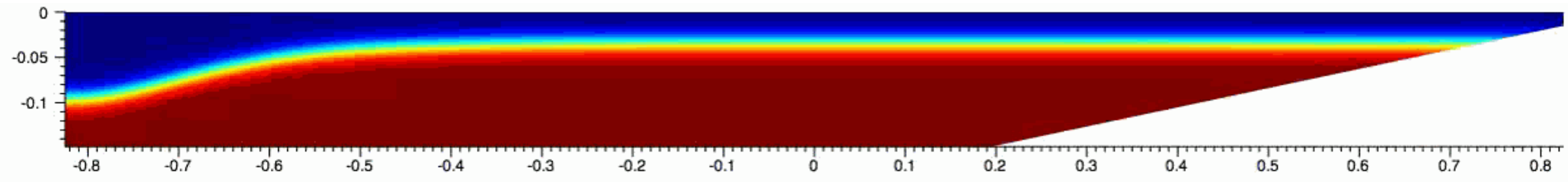

US-Japan Collaborative Research on Model Assessment of the March 11 2011 Earthquake, Tsunami Inundation and Initial Spread of Cs-137 in the Coastal Ocean

Changsheng Chen

Team members: Robert C. Beardsley[2], Zhigang Lai[1], Huichan Lin[1], Jian Lin[2], Jun Sasaki[3] and Rubao Ji[2]

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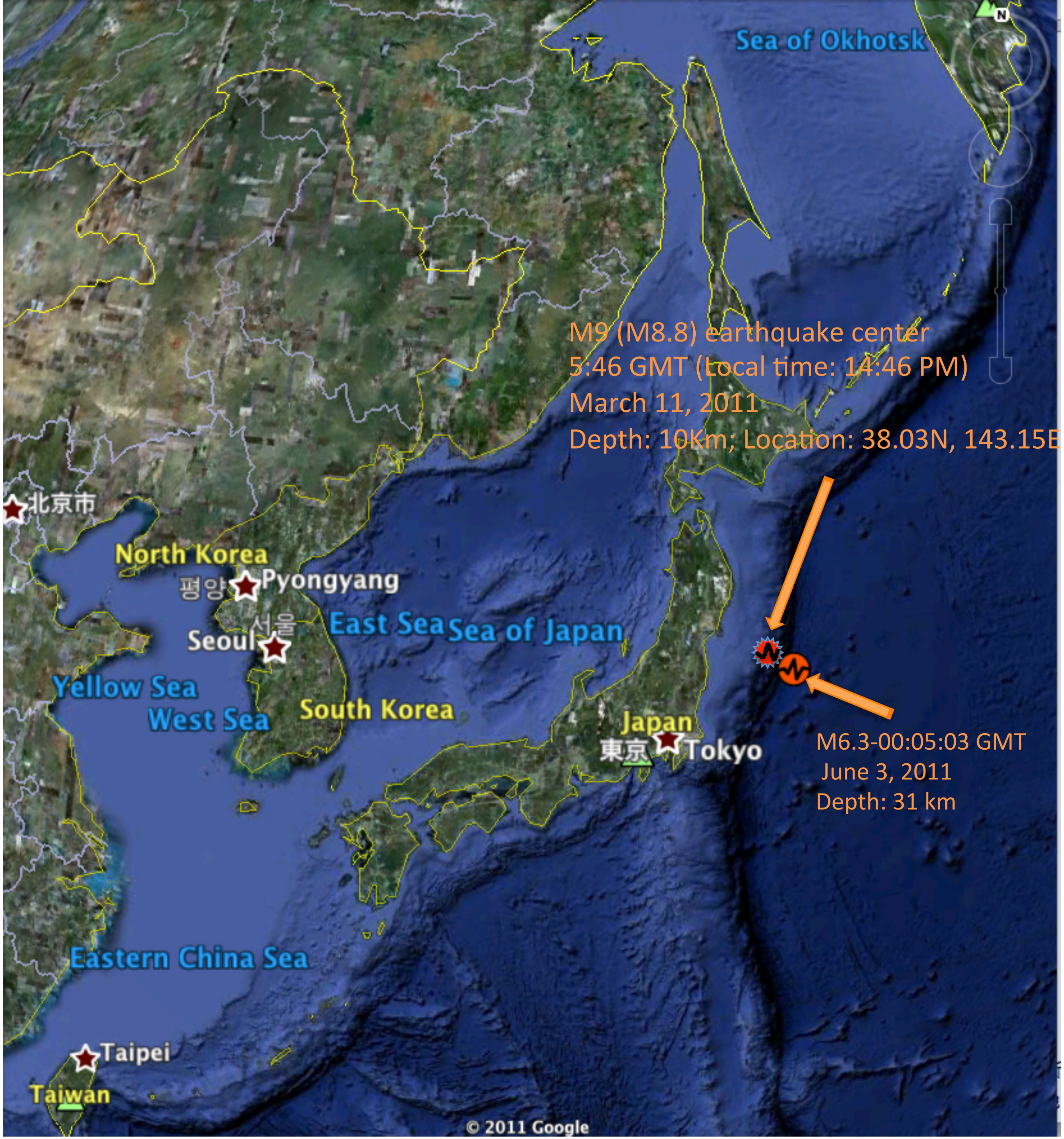
[2]Woods Hole Oceanographic Institution (WHOI), USA
[3]Yokohama National University, Japan

