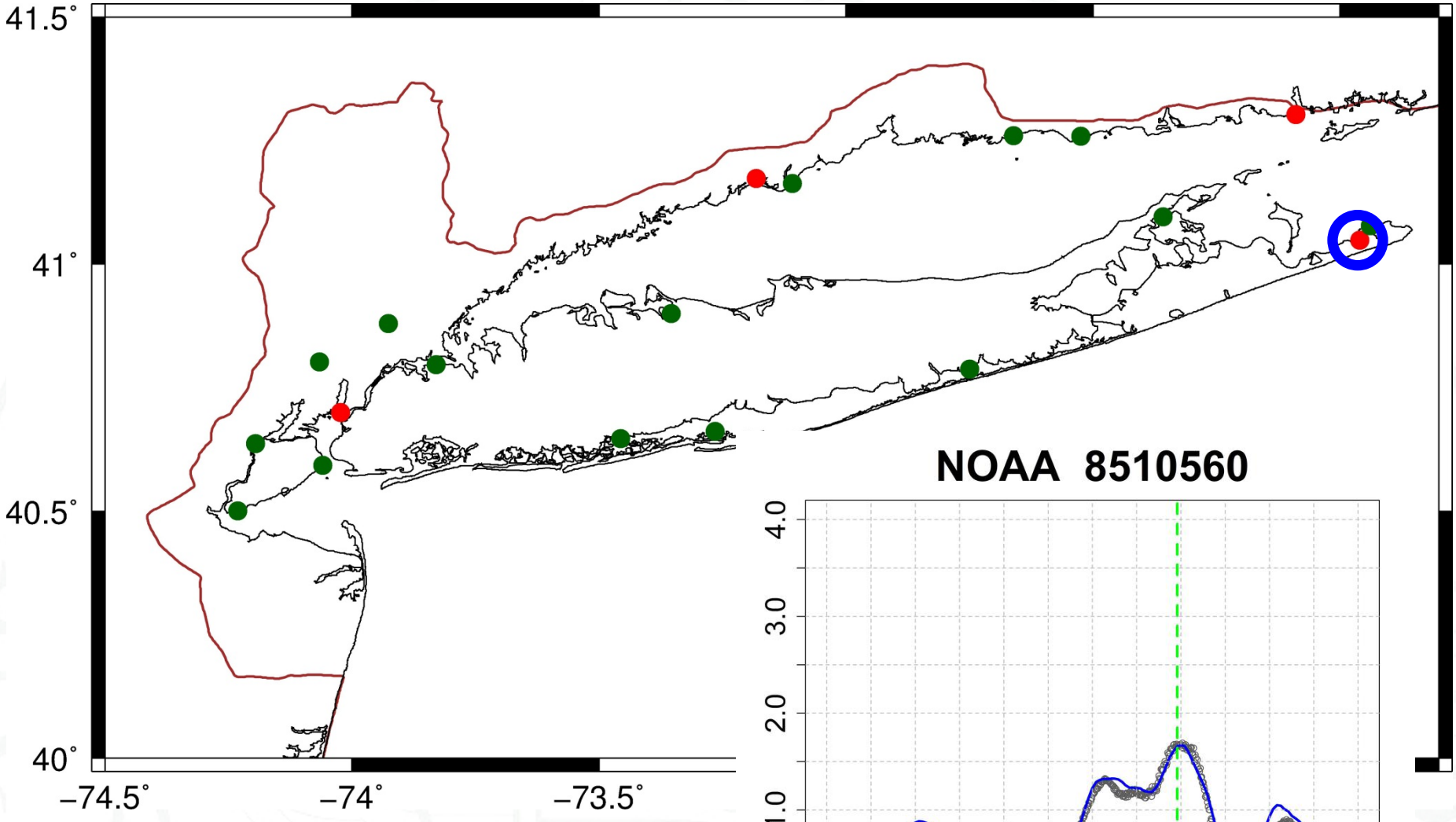
NOAA & USGS Water level comparisons

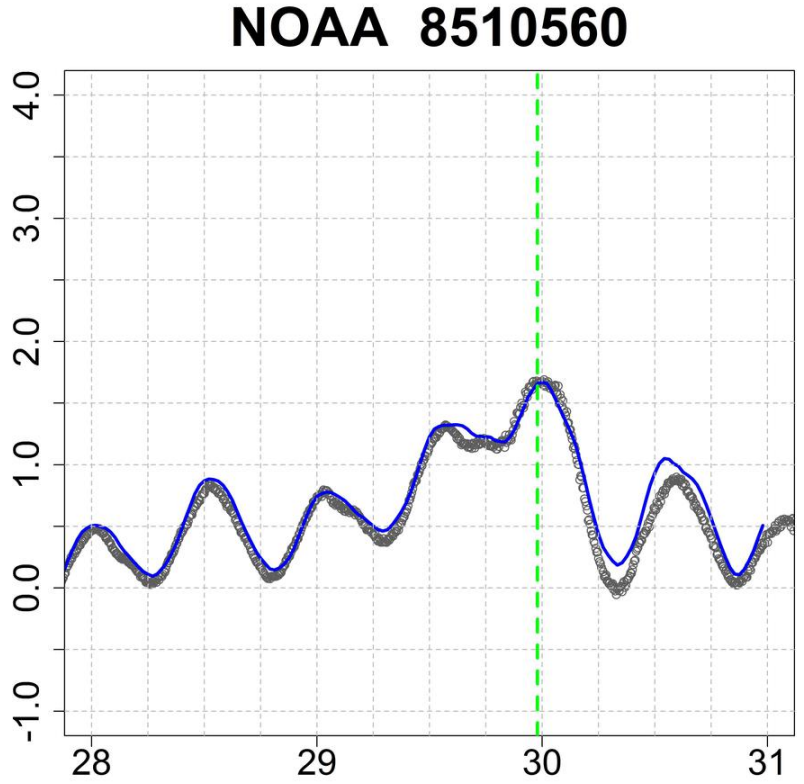




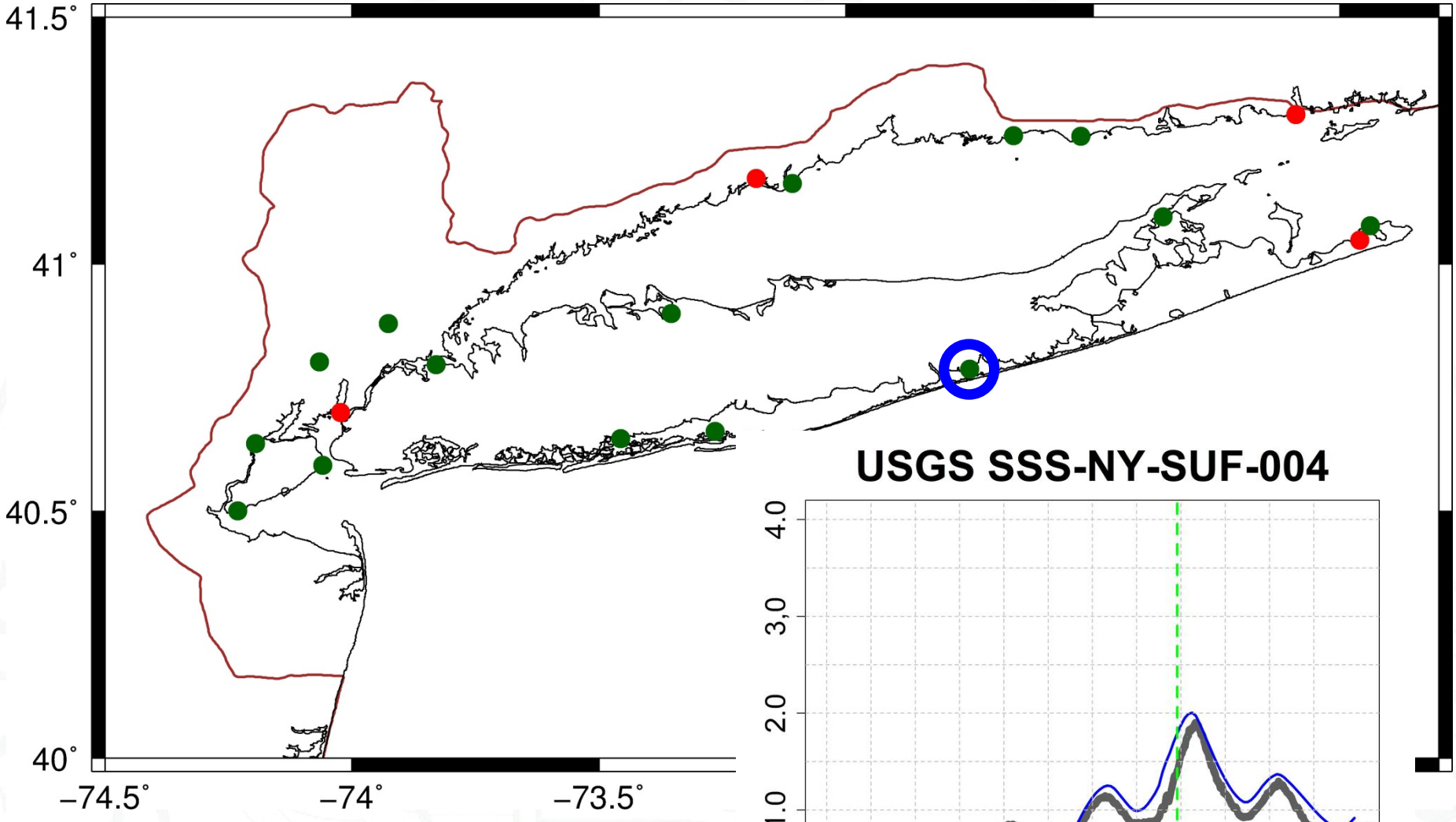


NOAA & USGS Water level comparisons

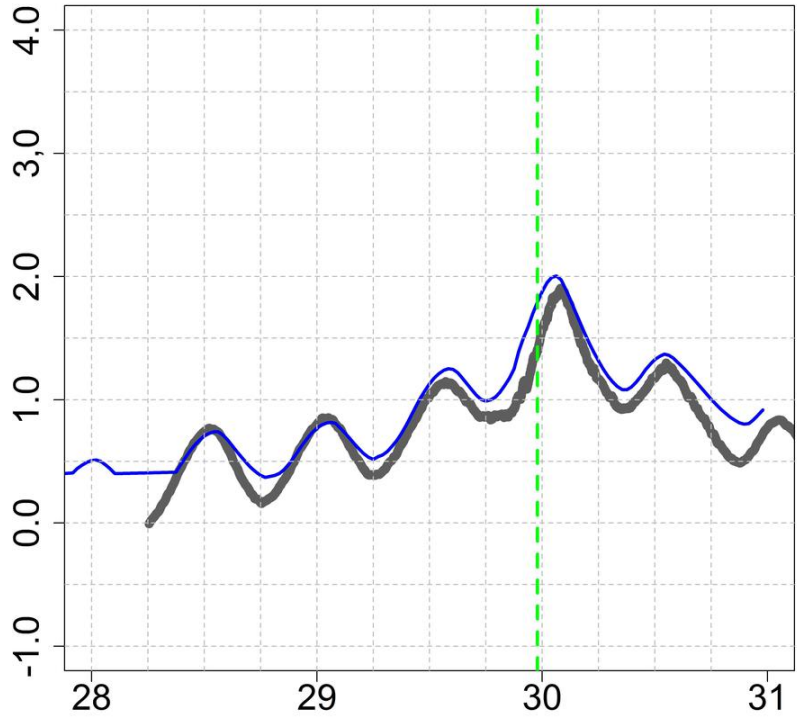




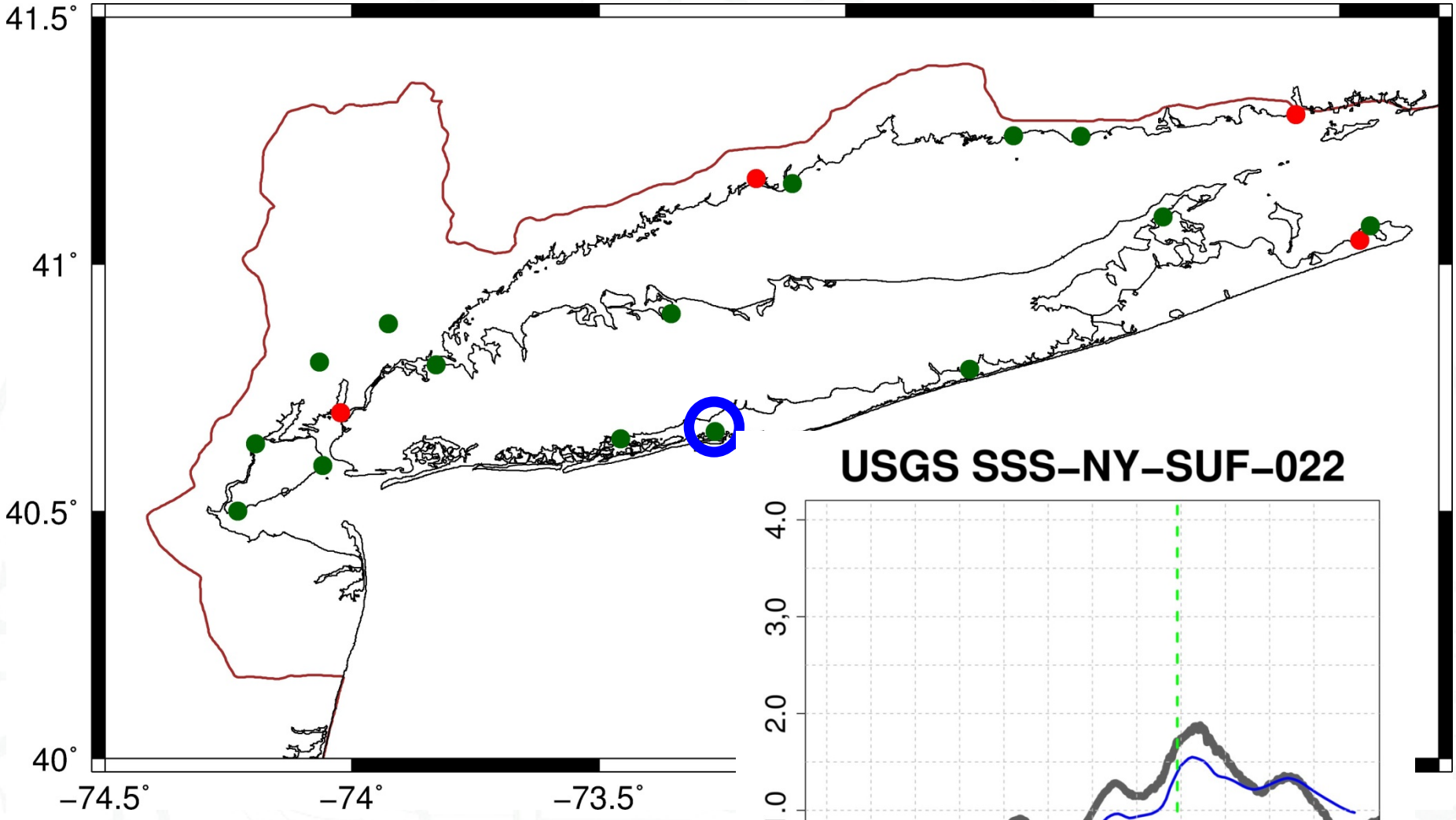
NOAA & USGS Water level comparisons

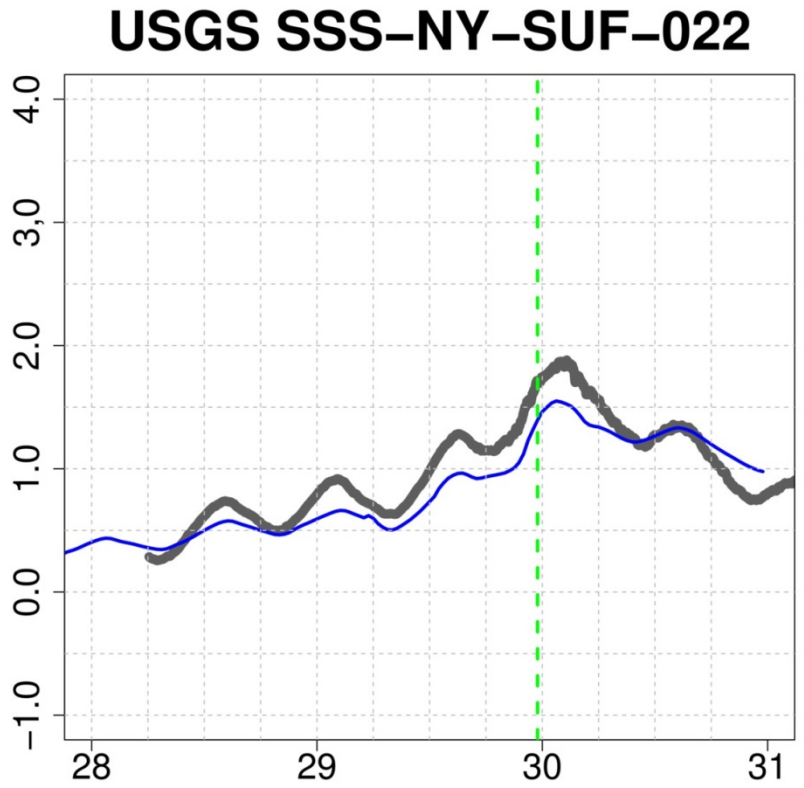


USGS SSS-NY-SUF-004

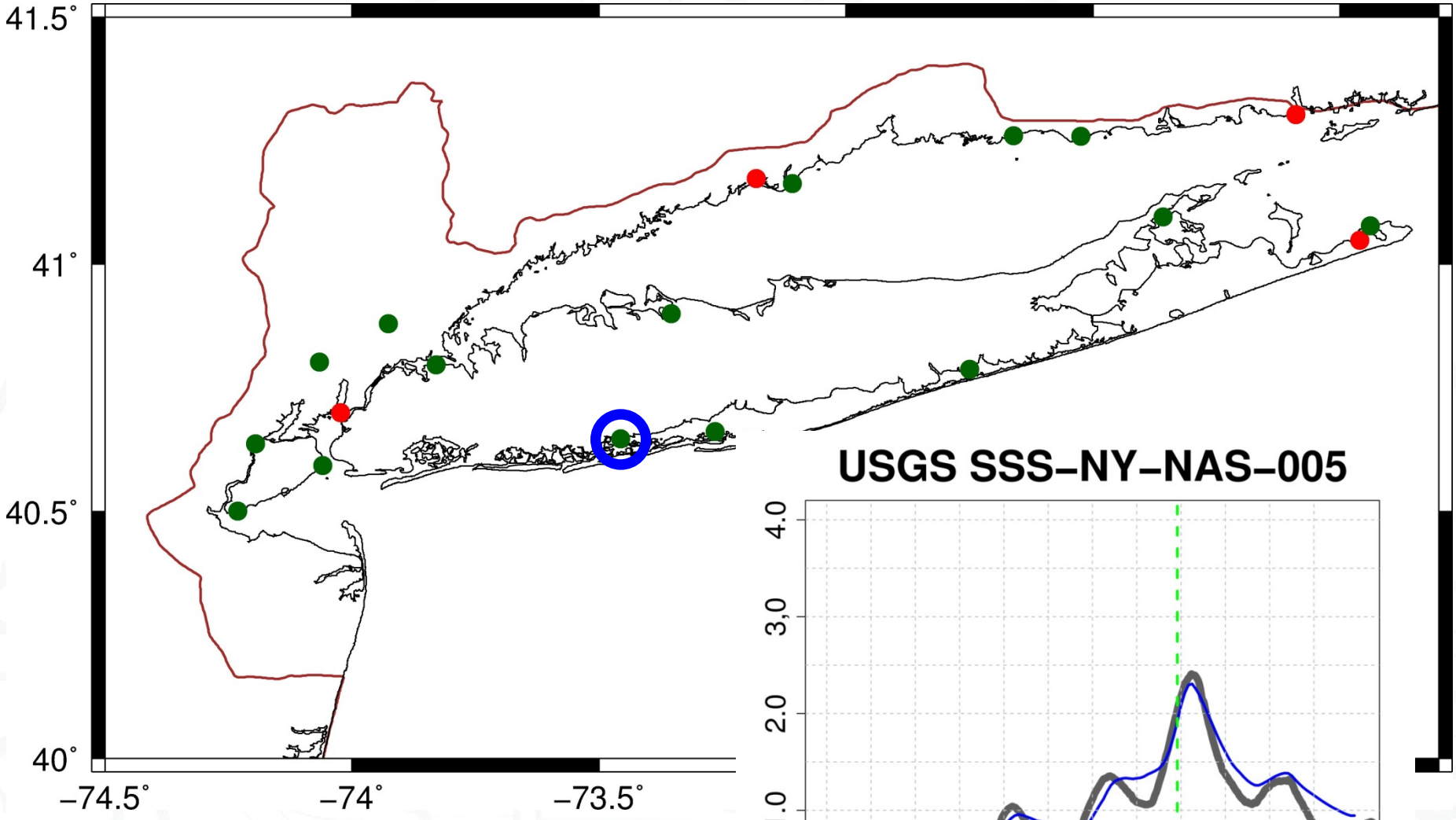


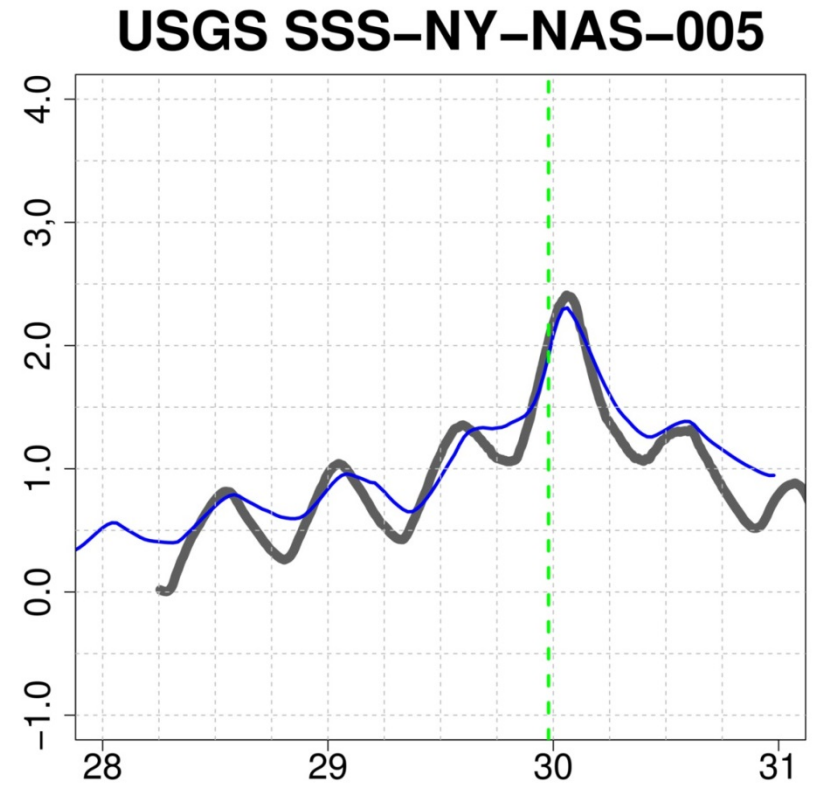
NOAA & USGS Water level comparisons





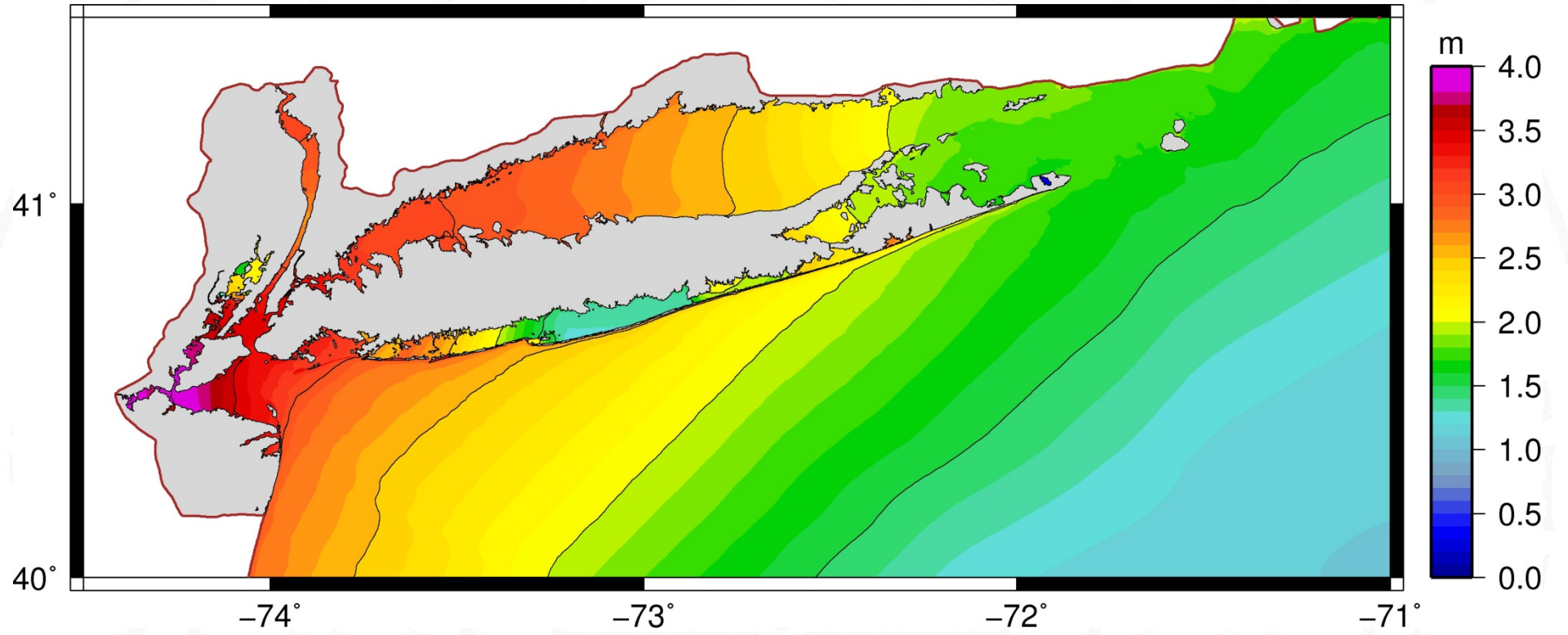
NOAA & USGS Water level comparisons



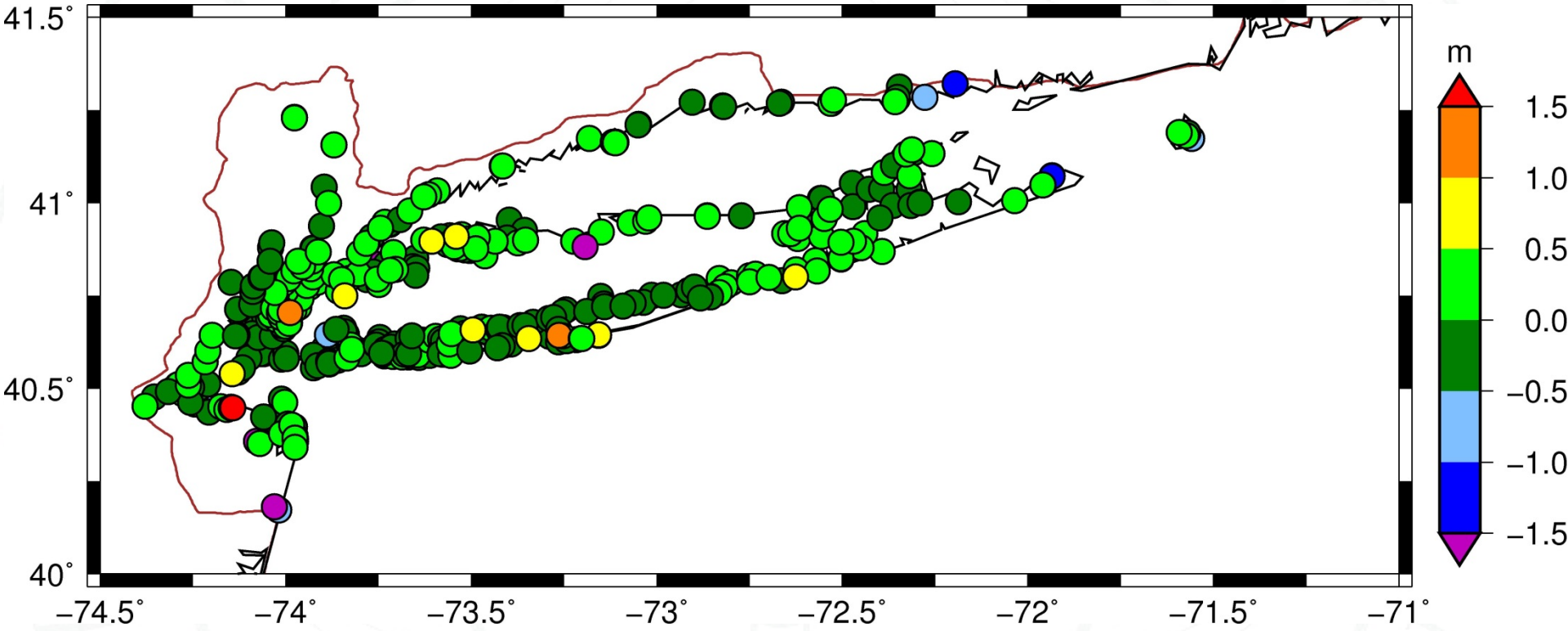


NOAA & USGS Water level comparisons

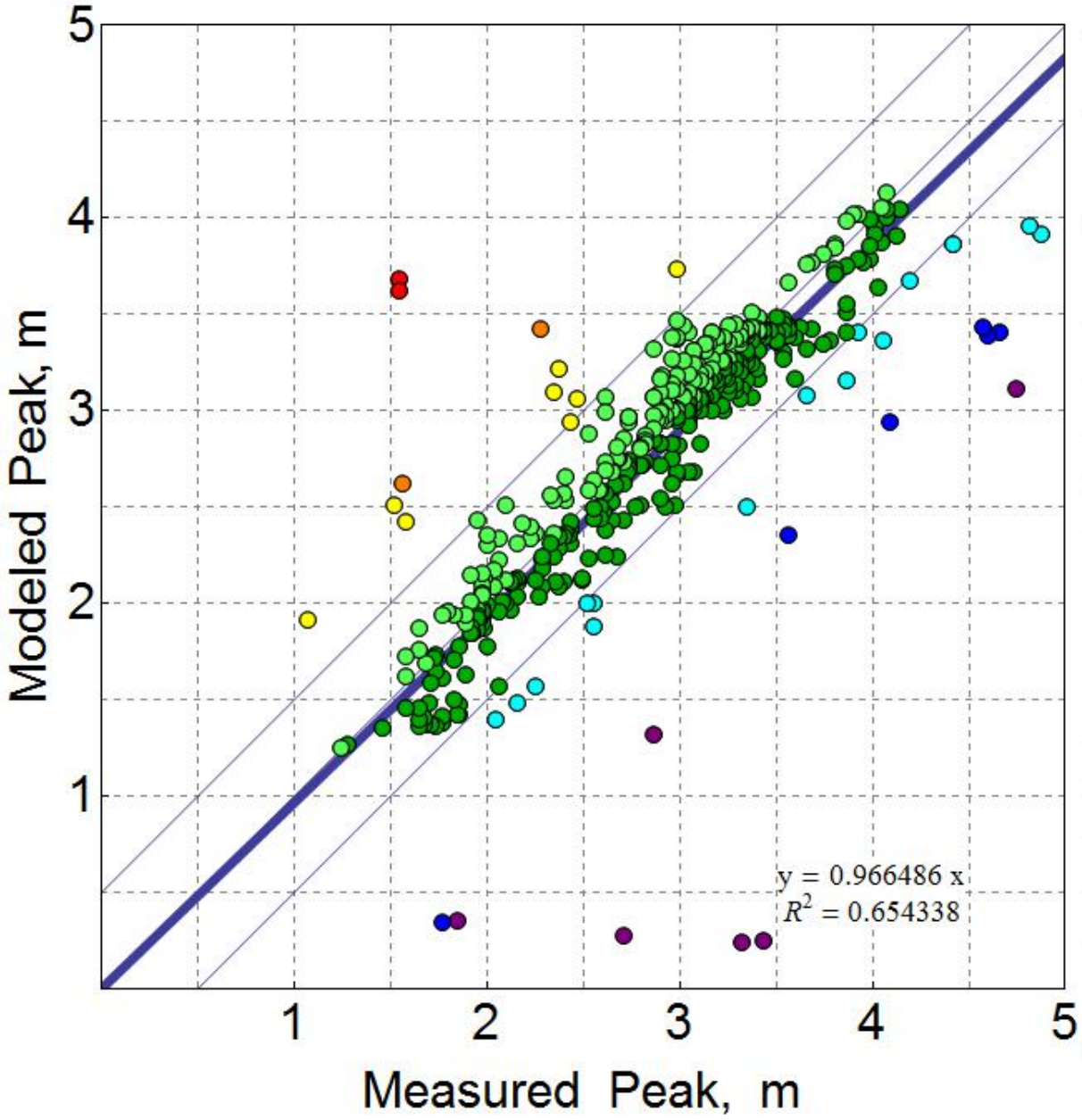
Sandy Maximum Water Surface Elevations



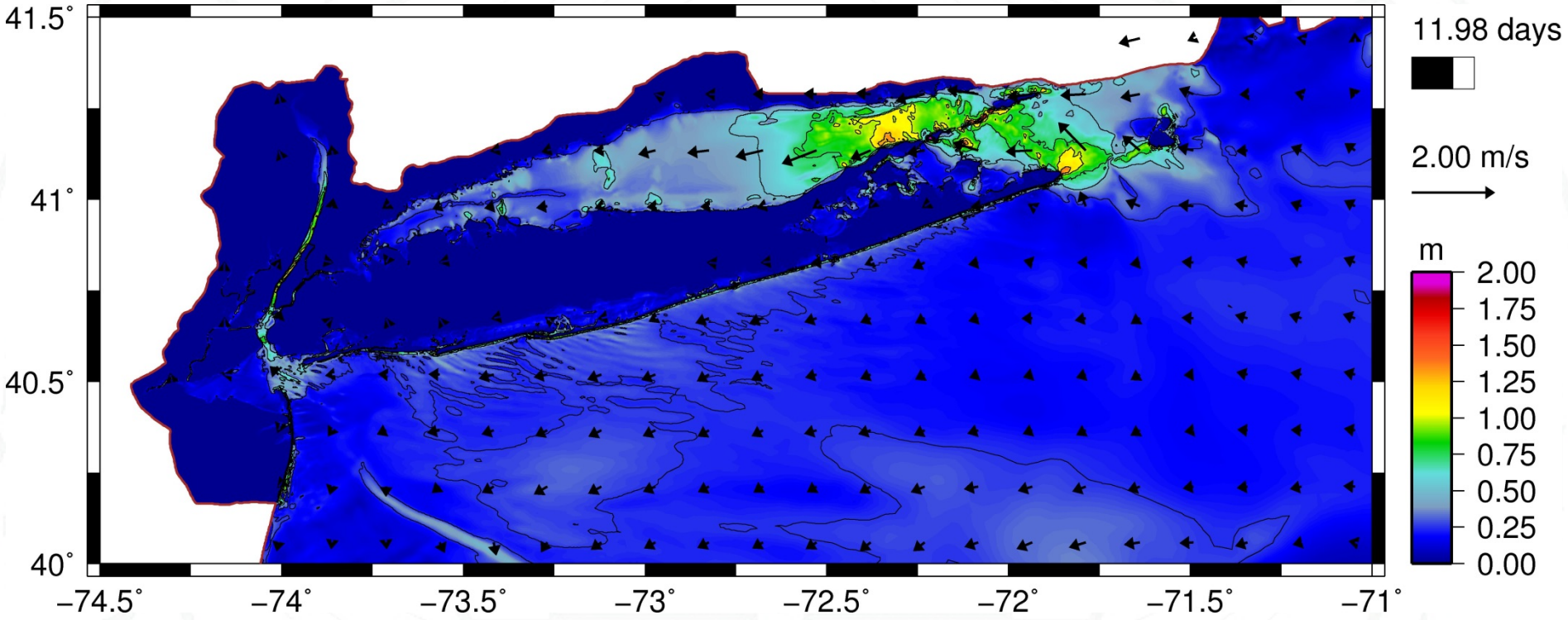
Sandy Computed minus Measured water surface elevation Differences



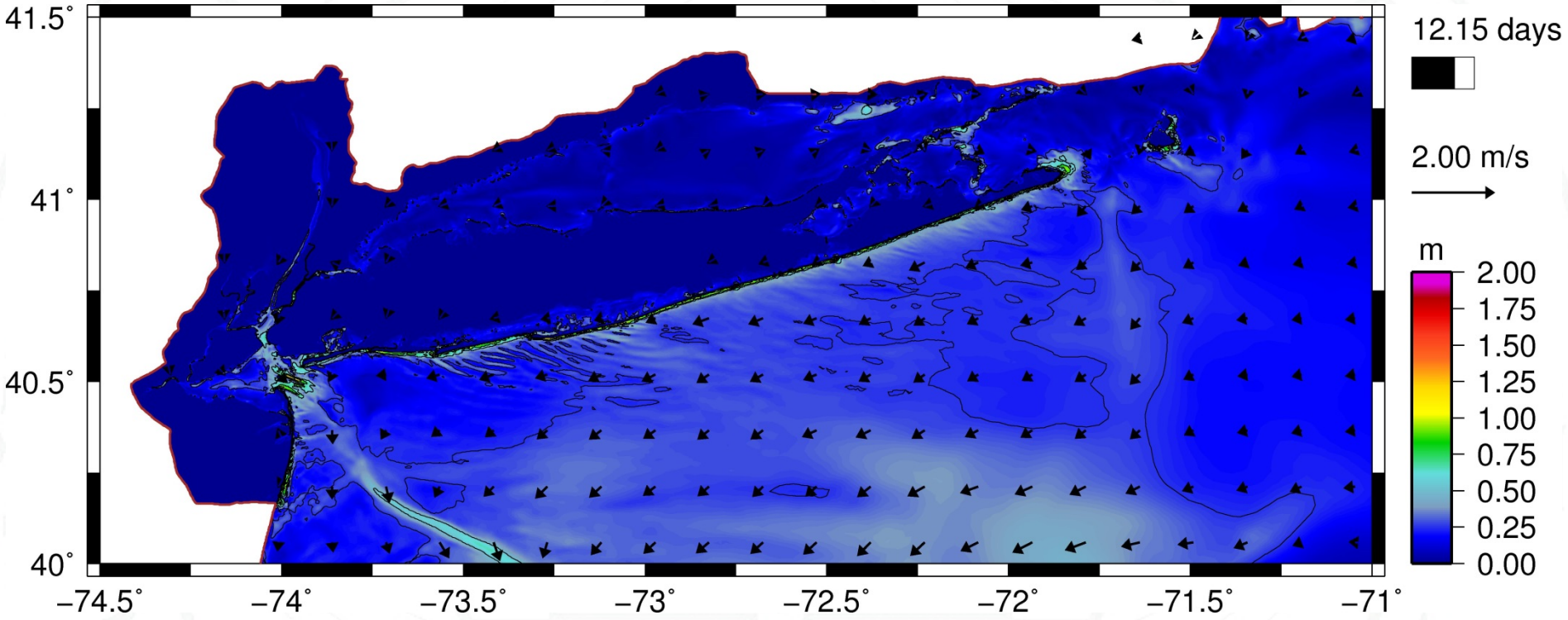
Sandy Computed Versus Measured water surface elevations