Contact: c1chen@umassd.edu; rbeardsley@whoi.edu

http://fvcom.smast.umassd.edu/research_projects/FVCOM_Tsunami/index.html


Sea of Okhotsk
M9 (M8.8) earthquake center
5:46 GMT (Local time: 14:46 PM)
March 11, 2011
Depth: 10Km; Location: 38.03N, 143.15E
北京市
North Korea
평양
Pyongyang
서울
Seoul
East Sea
Sea of Japan
Yellow Sea
West Sea
South Korea
Japan
東京
Tokyo
M6.3-00:05:03 GMT
June 3, 2011
Depth: 31 km
Eastern China Sea
Taipei
Taiwan
© 2011 Google

North of Sendai (仙台)

http://www.nytimes.com/interactive/2011/03/13/world/asia/satellite-photos-japan-before-and-after-tsunami.html

North of Sendai (仙台)

http://www.nytimes.com/interactive/2011/03/13/world/asia/satellite-photos-japan-before-and-after-tsunami.html

Sendai (仙台)

http://www.nytimes.com/interactive/2011/03/13/world/asia/satellite-photos-japan-before-and-after-tsunami.html

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Sendai (仙台)

http://www.nytimes.com/interactive/2011/03/13/world/asia/satellite-photos-japan-before-and-after-tsunami.html

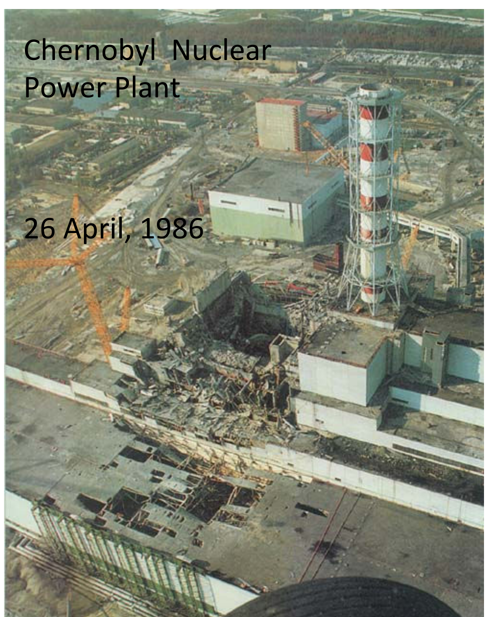
Fukushima Daiichi Nuclear Plant

http://www.nytimes.com/interactive/2011/03/13/world/asia/satellite-photos-japan-before-and-after-tsunami.html