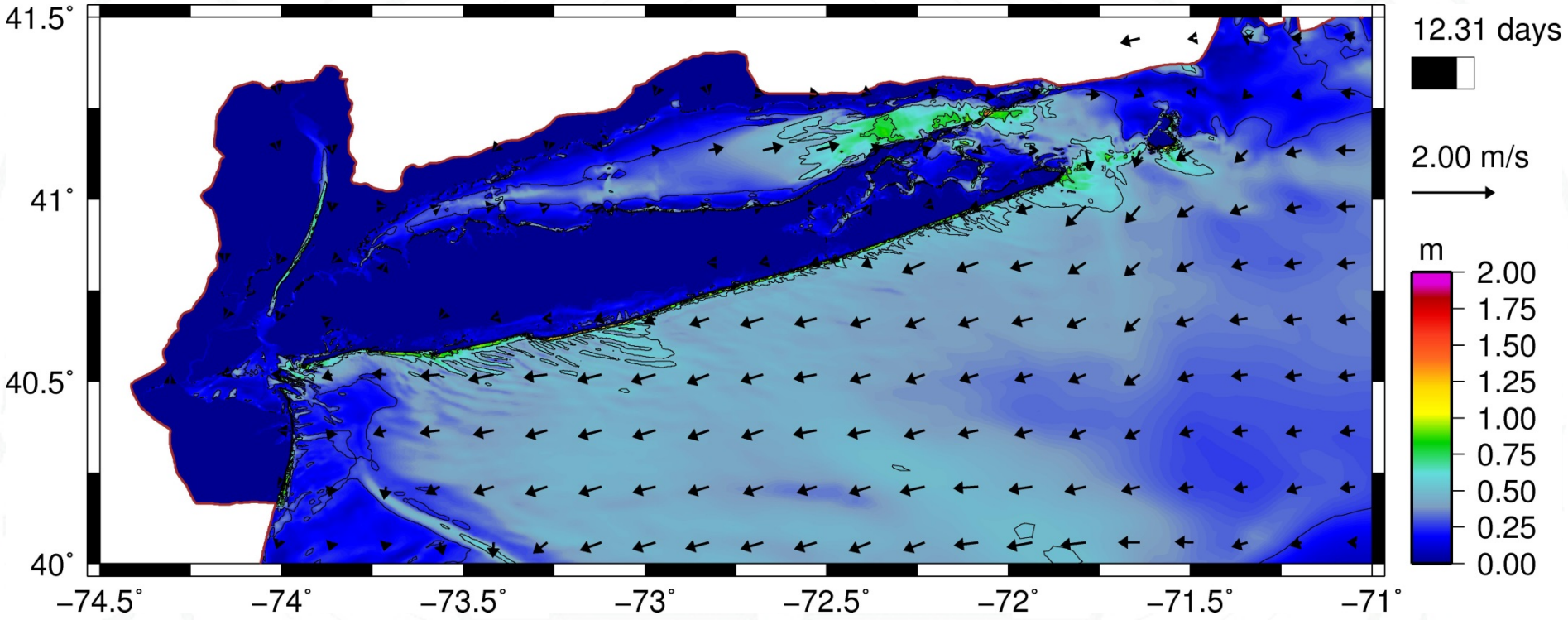
Currents -24 hrs



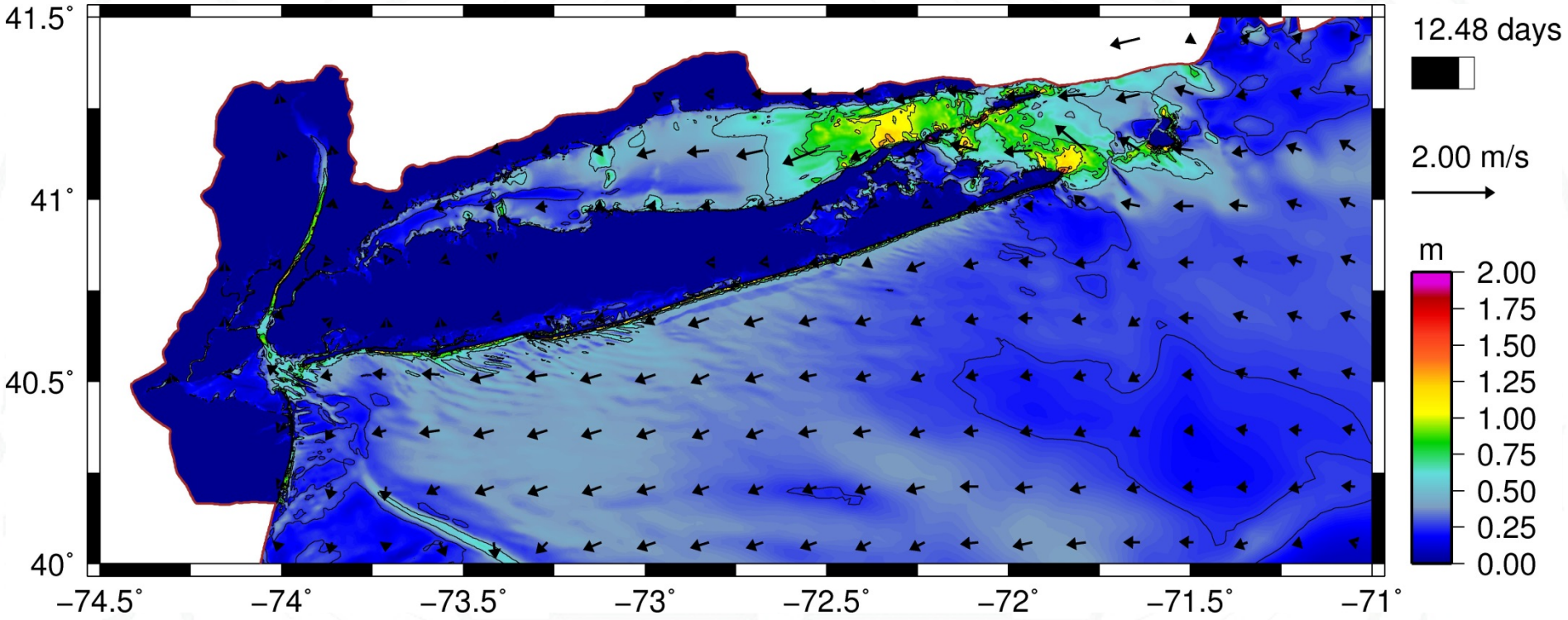
Currents -20 hrs



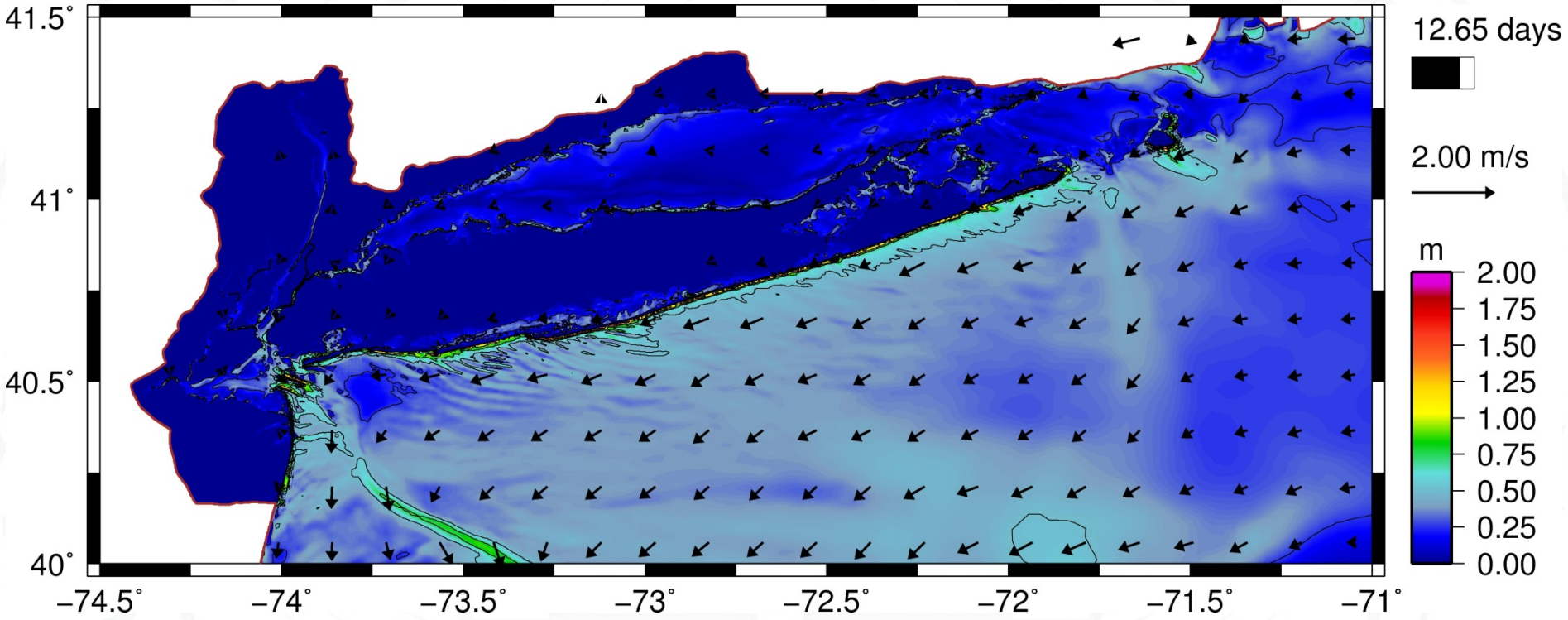
Currents -16 hrs



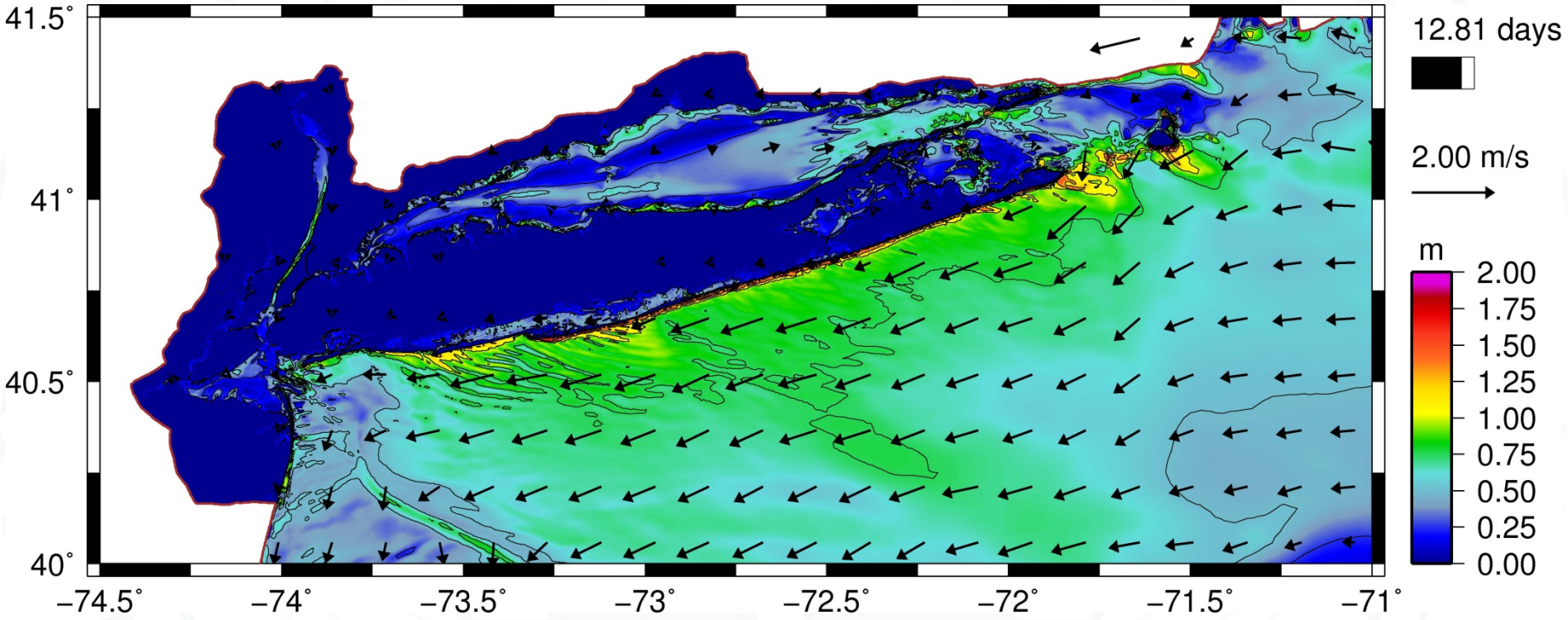
Currents -12 hrs



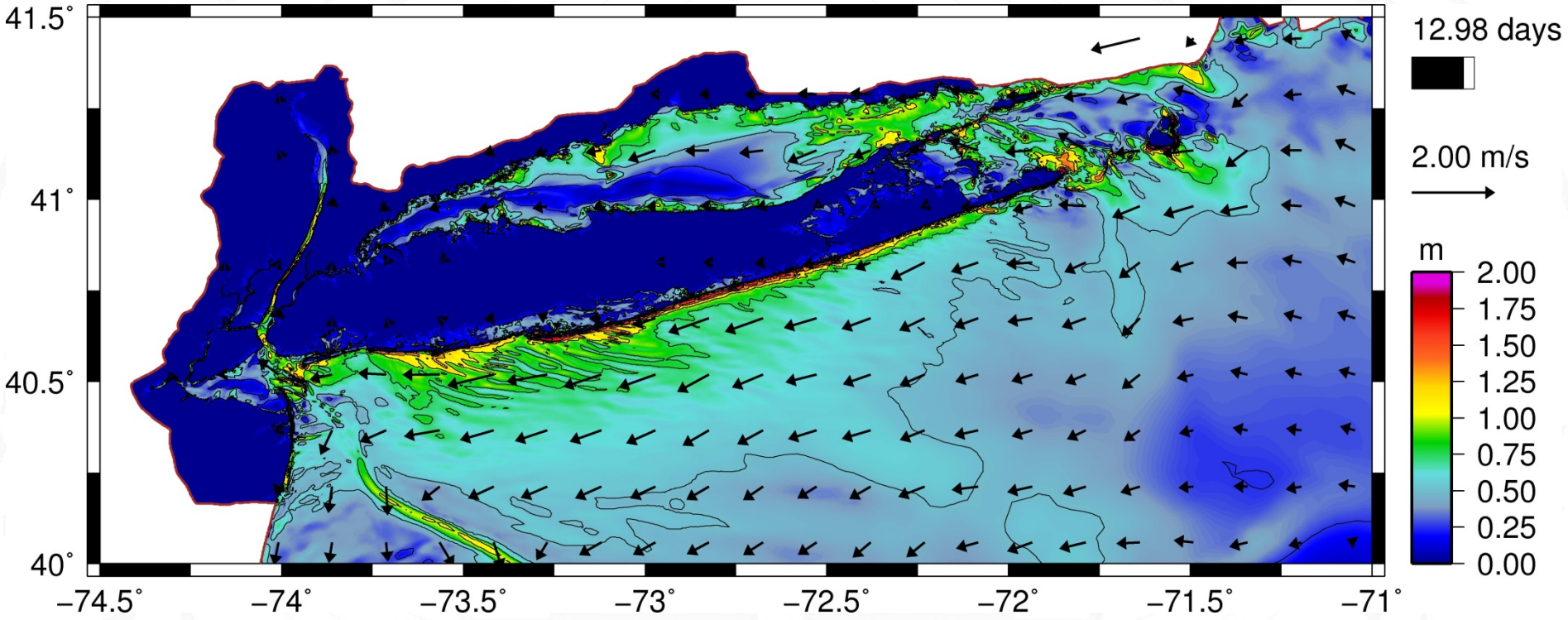
Currents -8 hrs



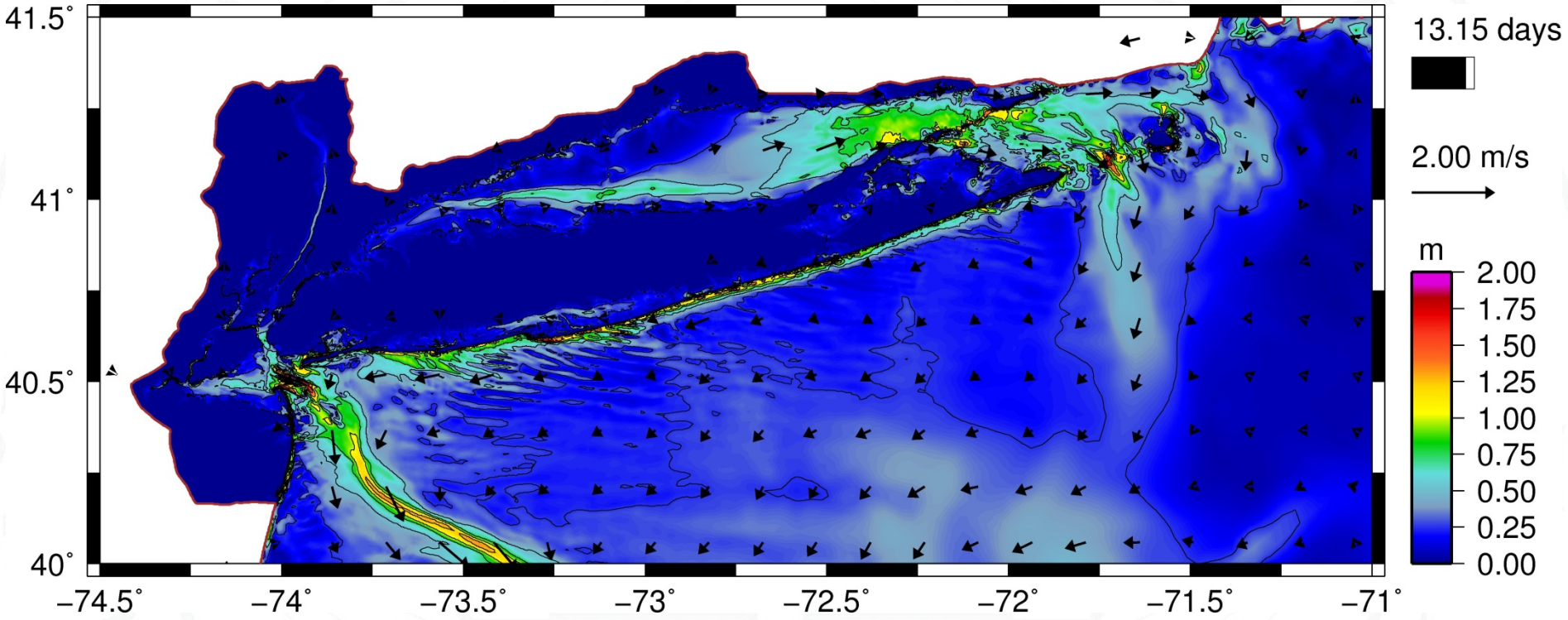
Currents -4 hrs



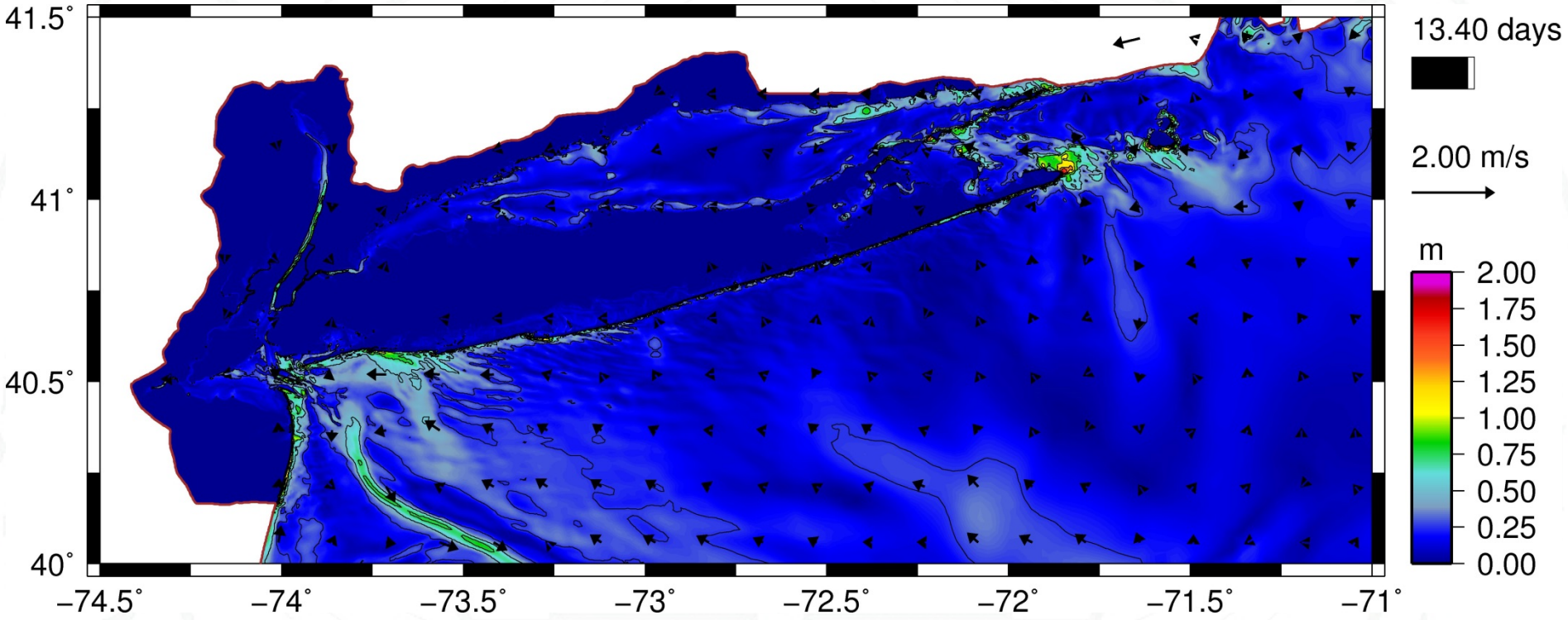
Currents 0 hrs LANDFALL



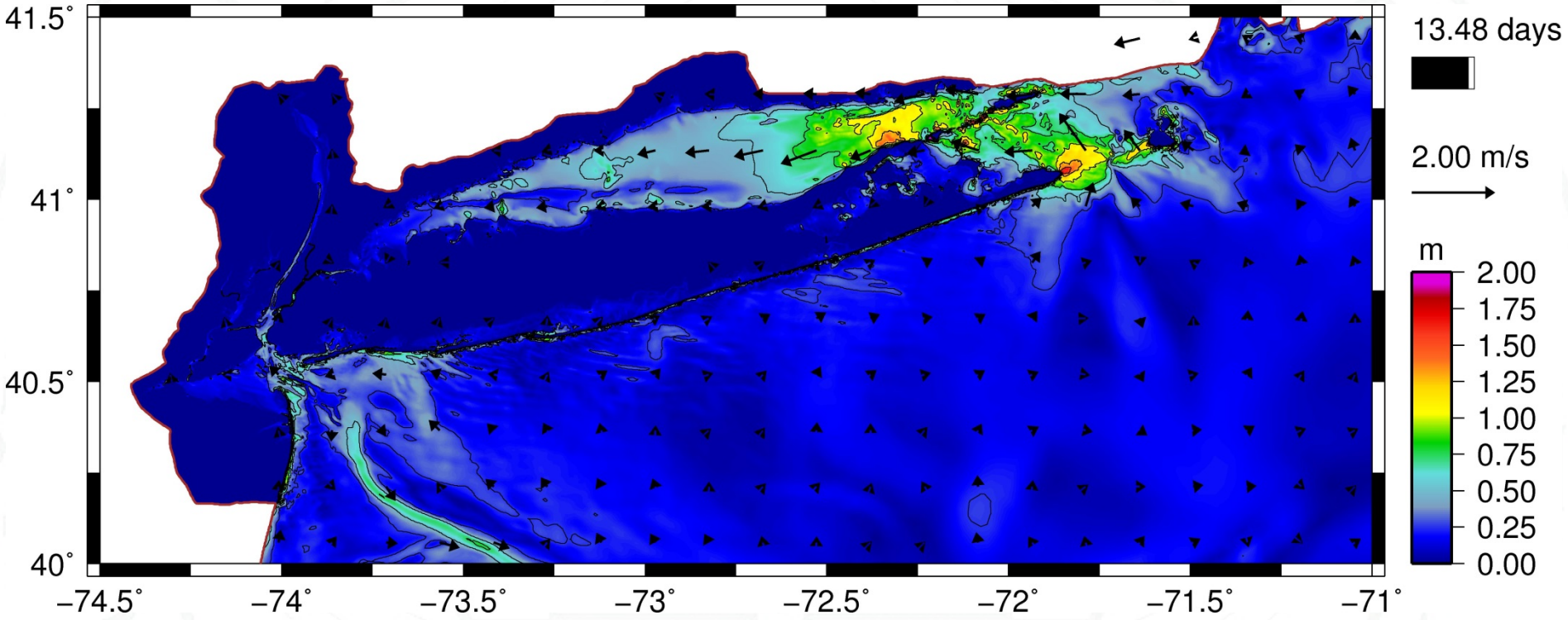
Currents +4 hrs



Currents +8 hrs



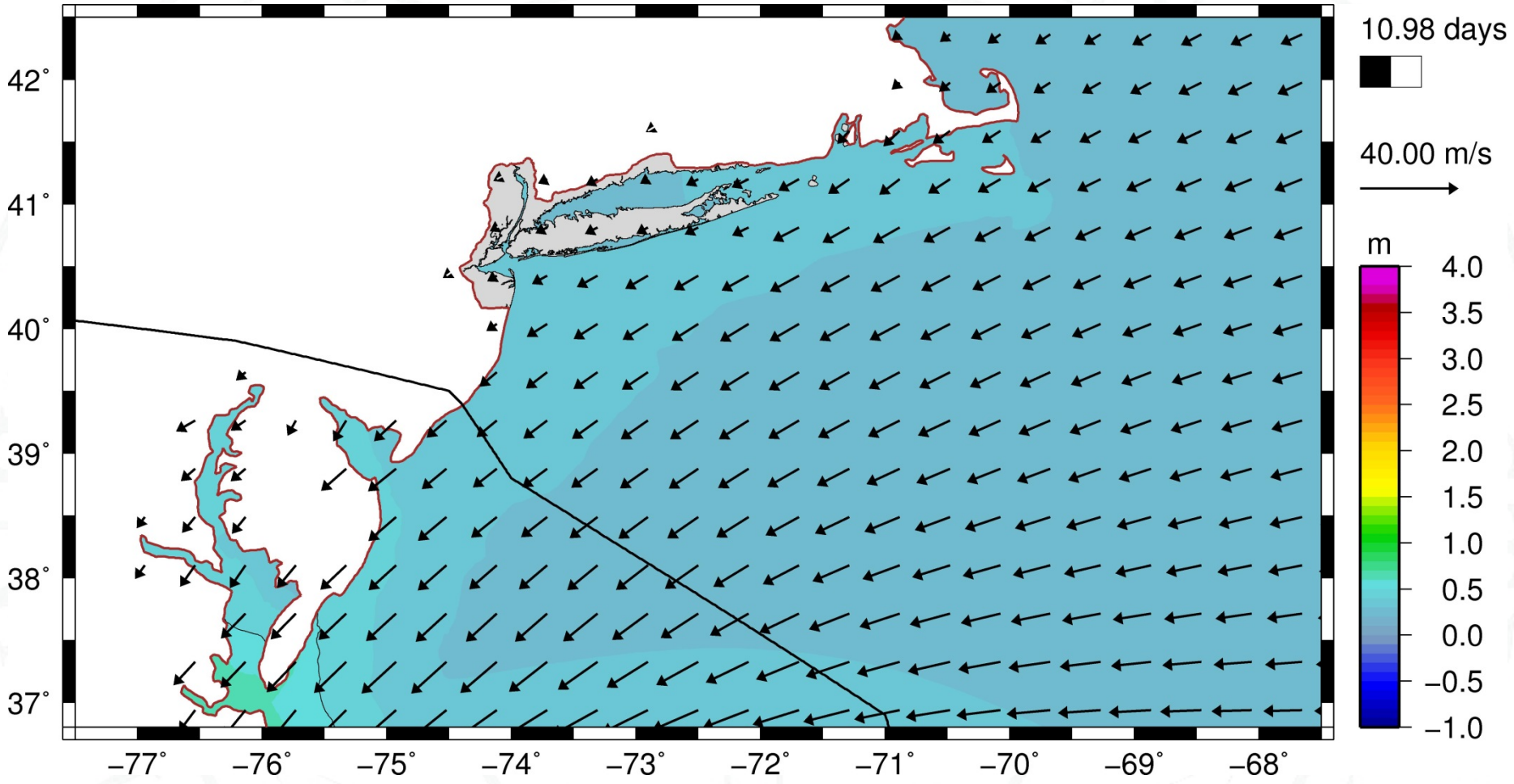
Currents +12 hrs



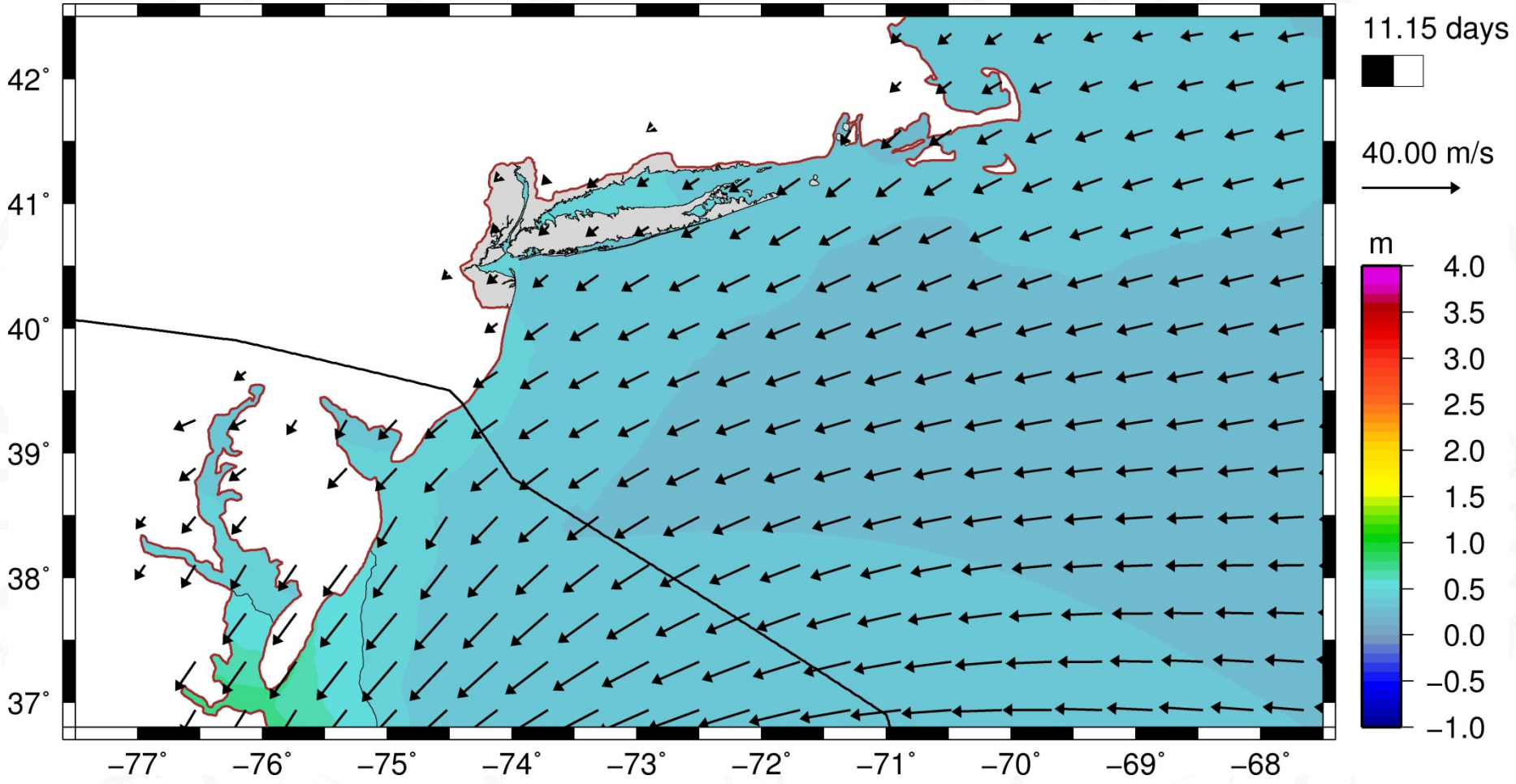
Analysis

- Sandy Hindcast, Validation and Analysis
  - Winds, Waves, Surge, Shelf velocities
  - Validation
  - Geostrophic setup
  - Long Island Sound resonance
  - Wave effects
  - Tidal nonlinearities
  - Effect of storm speed and abrupt wind ending

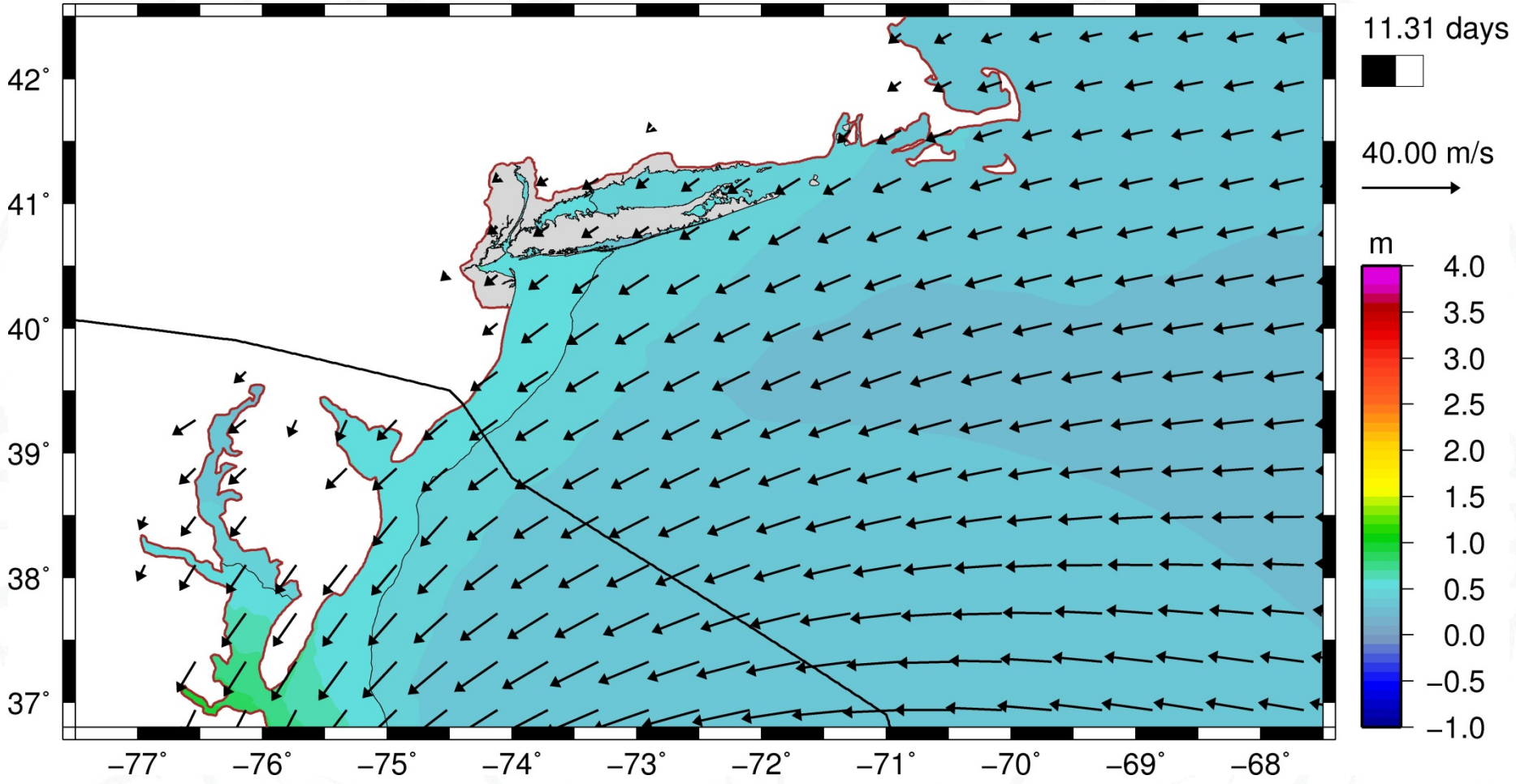
WSE No tides -48 hrs



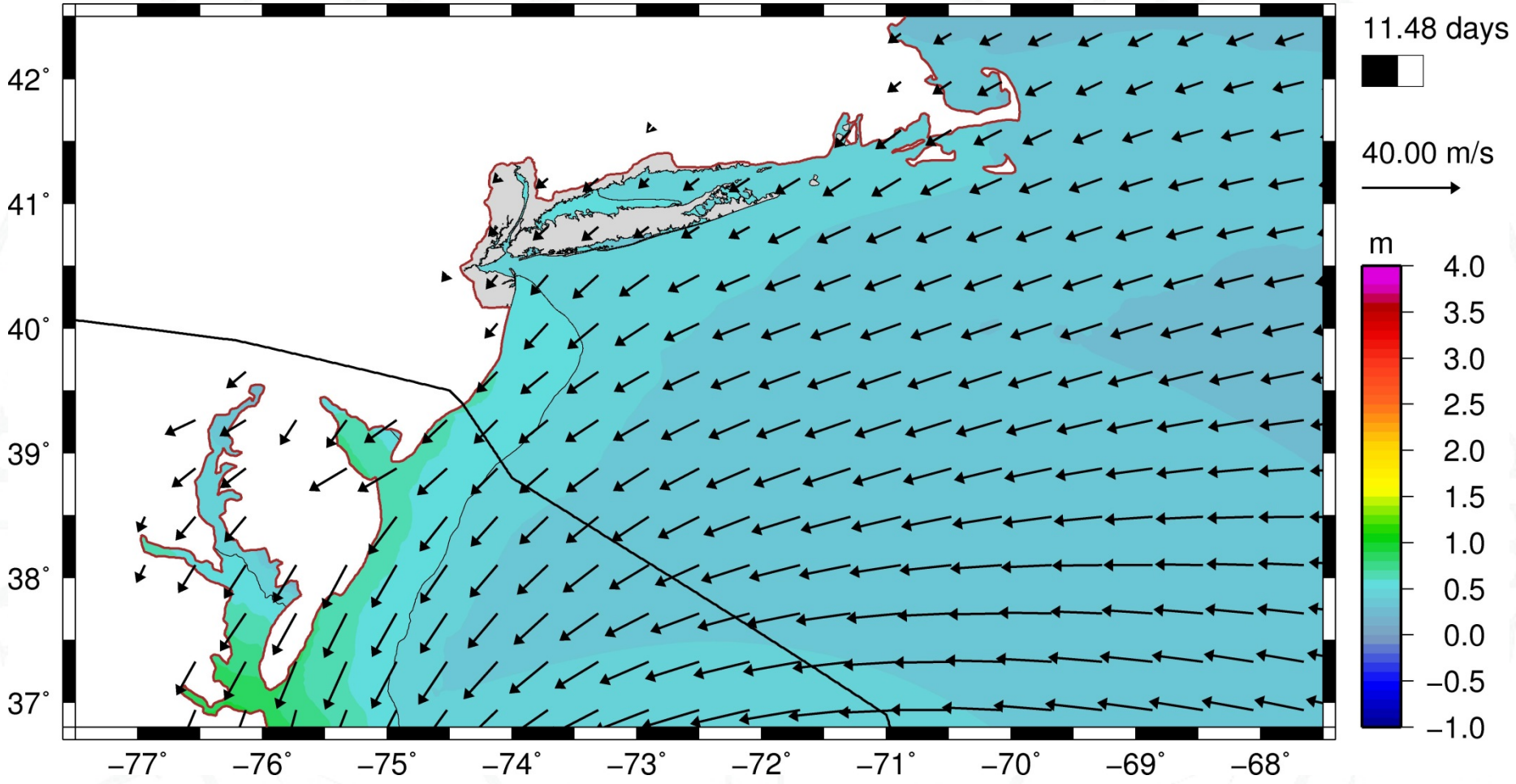
WSE No tides -44 hrs



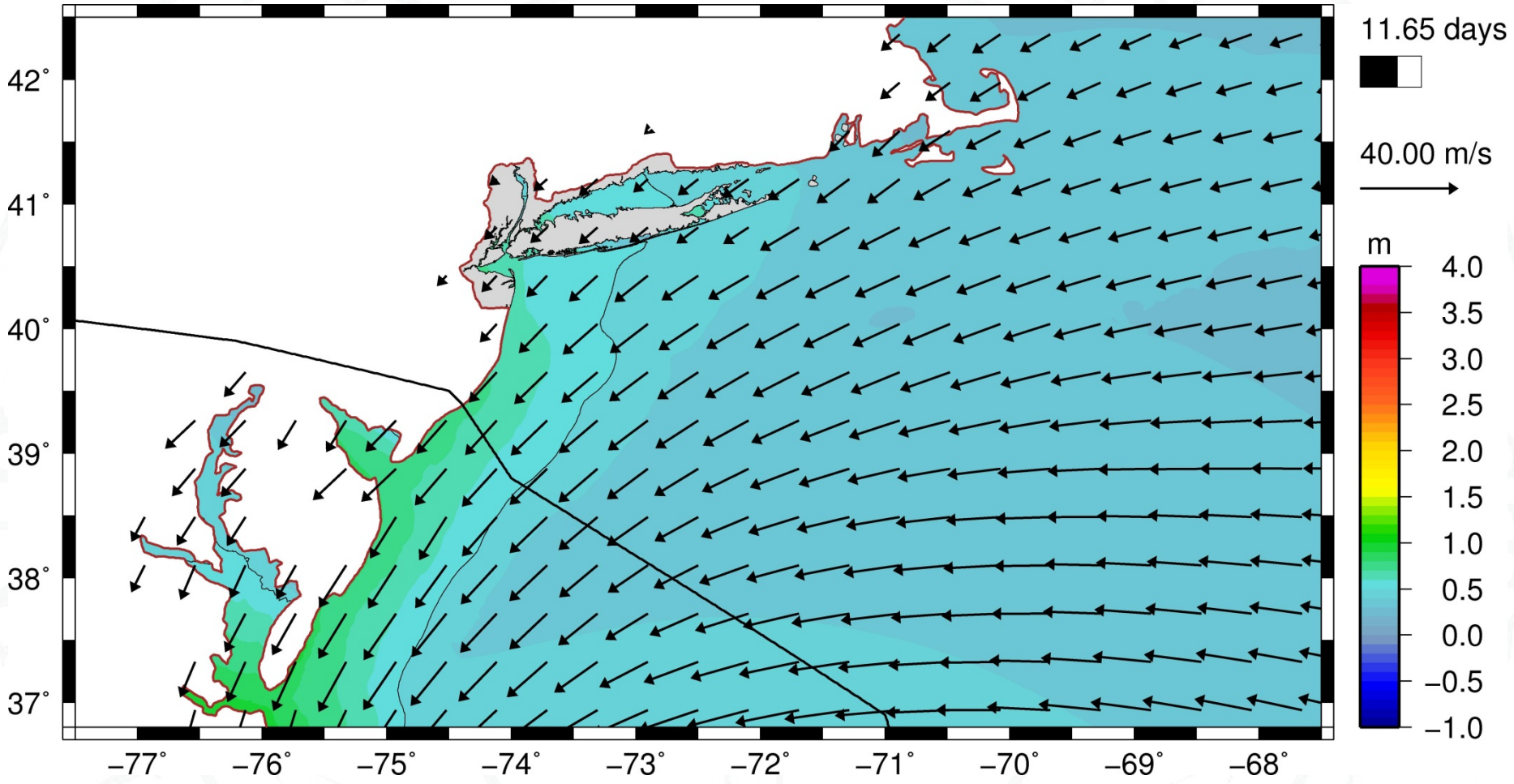
WSE No tides -40 hrs



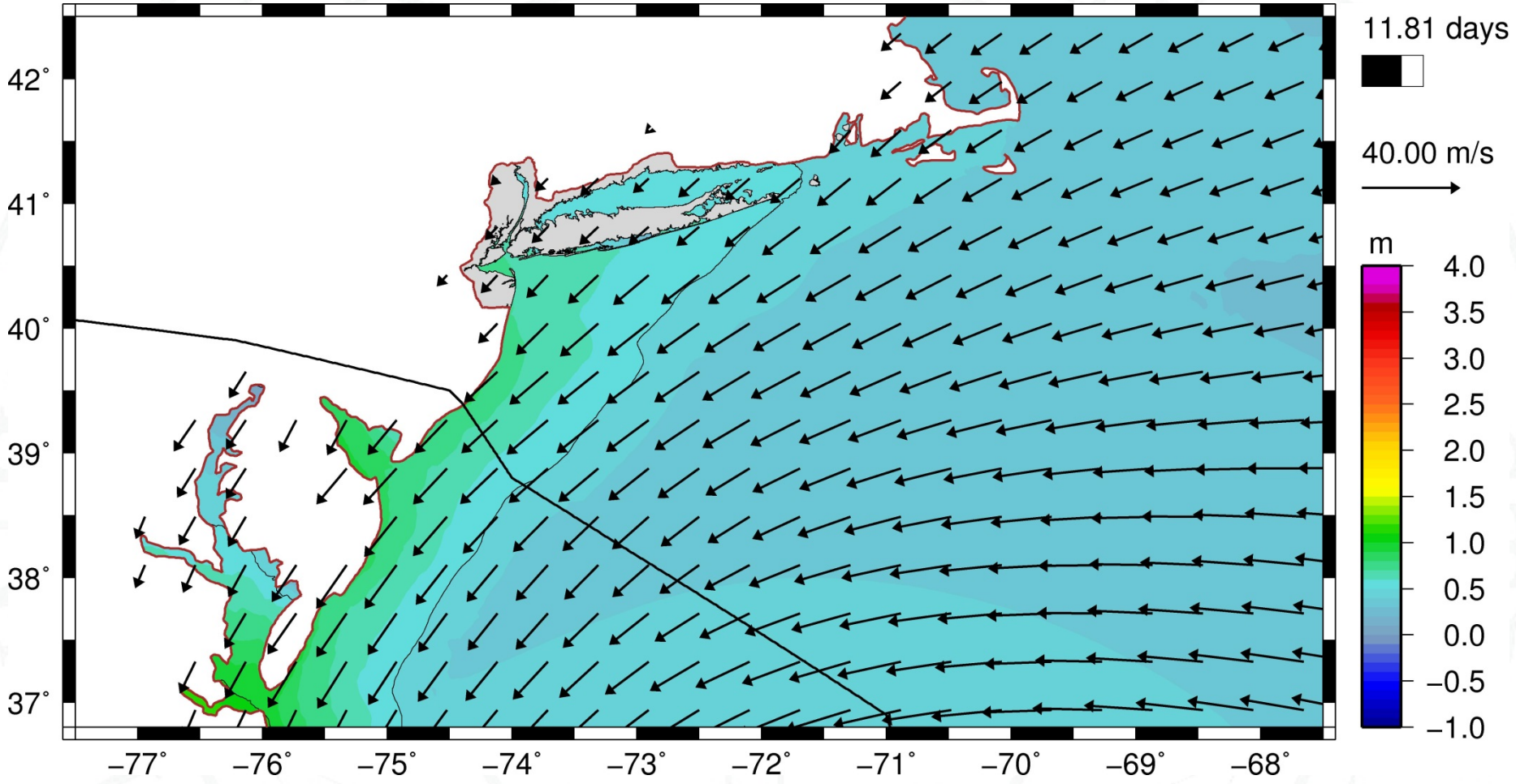
WSE No tides -36 hrs



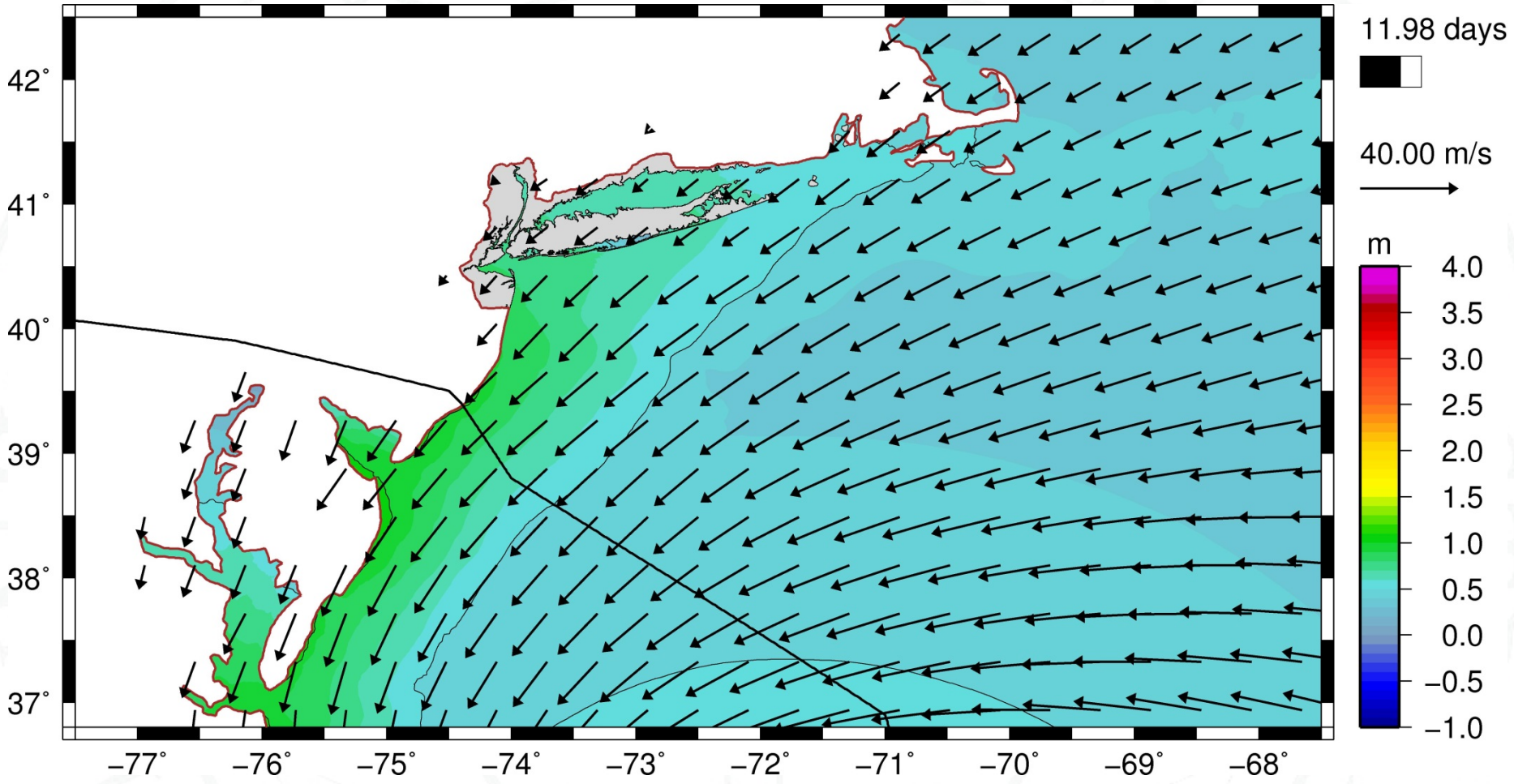
WSE No tides -32 hrs



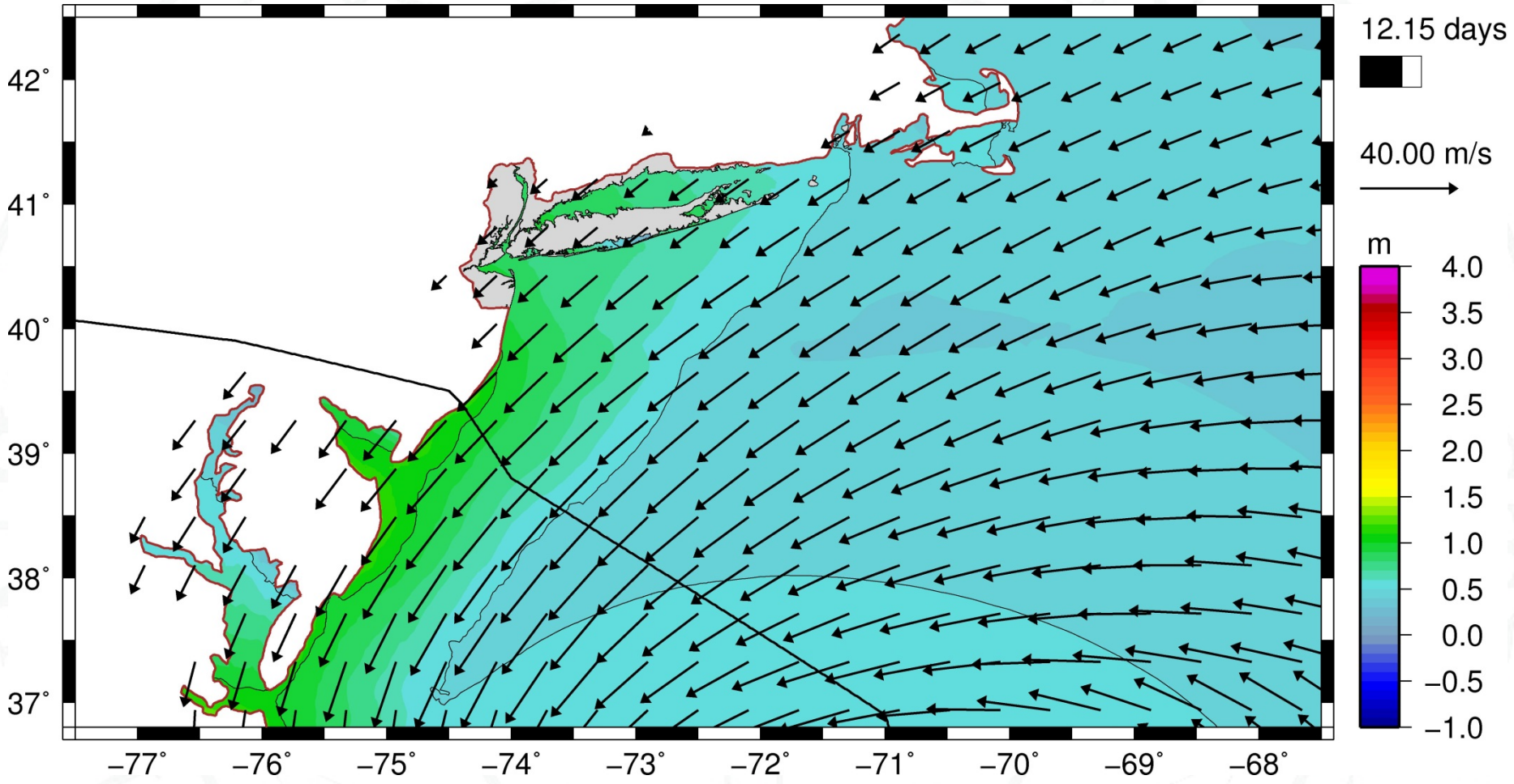
WSE No tides -28 hrs



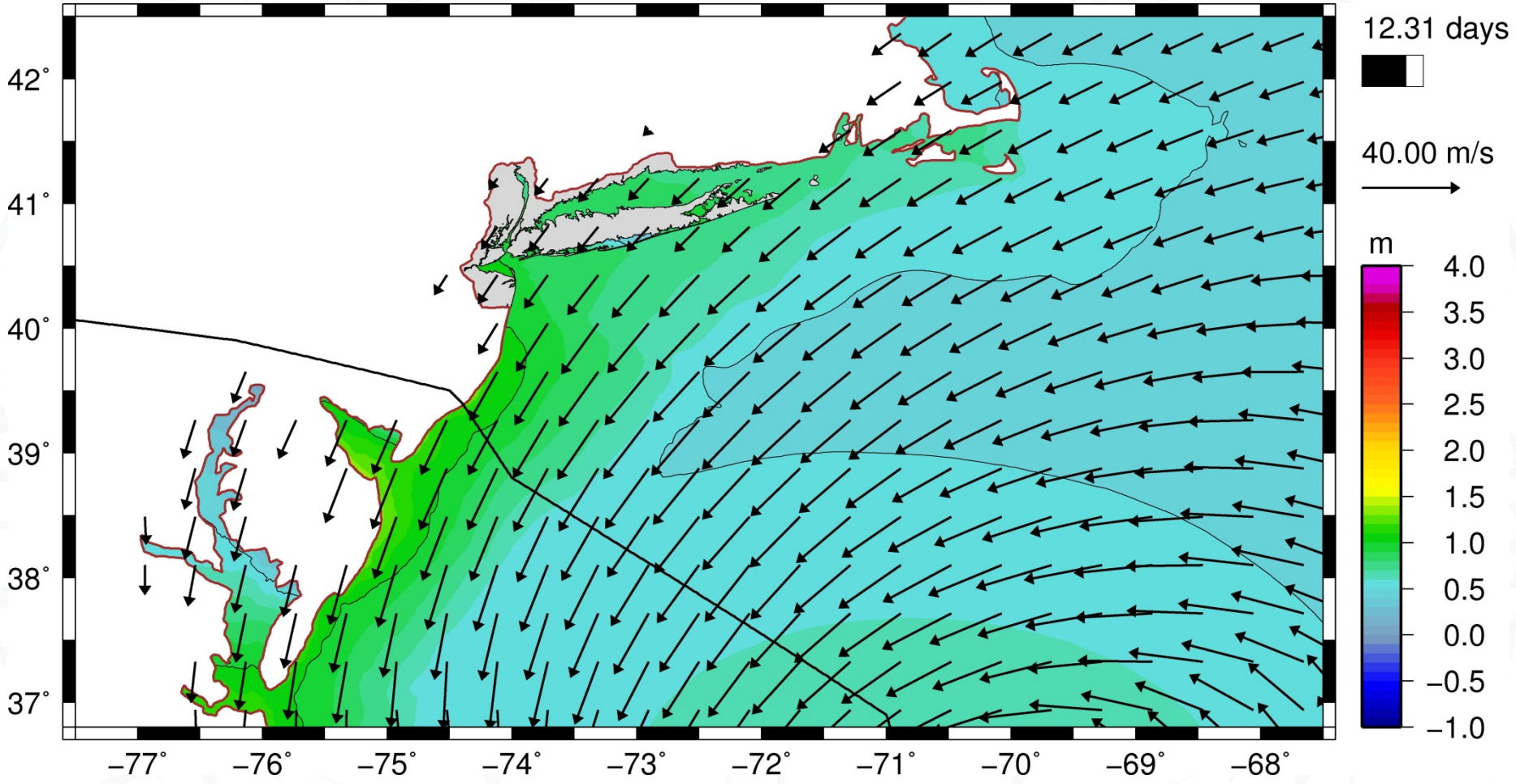
WSE No tides -24 hrs



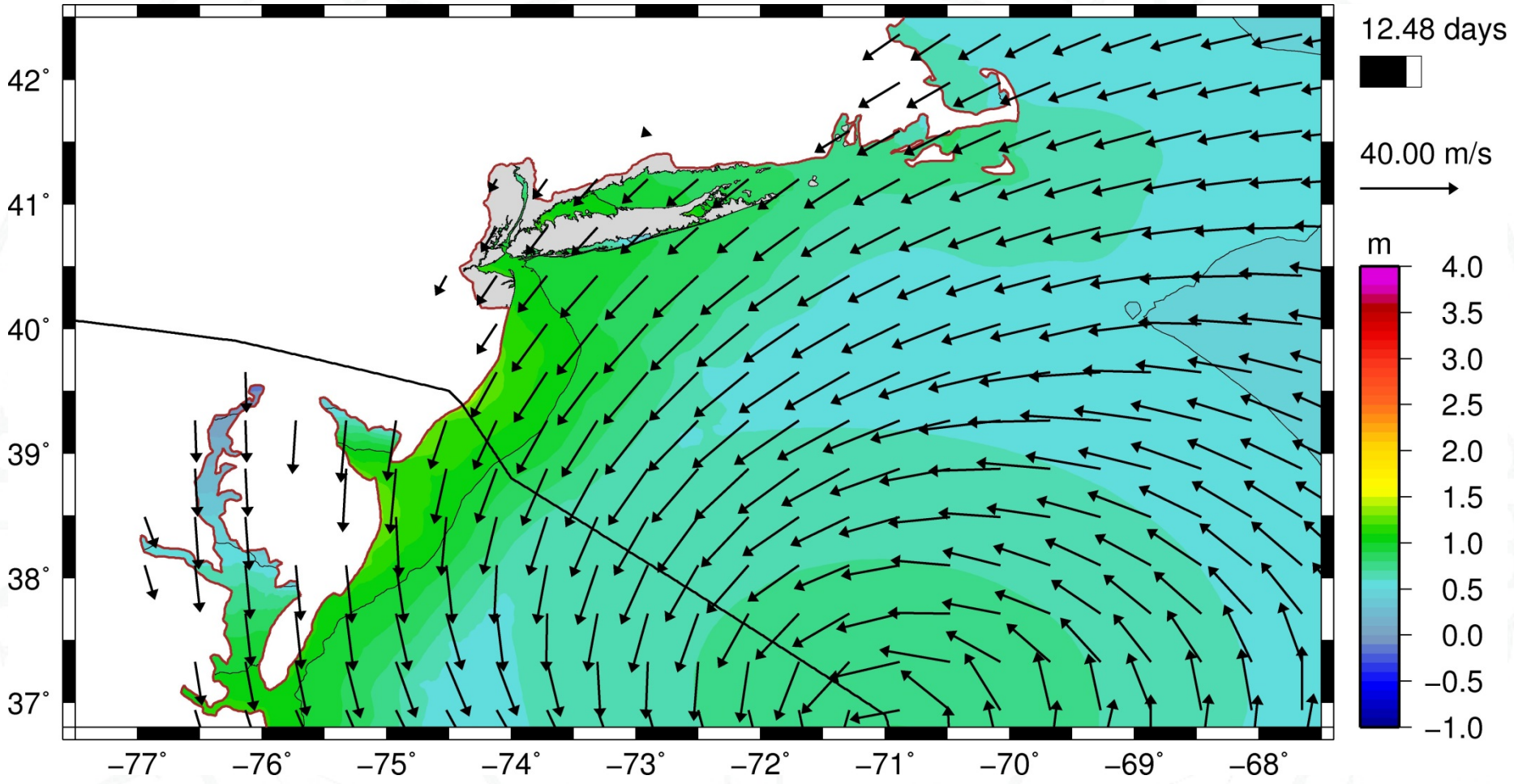
WSE No tides -20 hrs