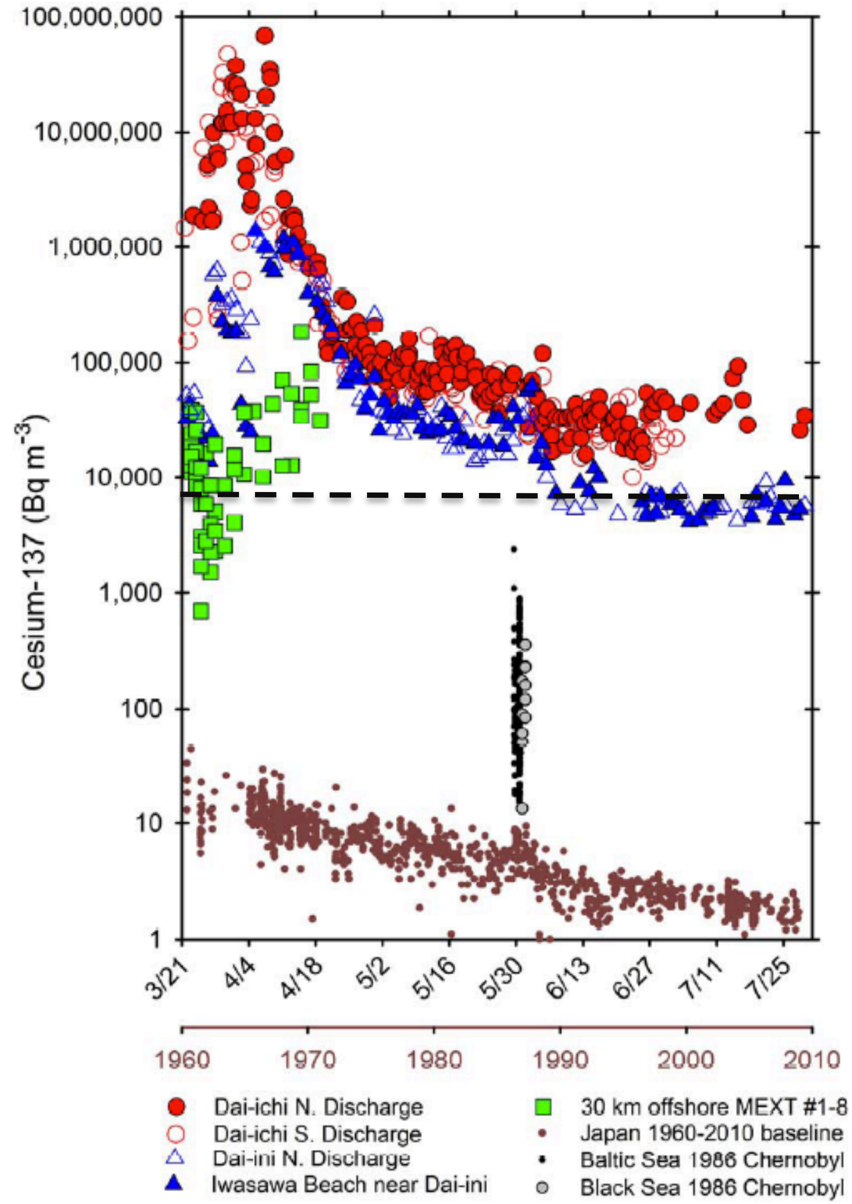
Fukushima Dai-ichi Radionuclides

Cs-137: Half life is 30 years
Cs-134: Half life is 2 years
I-131: Half life is 8 days

- (red circle) Fukushima Source
- (blue triangle) coastal water (5-10 km)
- (green square) 30 km offshore
- (small dot) Japan 1960-2010 baseline
- (black dot) Baltic Sea 1986 Chernobyl
- (grey circle) Black Sea 1986 Chernobyl
- (dashed line) US EPA drinking water standard



Buesseler et al. (2011)