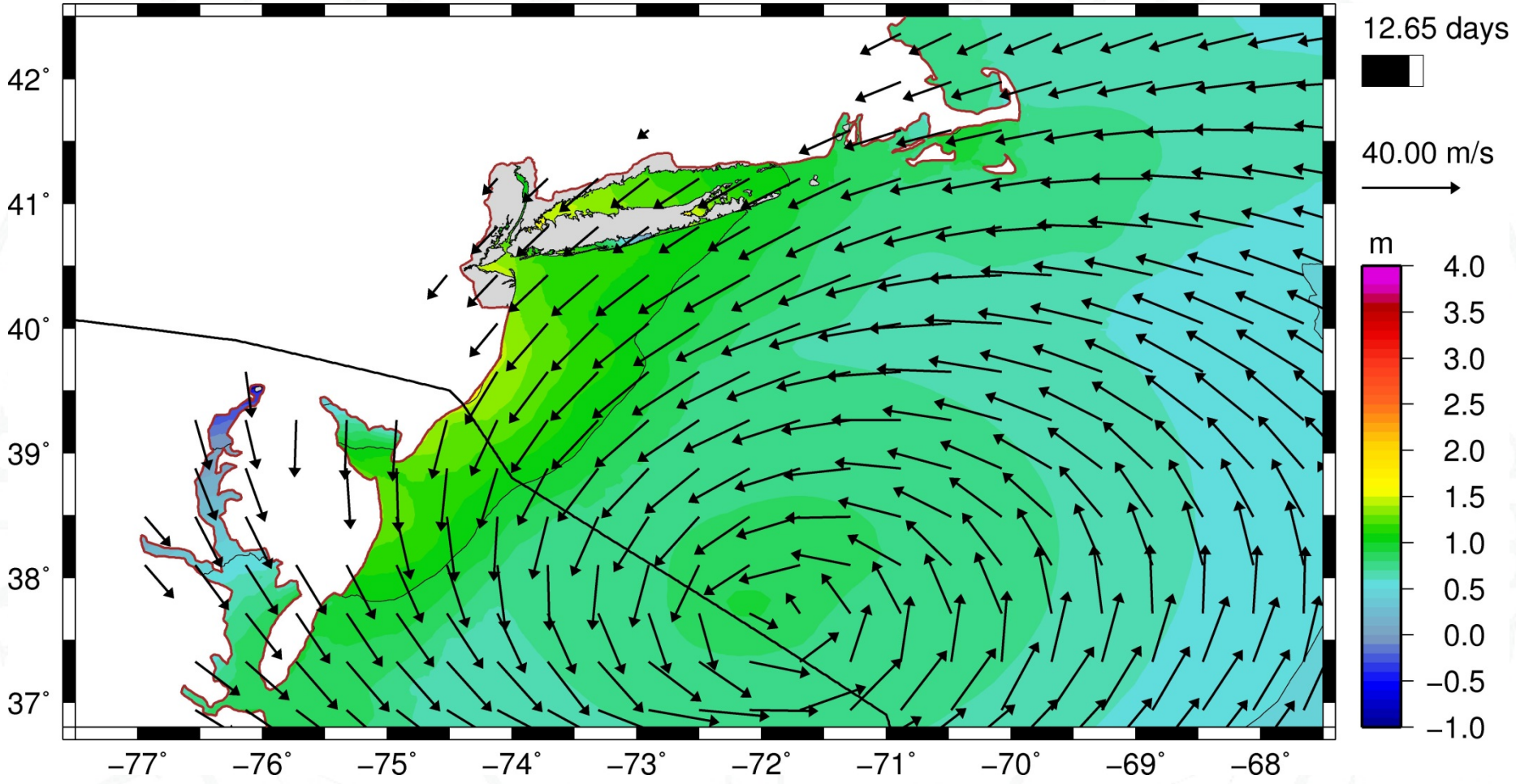
WSE No tides -16 hrs



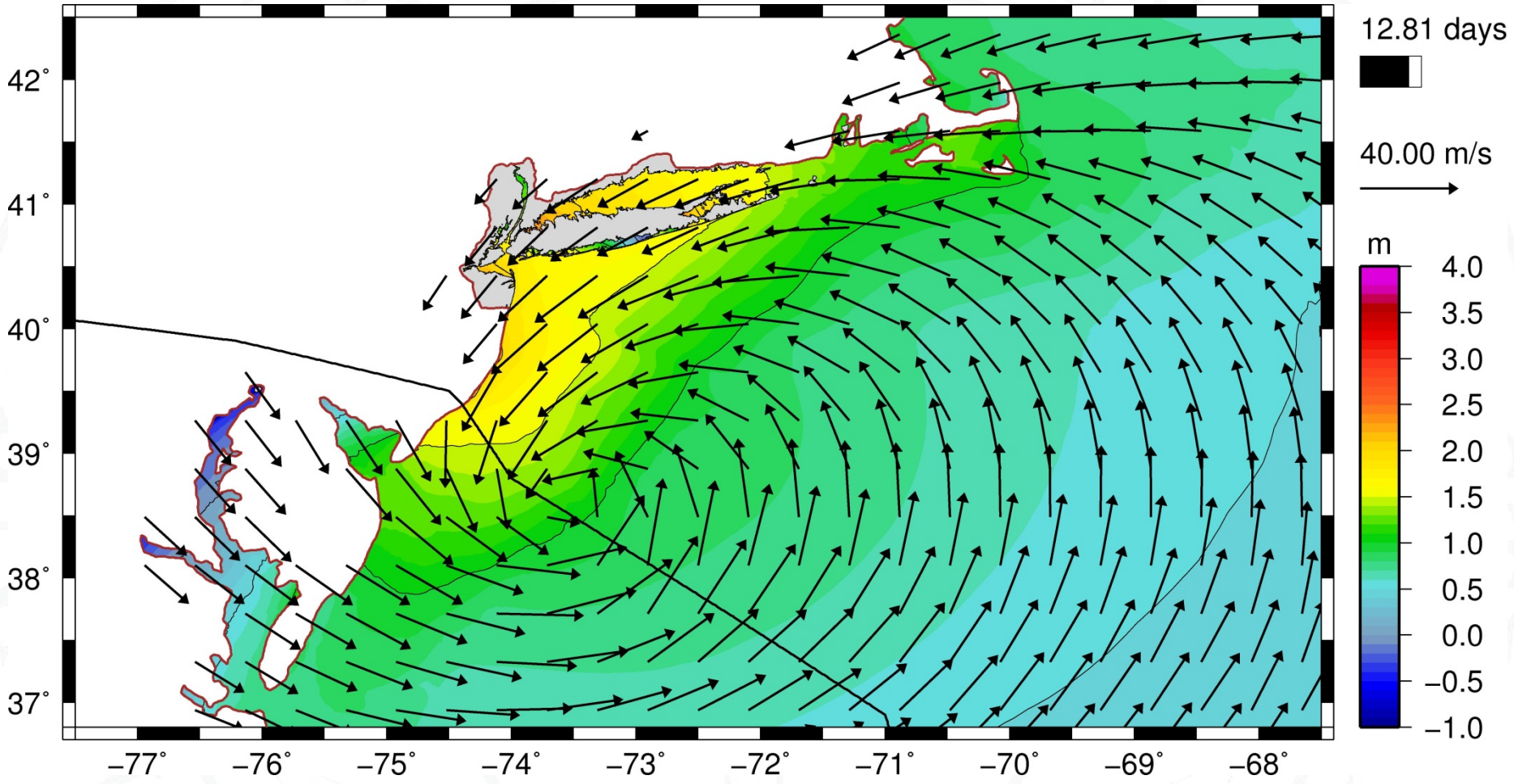
WSE No tides -12 hrs



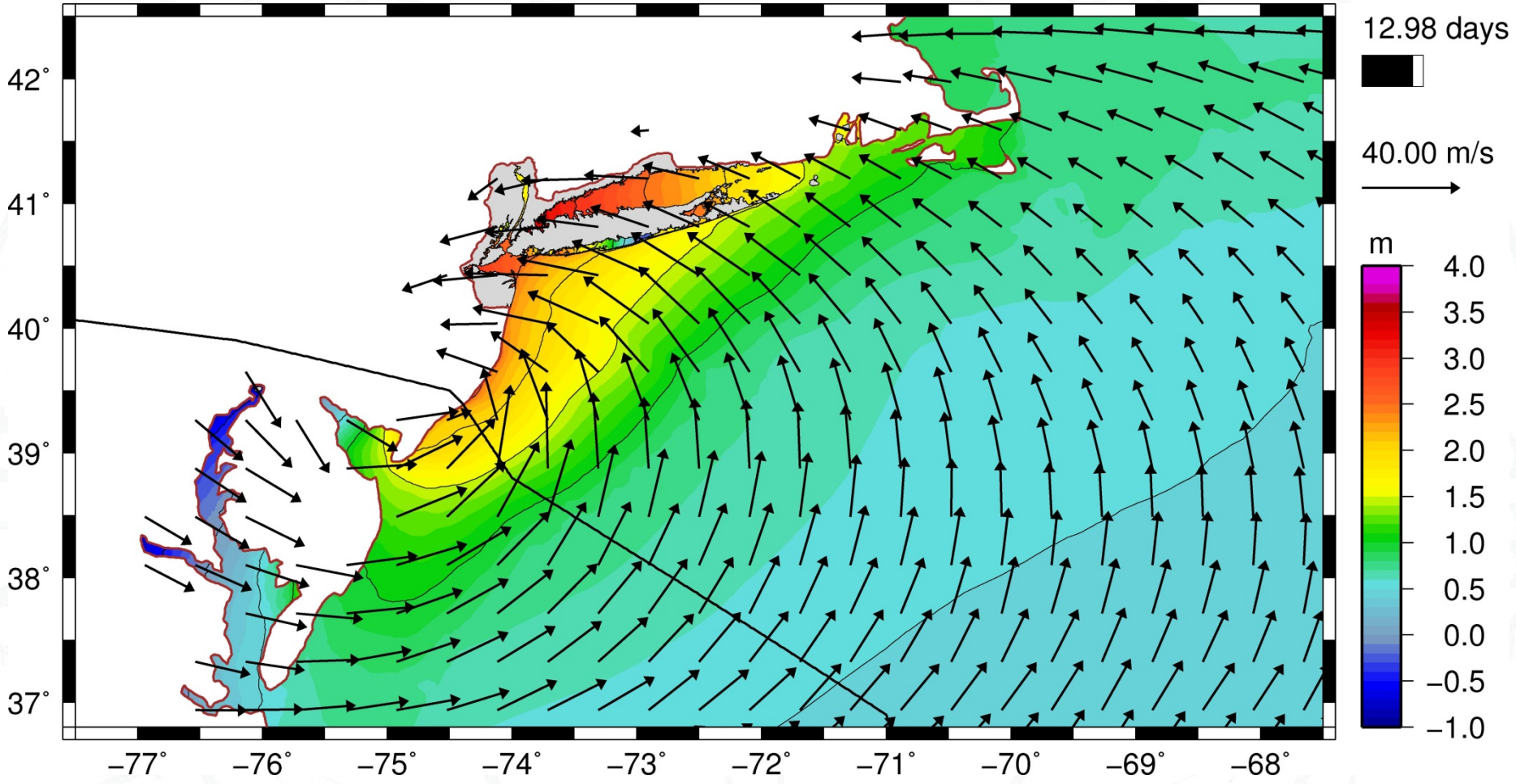
WSE No tides -8 hrs



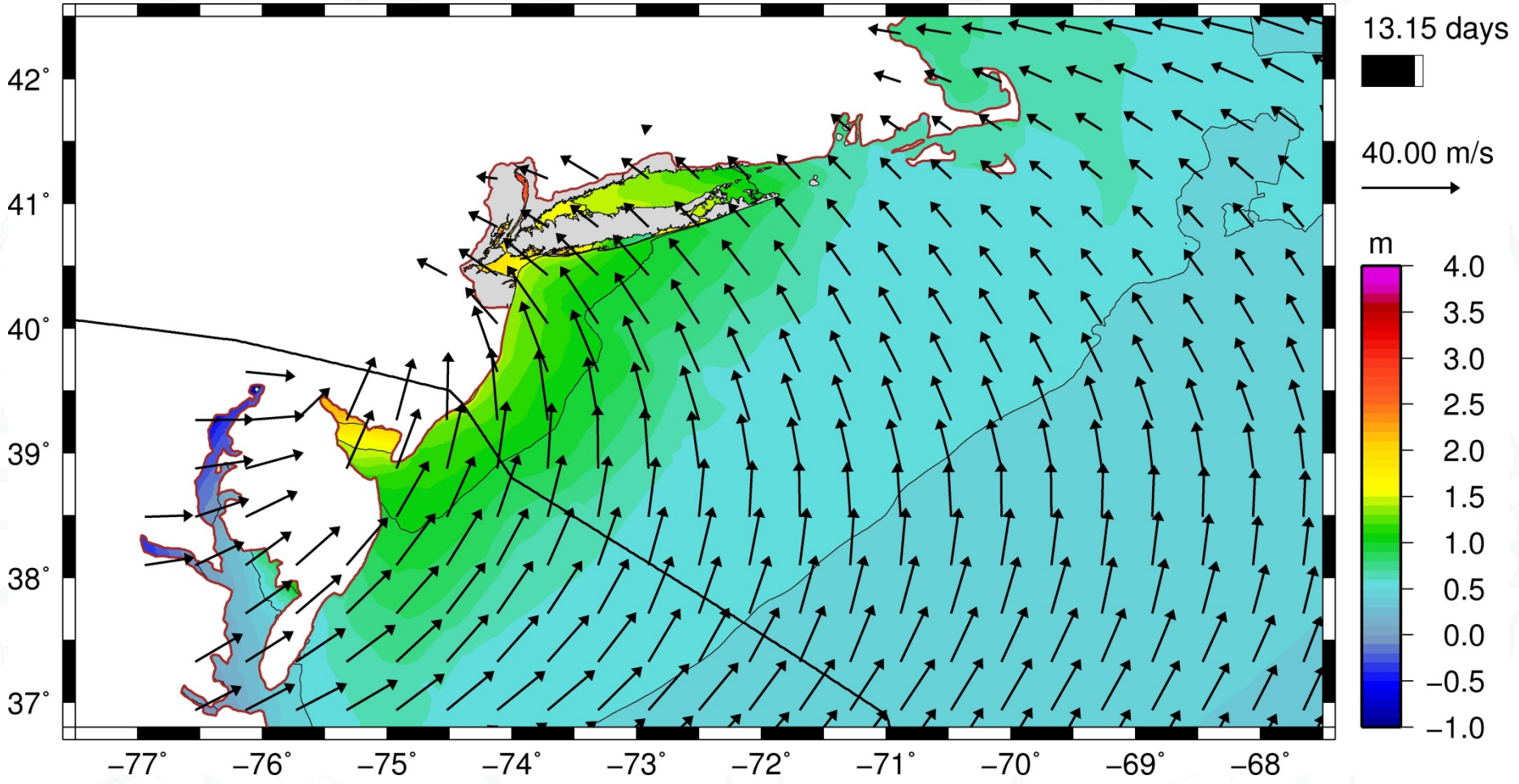
WSE No tides -4 hrs



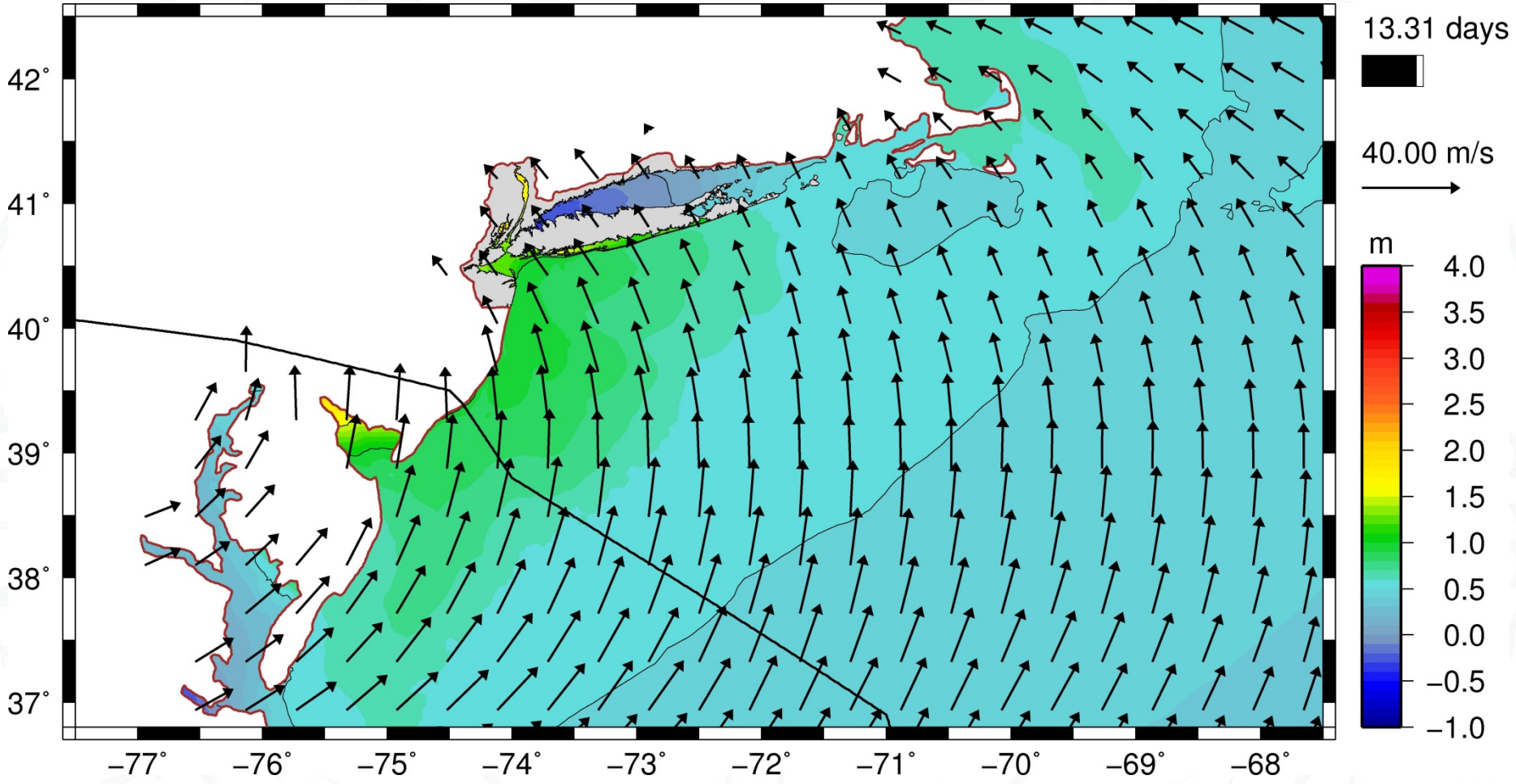
WSE No tides 0 hrs LANDFALL



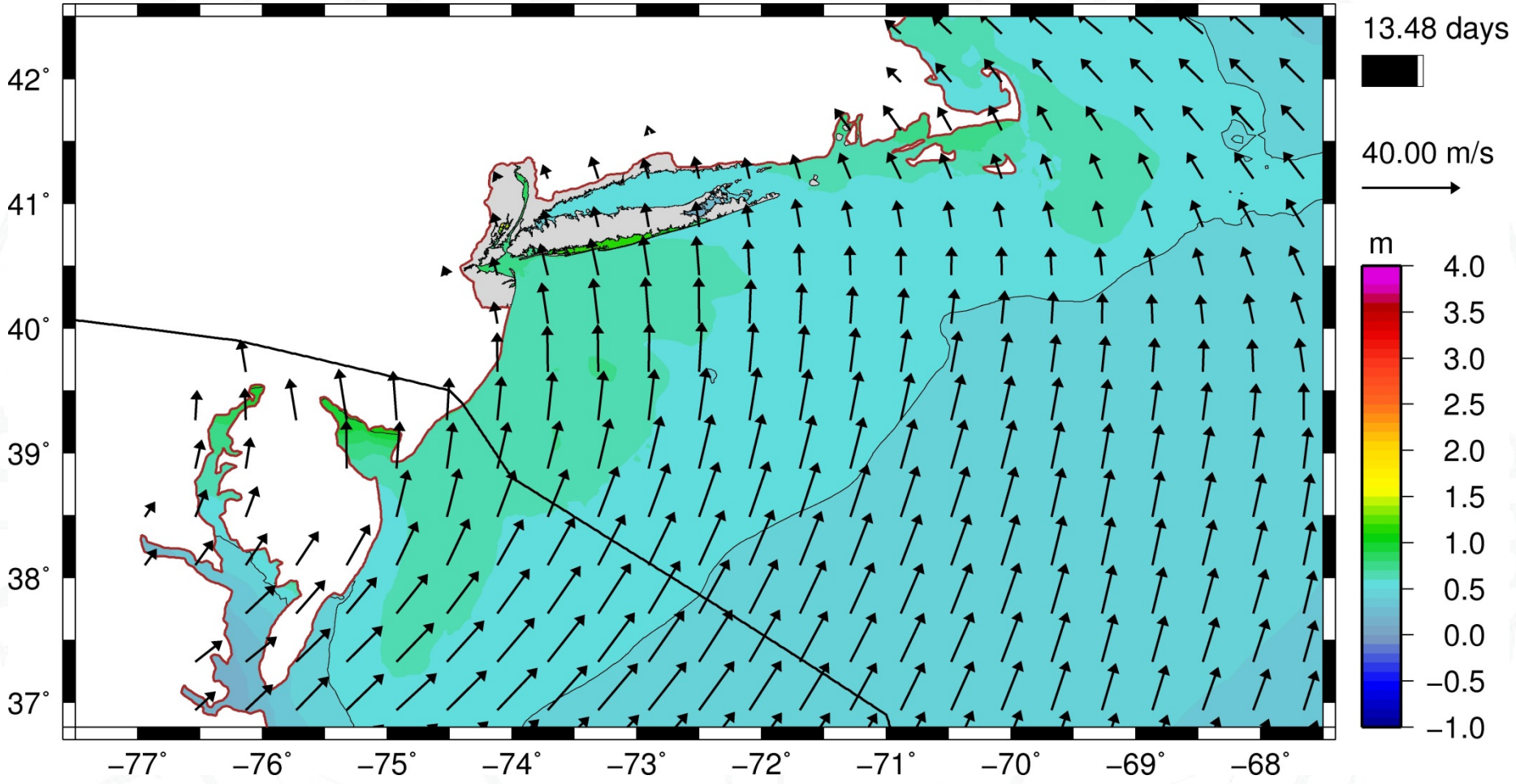
WSE No tides +4 hrs



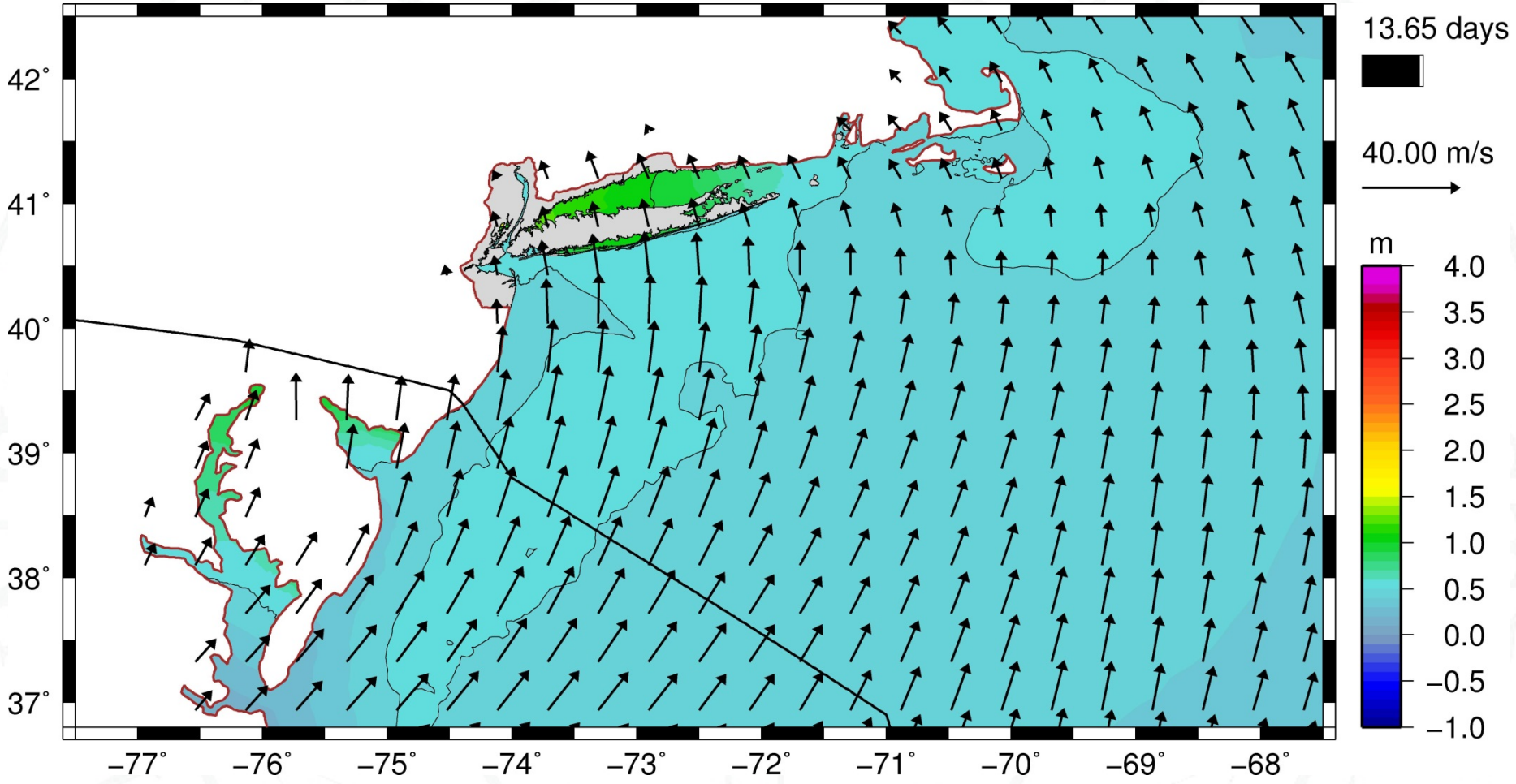
WSE No tides +8 hrs



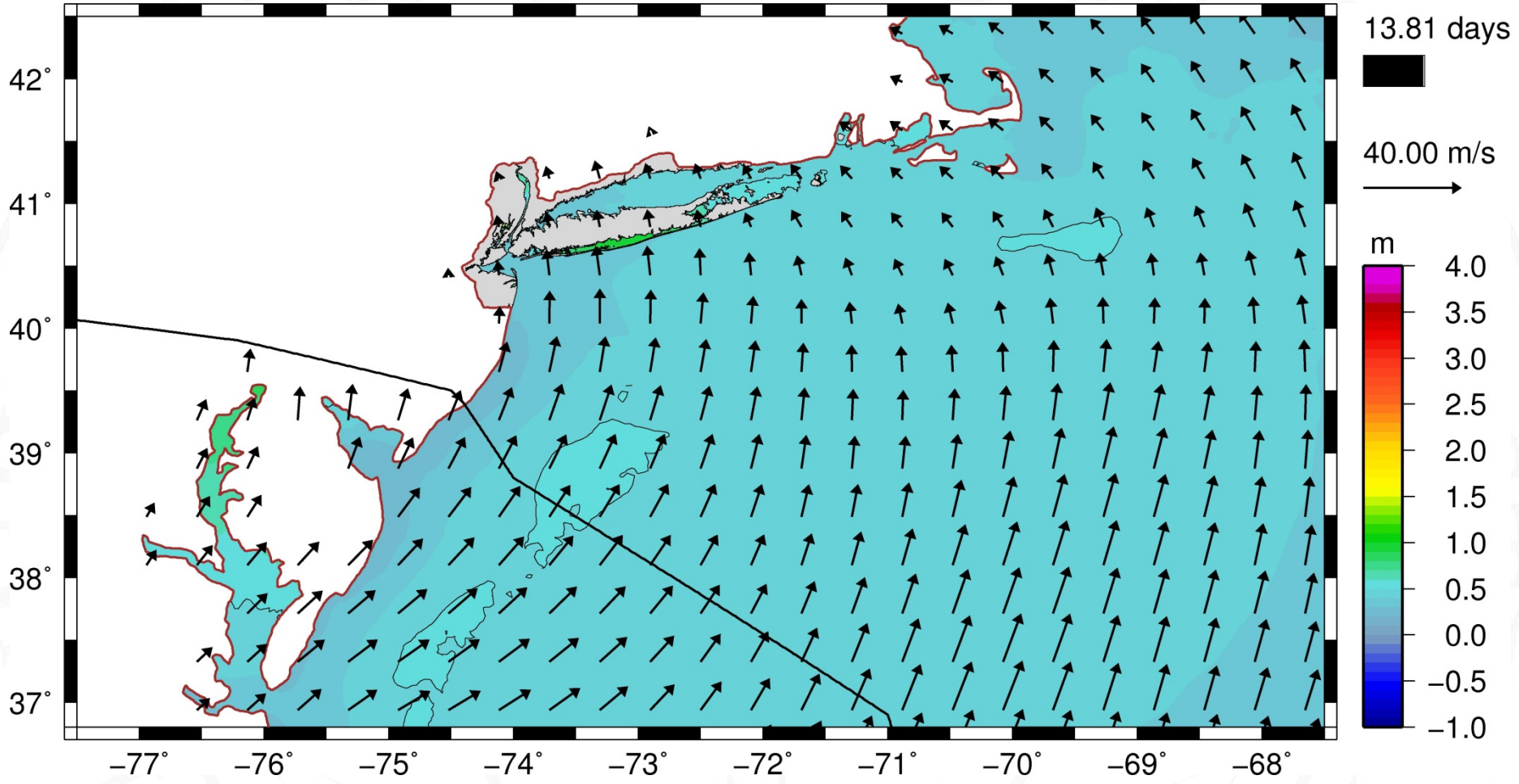
WSE No tides +12 hrs



WSE No tides +16 hrs