Bq is a measuring unit for radioactivity,1Bq=1 atomic disintegration per second

Radioactive Water Loading

Time	Types	Source	Amount (ton)
7:03 PM April 4 to 5:40 PM, April 10	Dumping (LLRW)	A facility at crippled nuclear power complex to make room for the storage of highly contaminated water	**9070**
9:00 PM April 4 to 6:52 PM, April 9	Dumping (LLRW)	A sub-drain pit of Unit 5	**95**0
9:00 PM April 4 to 6:52 PM, April 9	Dumping (LLRW)	A sub-drain pit of Unit 6	**37**3
?? April 1 to 5:38 AM April 6	Leaking (HLRW)	Unit 2	**520** Cs-137: 9.4×10^{14} becquerels (Bq) Cs-134: 9.4×10^{14} Bq I-131: 2.8×10^{15} Bq
2:00 AM May 10 to 6:45 PM, May 11	Leaking (HLRW)	Unit 3	**250** Cs-137: 9.8×10^{12} Bq Cs-134: 9.3×10^{12} Bq I-131: 8.5×10^{11} Bq

LLRW: Low-level radioactive water; HLRW: High-level radioactive water

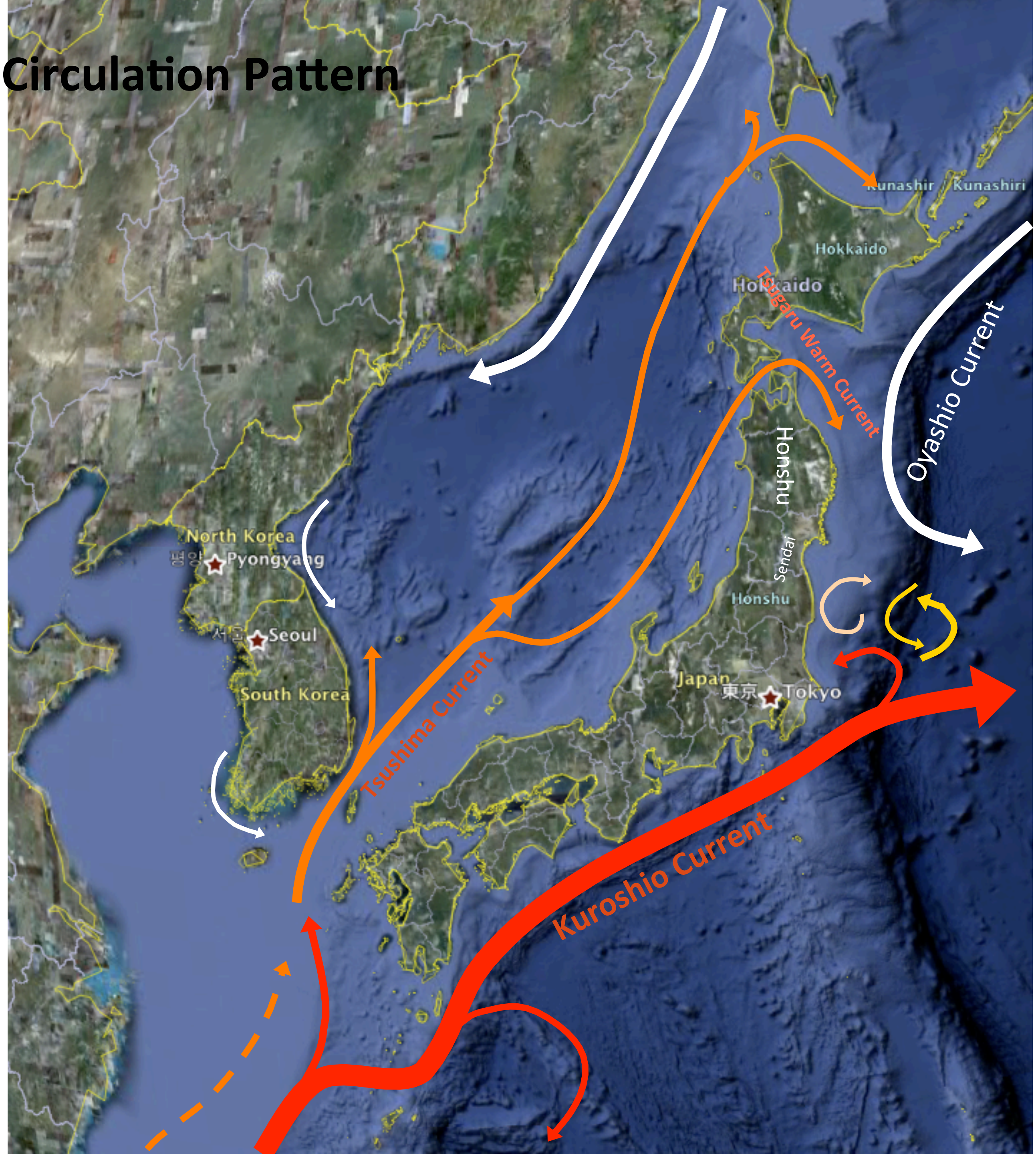
Questions:

1. Tsunami Inundation: How does Tsunami-solitary wave propagate towards the coast? In particularly, how does the water flood onto the coastal land and into Fukushima Daiichi Nuclear Plant?

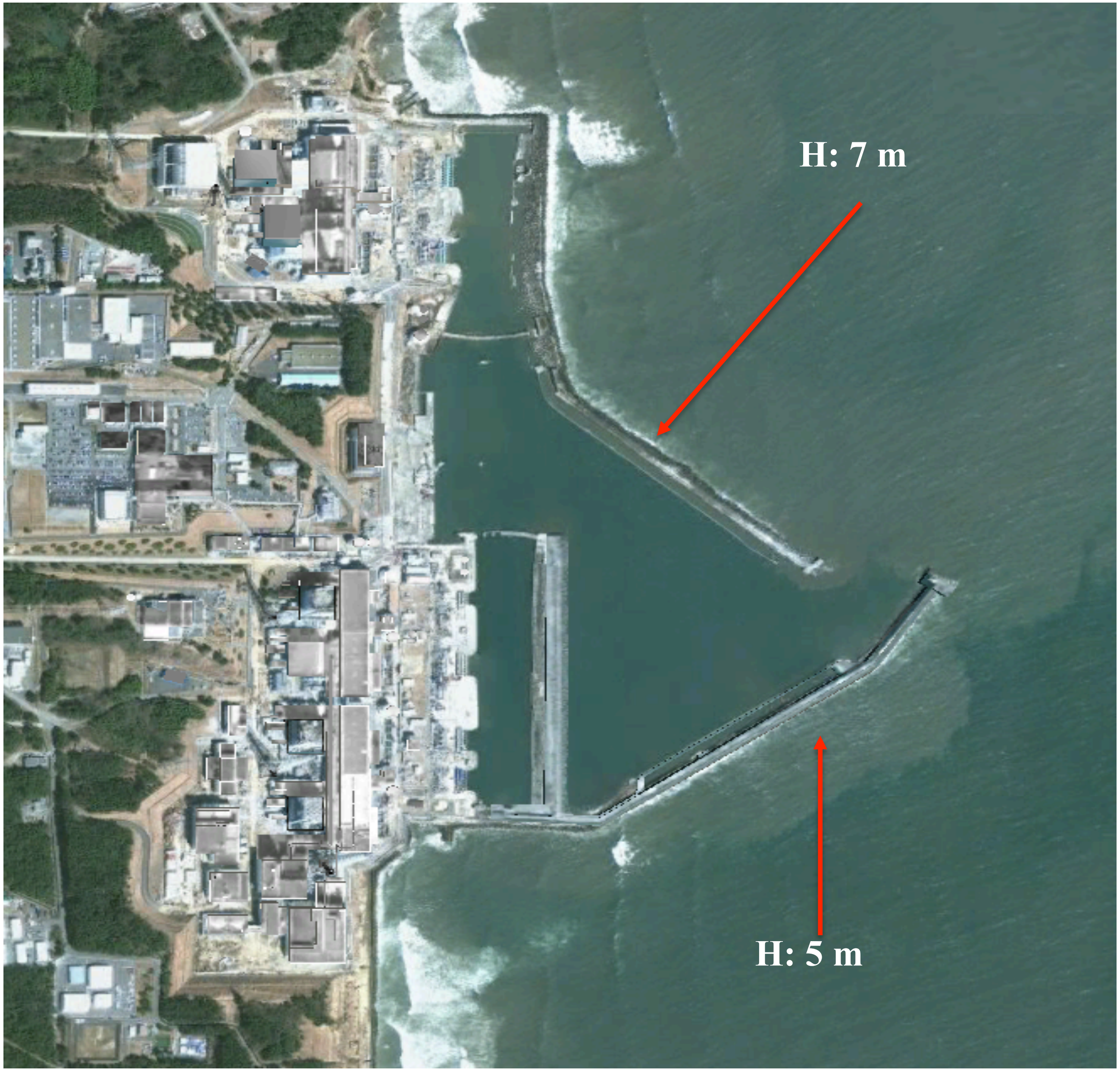
2. How the high-radioactive water flow out onto the shelf from Fukushima Daiichi Nuclear Plant? How high percent of Cs-134 and Cs-137 could be advected to the Pacific Ocean?