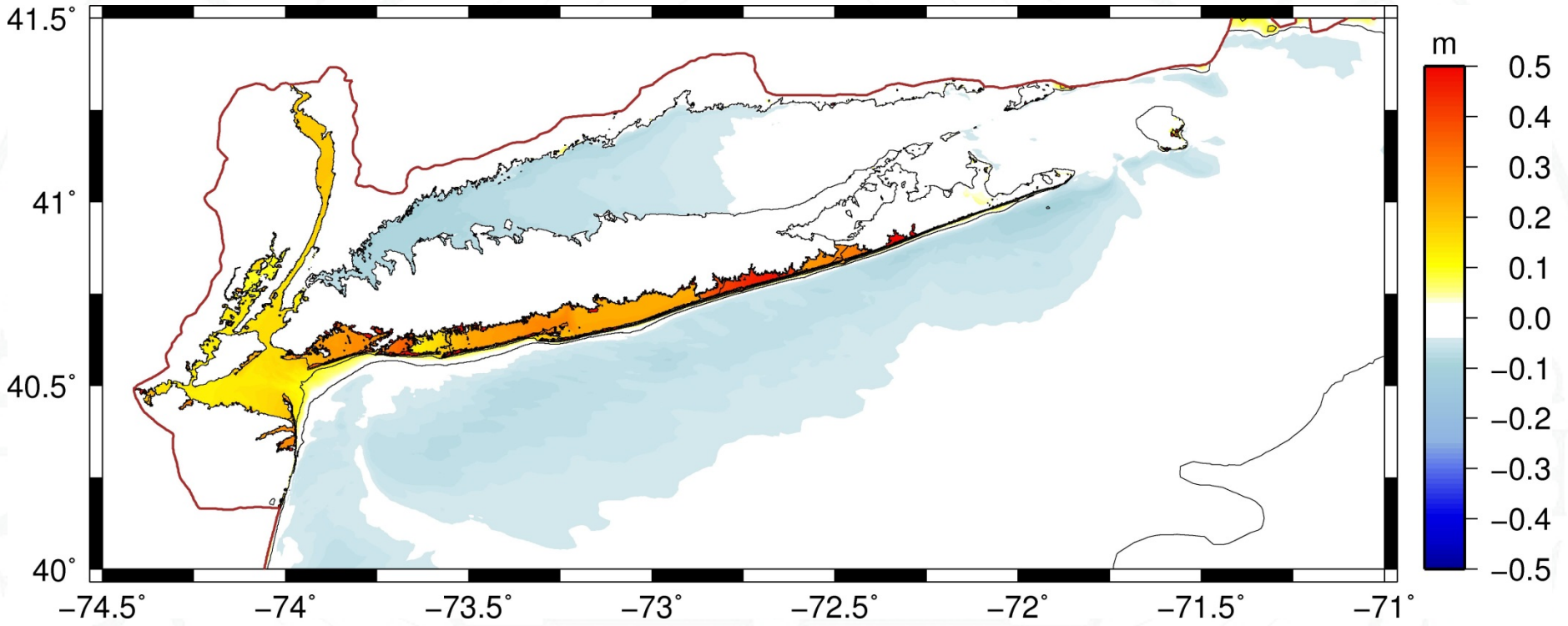
WSE No tides +20 hrs



Analysis

- Sandy Hindcast, Validation and Analysis
  - Winds, Waves, Surge, Shelf velocities
  - Validation
  - Geostrophic setup
  - Long Island Sound resonance
  - Wave effects
  - Tidal nonlinearities
  - Effect of storm speed and abrupt wind ending

Effect of Wave Radiation Stress



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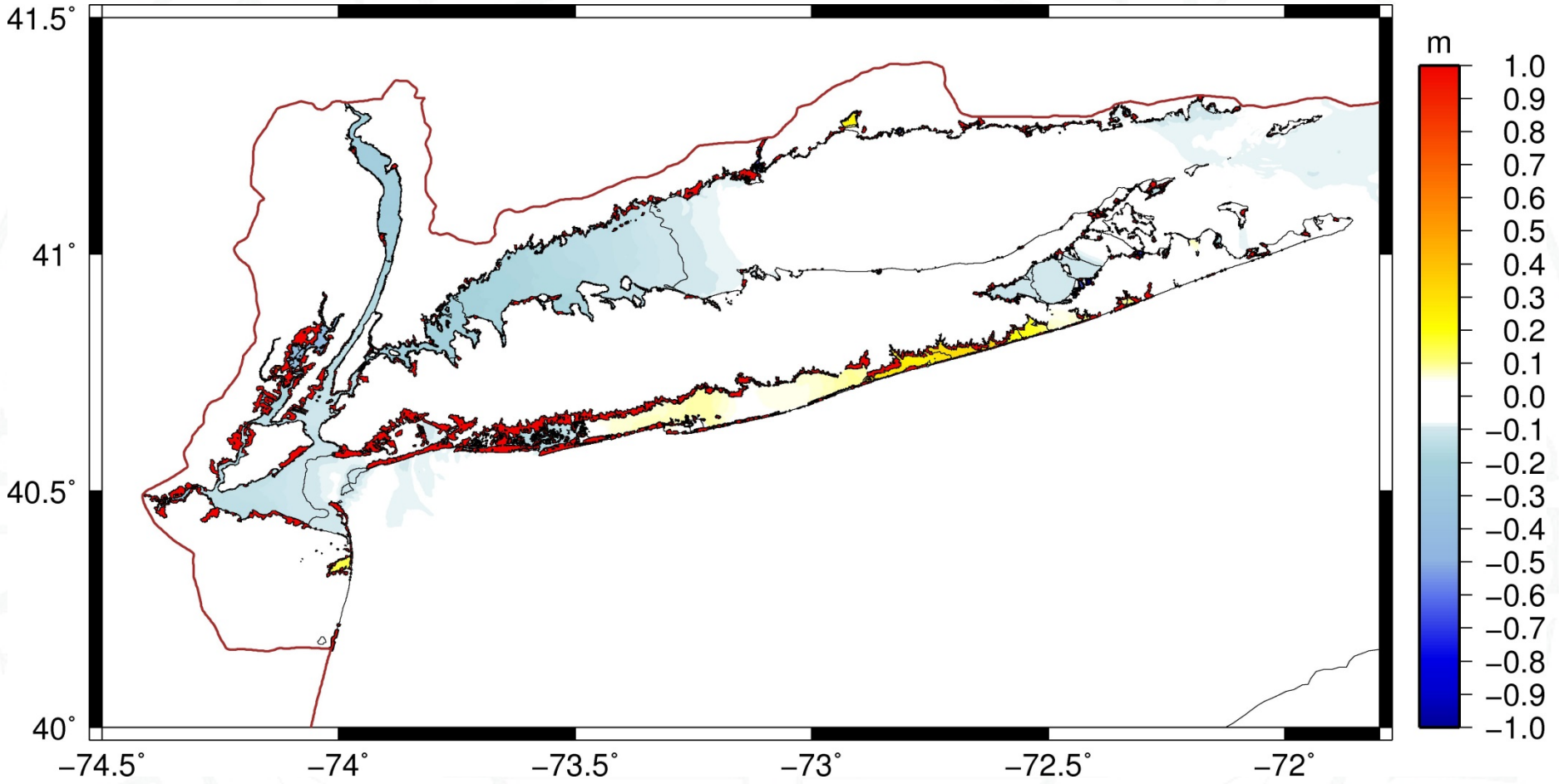
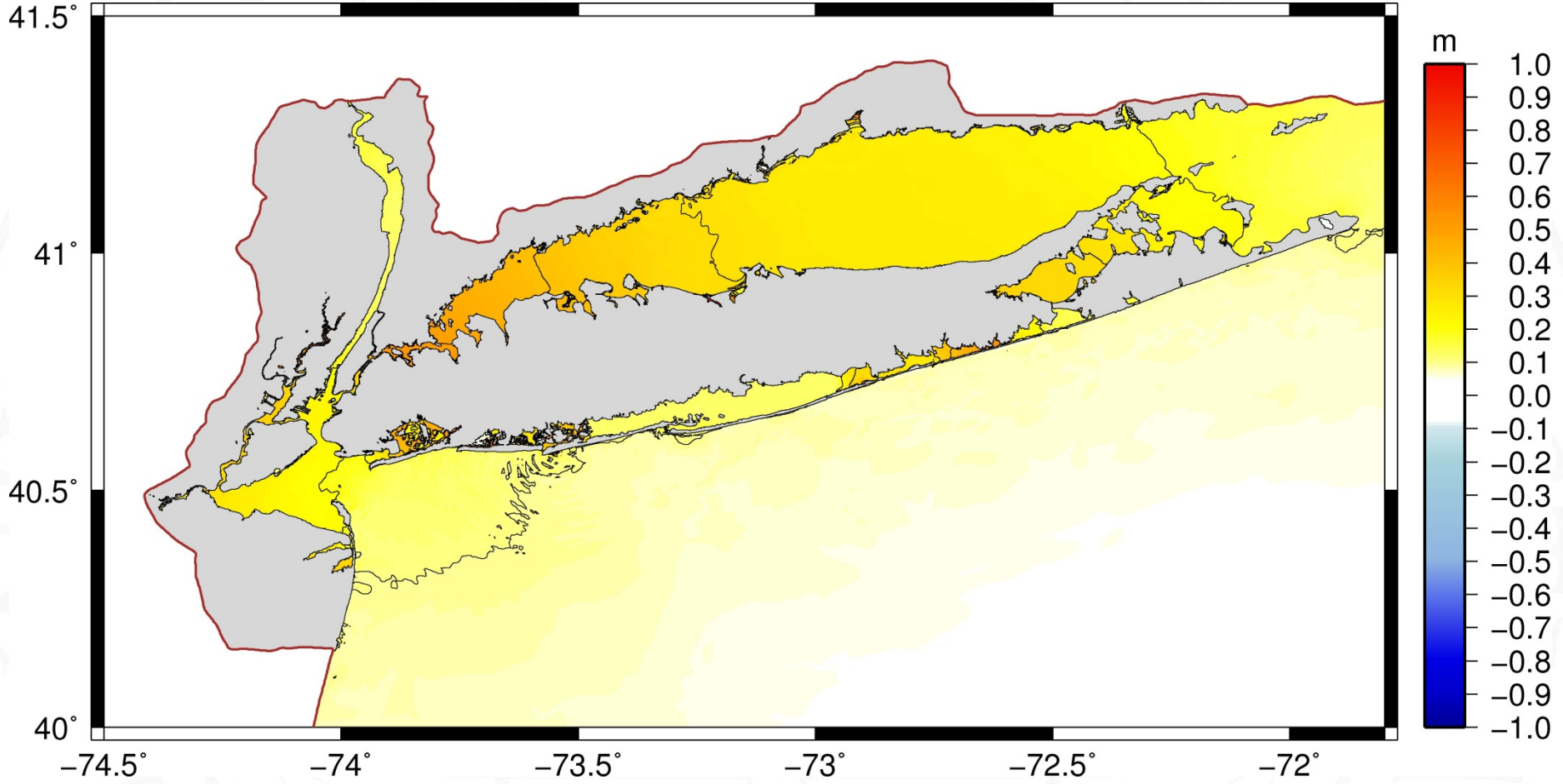
Effect of Tidal Nonlinearities on Maximum Surge

Max (Full Run) – Max (No Tides Run + Tides)



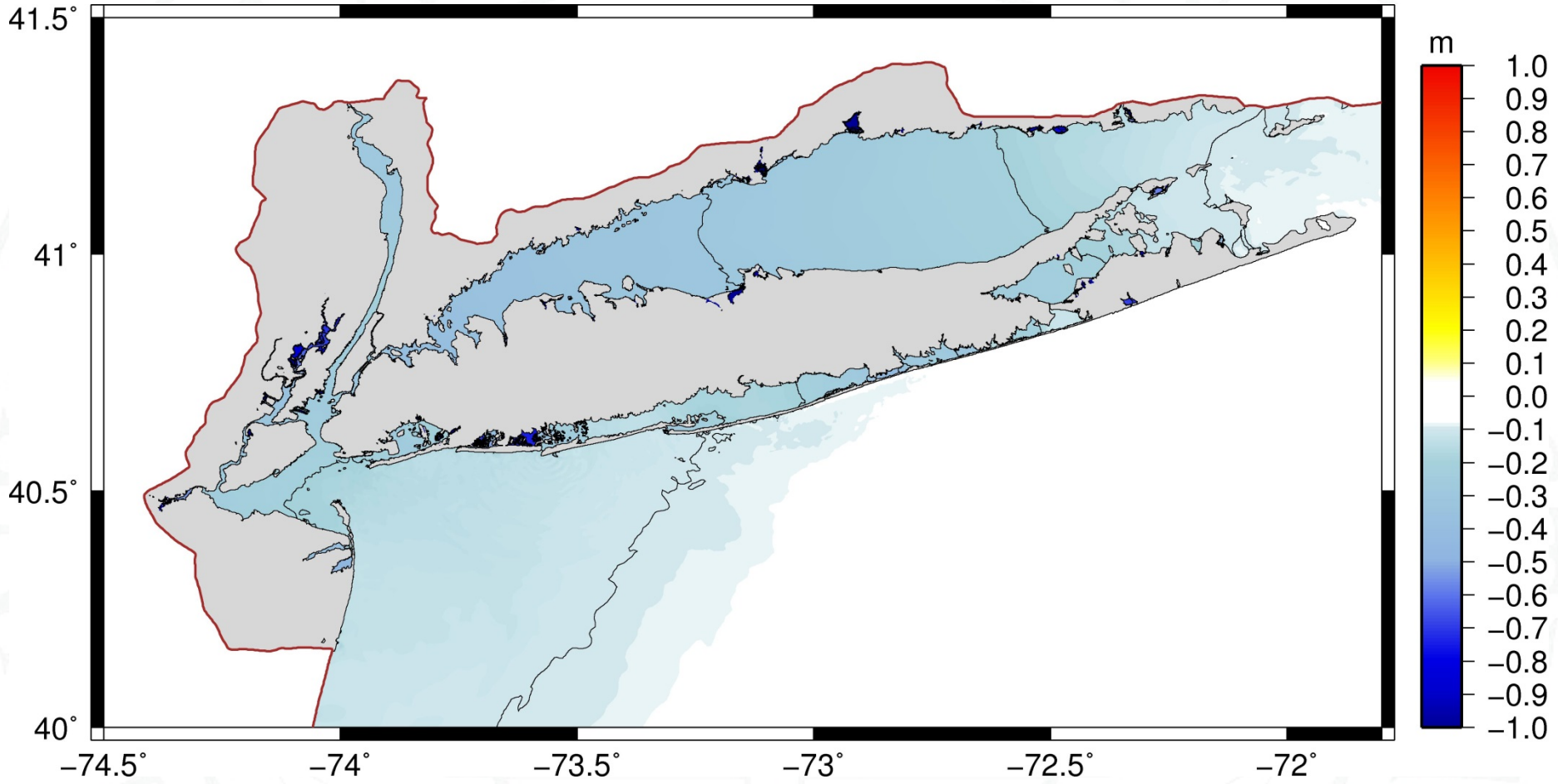
Effect of Tidal Nonlinearities on Surge Timing

Max [(Full Run) – (No Tides Run + Tides)]



Effect of Tidal Nonlinearities on Surge Timing

Min [(Full Run) – (No Tides Run + Tides)]



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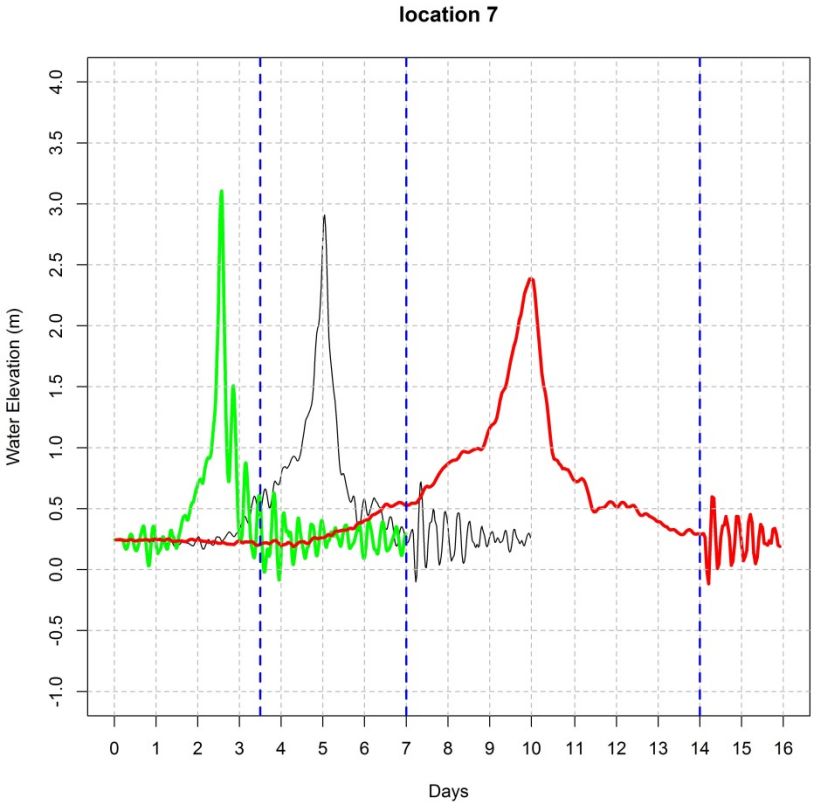
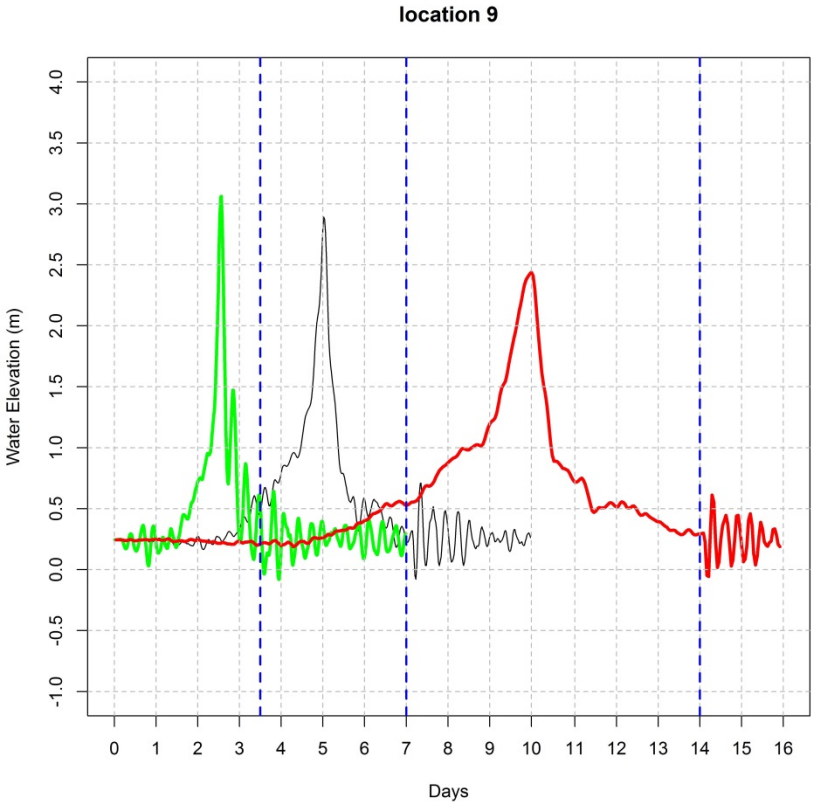
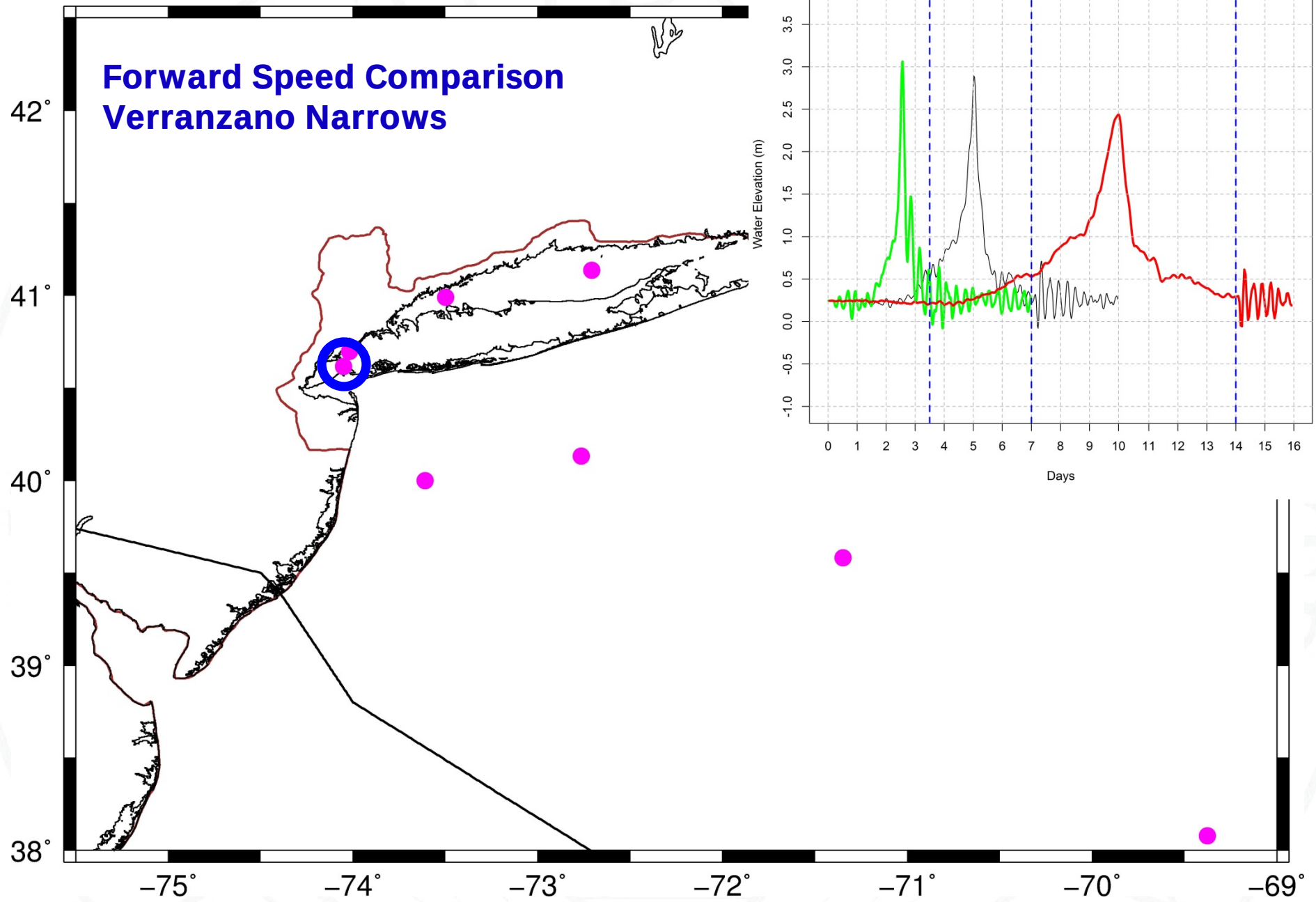
Forward Speed Comparison
NY Battery

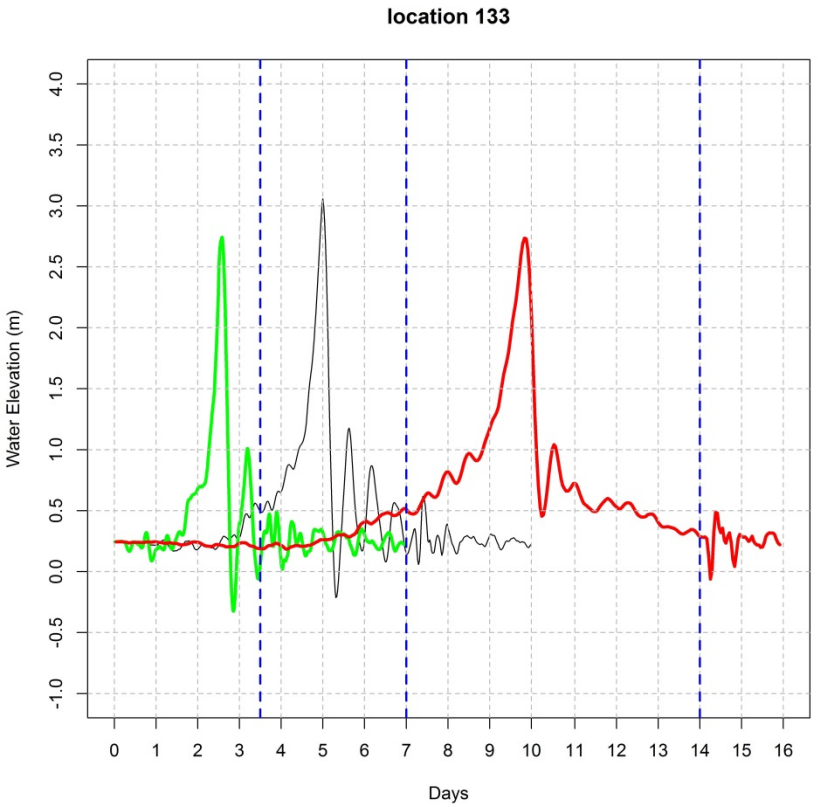


Forward Speed Comparison
Verranzano Narrows

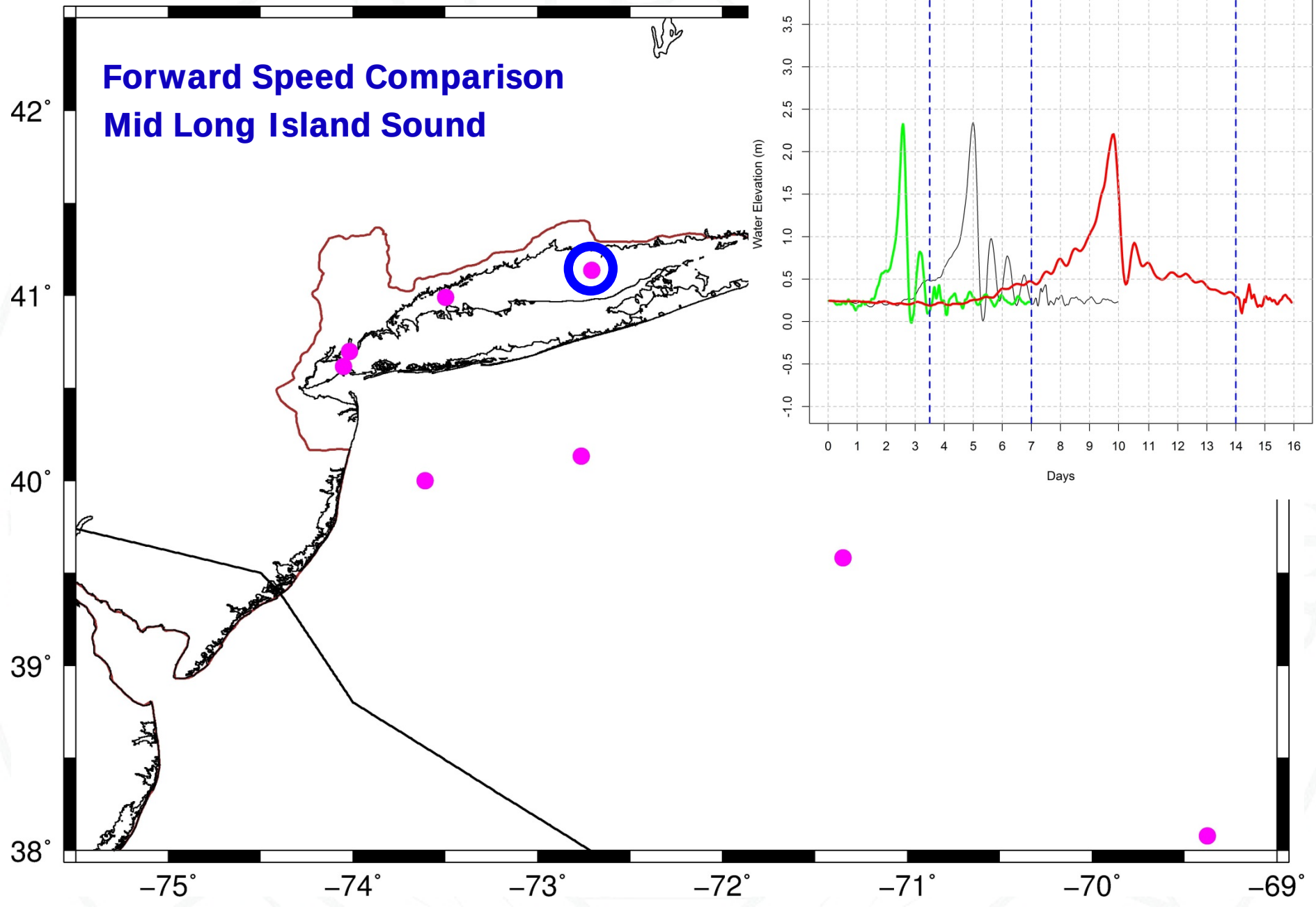


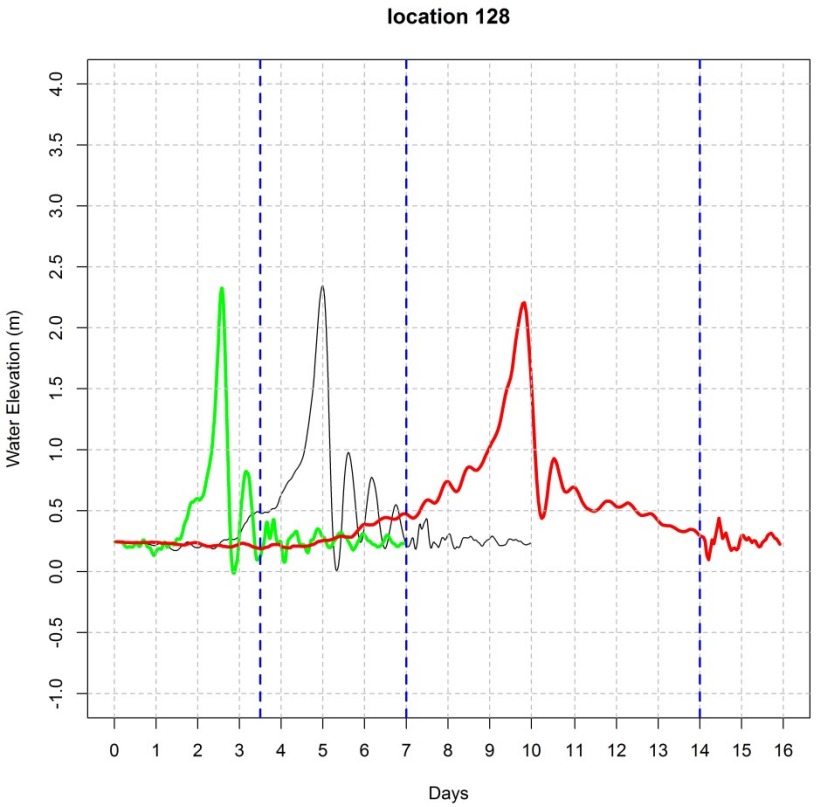


Forward Speed Comparison
LI Sound Off Stamford, CT

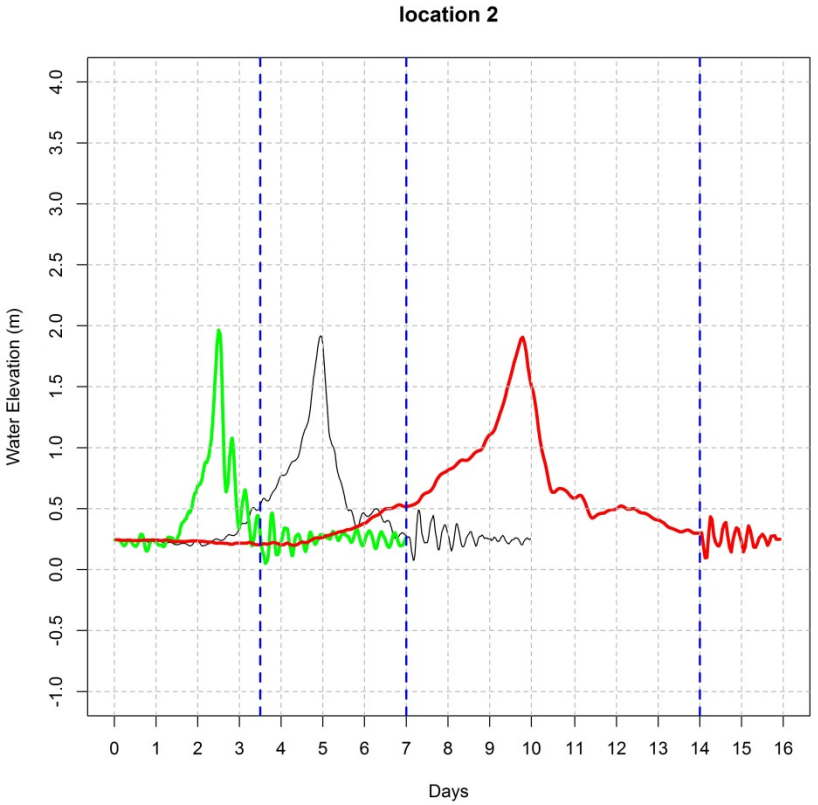


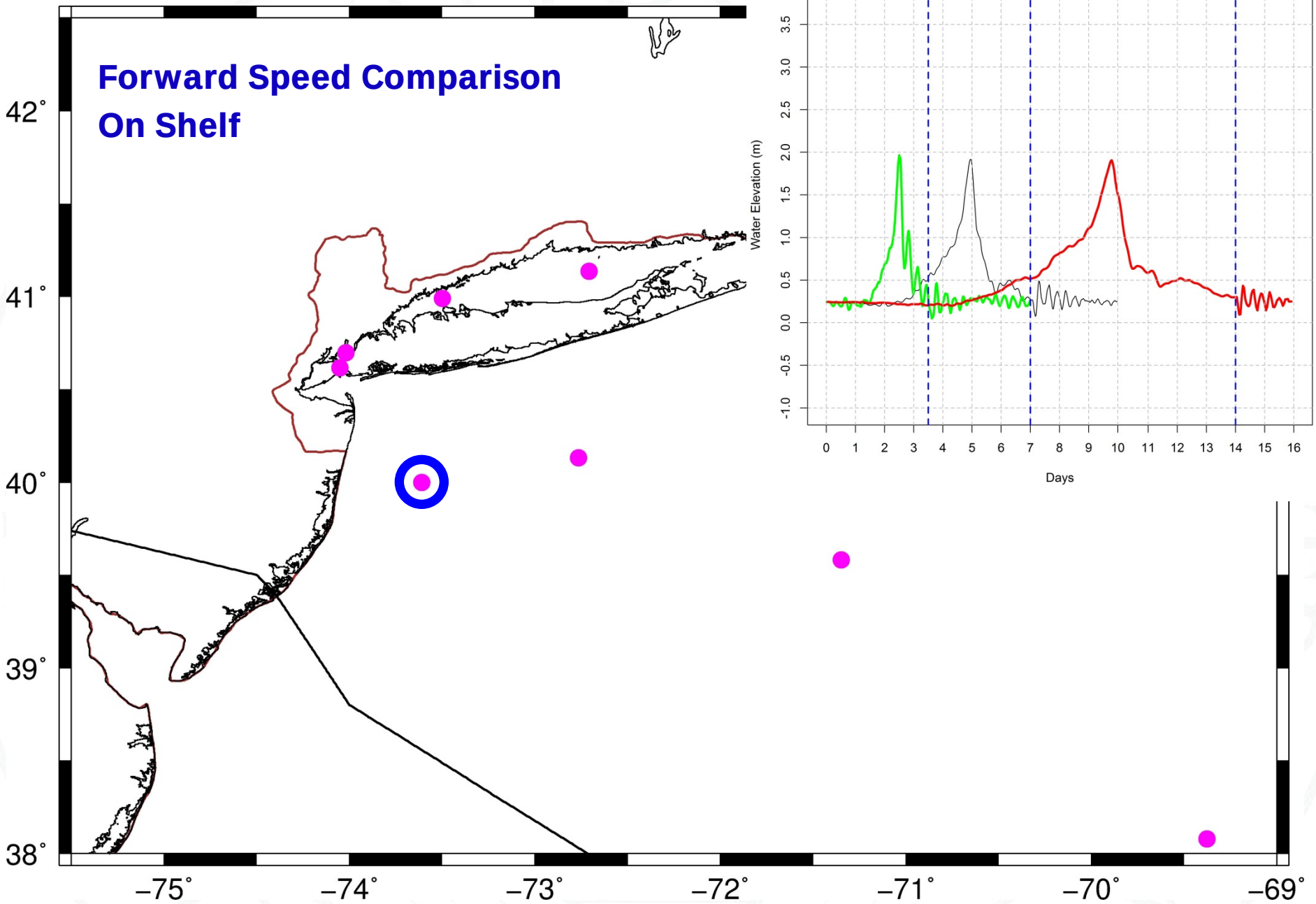
Forward Speed Comparison
Mid Long Island Sound



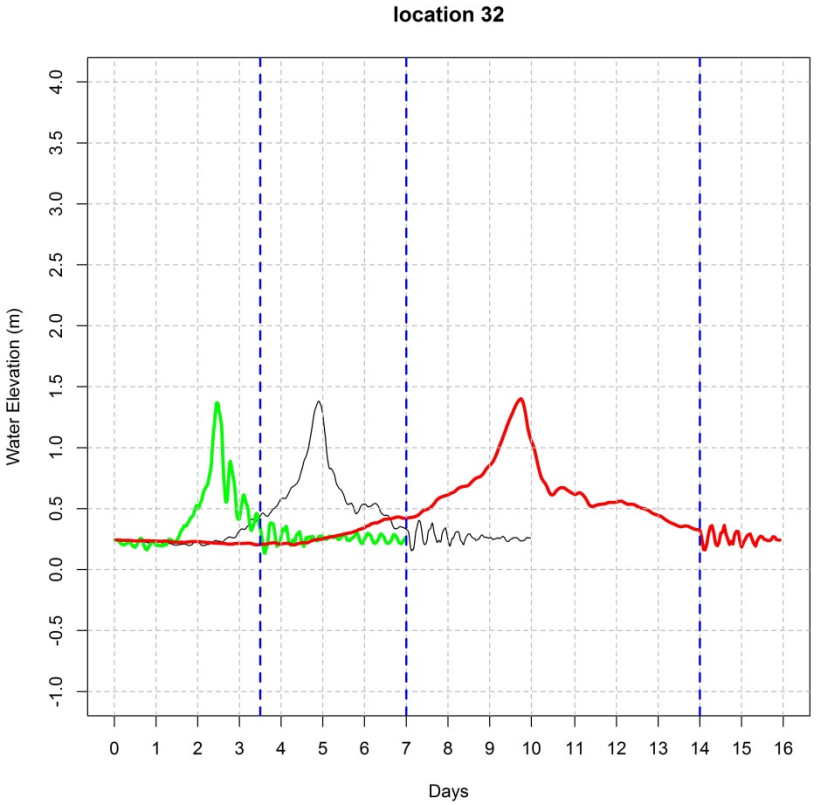


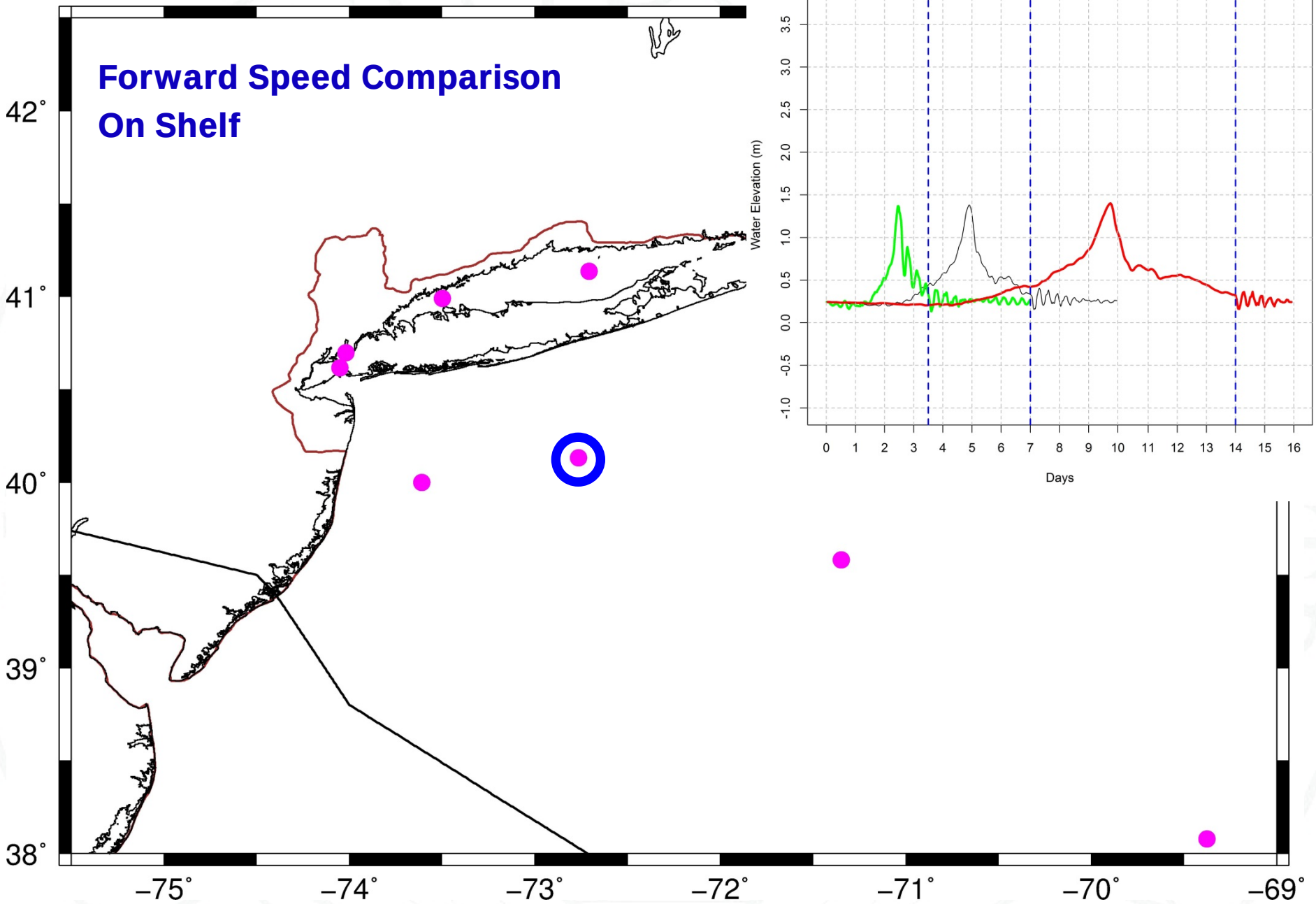
Forward Speed Comparison On Shelf



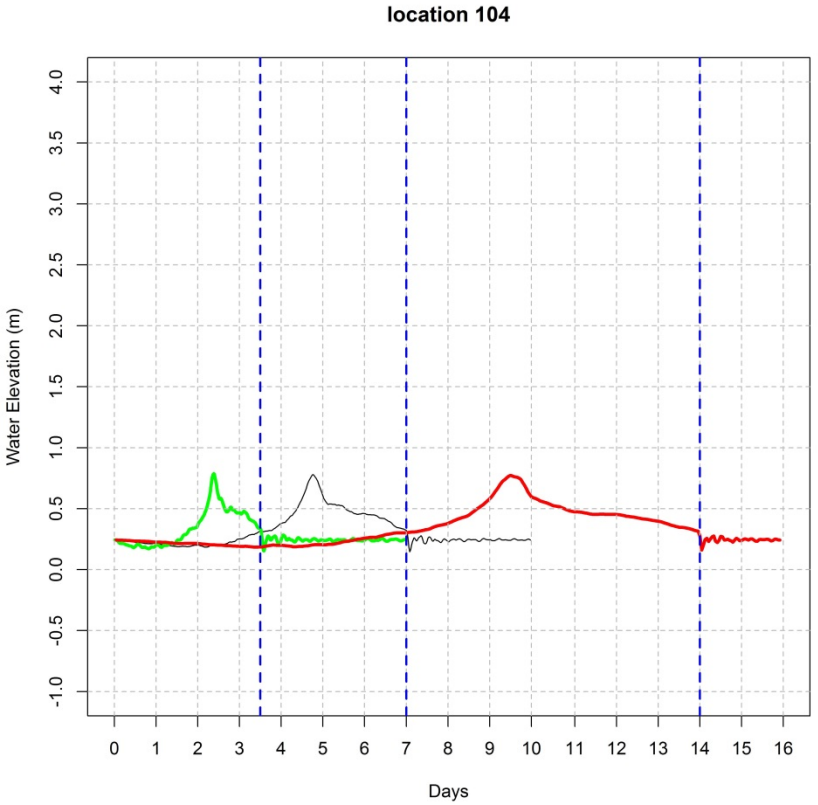


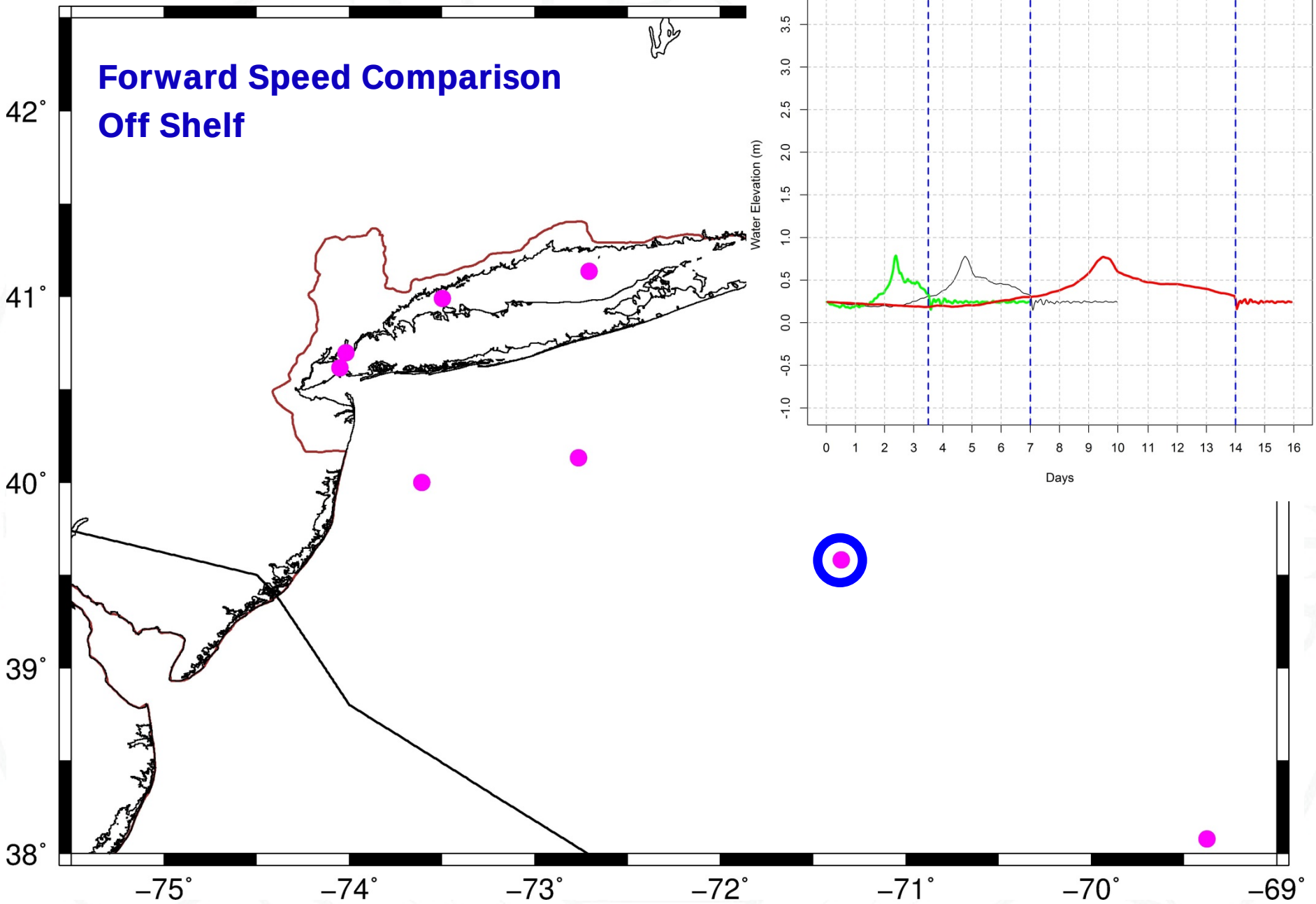
Forward Speed Comparison
On Shelf



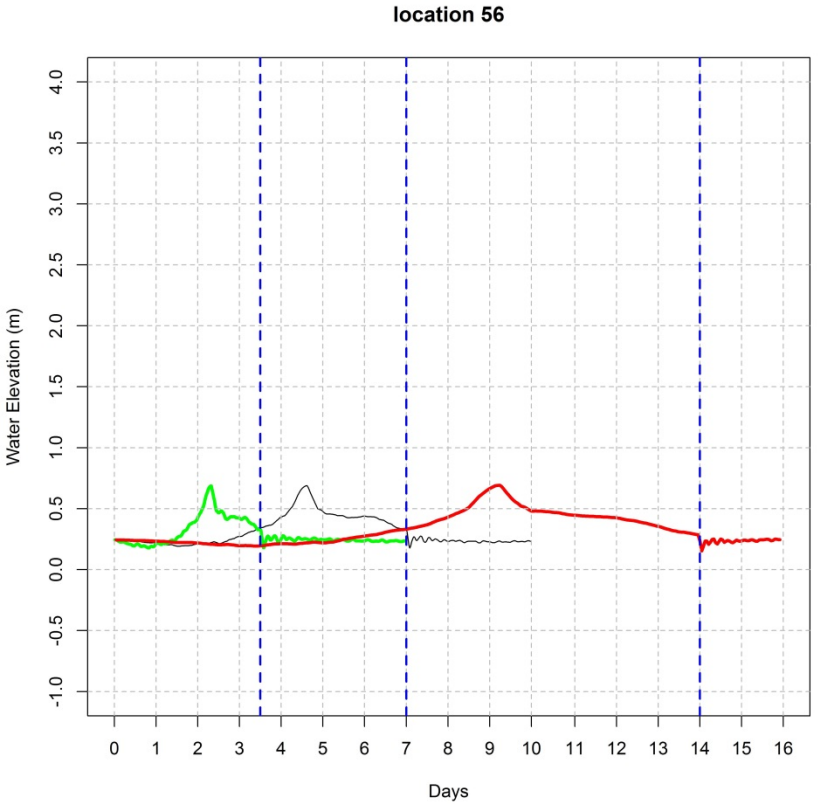


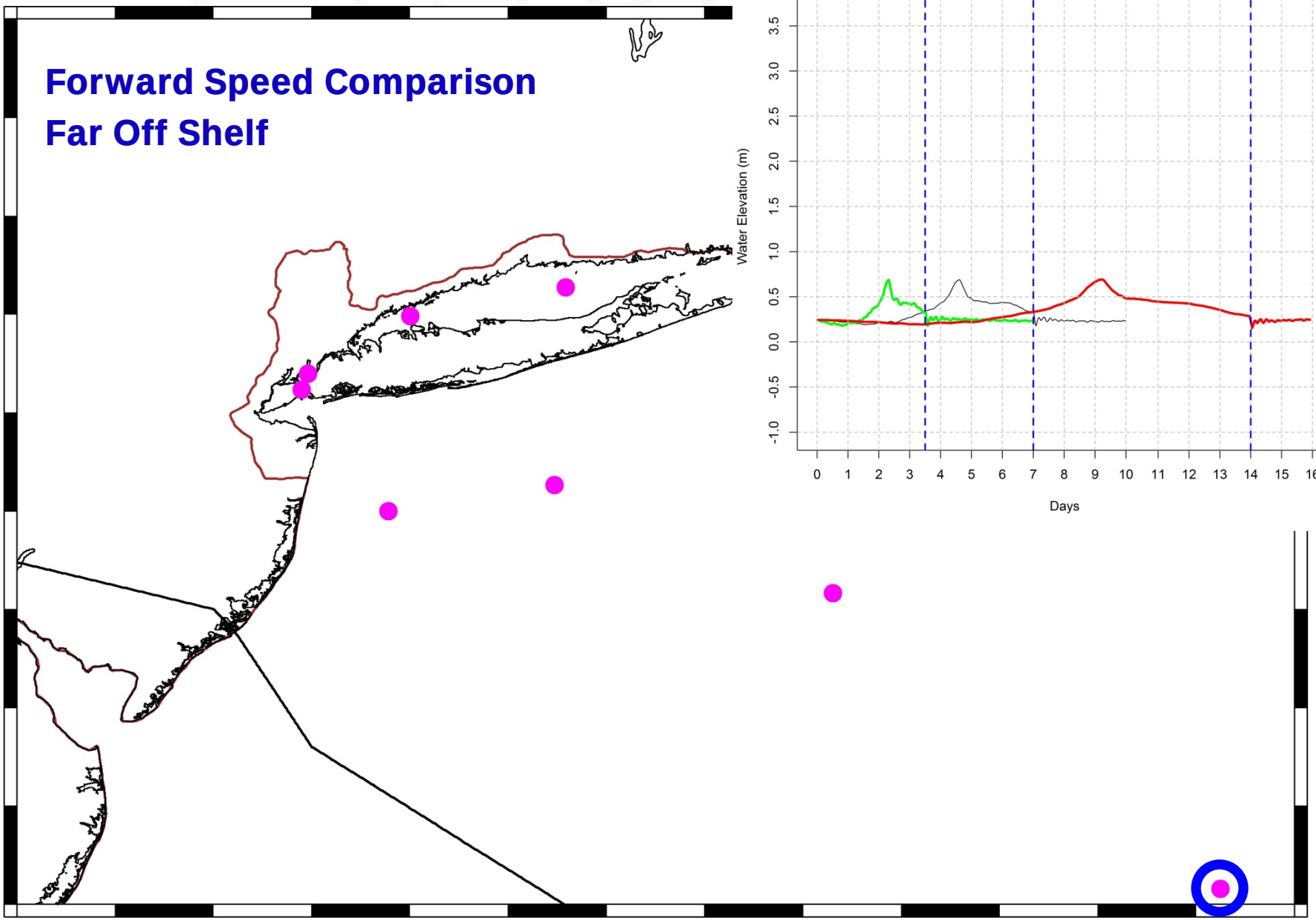
Forward Speed Comparison
Off Shelf





Forward Speed Comparison
Far Off Shelf





Current development efforts

- Discontinuous Galerkin (DG) Finite Element Implementations
  - High Order Efficiency
  - Advection and propagation
  - Non-conforming *h-p* adaptation
- Coupling and integrating modules
  - DG for SWAN like models
  - Phase resolving: Non-hydrostatic using Green-Nagdy expansions – wave transformation and run-up
  - Small scale channel networks
  - Rainfall
  - Morphology
- Applications
  - Puerto Rico and the U.S. Virgin Islands
  - New York and New Jersey
  - Alaska
  - South China Sea

Acknowledgments

- National Science Foundation
- Office of Naval Research
- U.S. Army Engineer Research and Development Center
- U.S. Army Corps of Engineers MVN
- NOAA
- IOOS
- Department of Homeland Security
- FEMA
- Naval Research Laboratory
- FM Global

References available at *coast.nd.edu*