3. If Cs-134 and Cs-137 is advected to the Pacific Ocean, how long could they be transferred to the US coast and other coasts of surrounding countries?

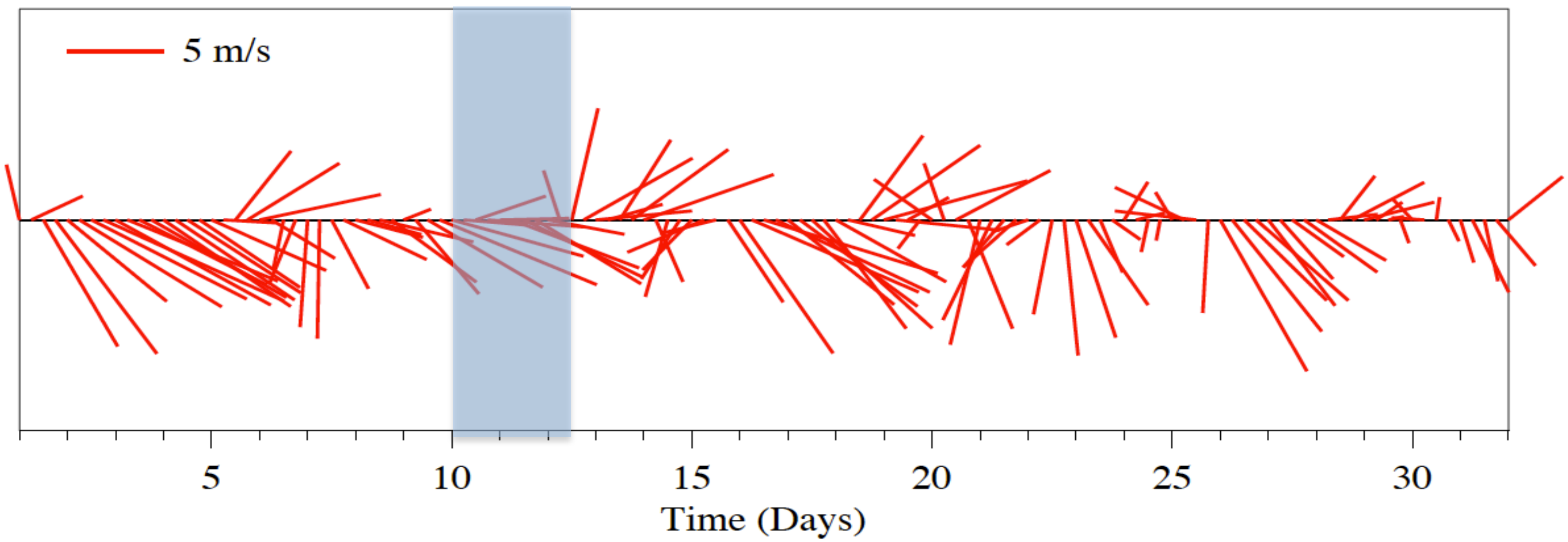
Regional Circulation Pattern

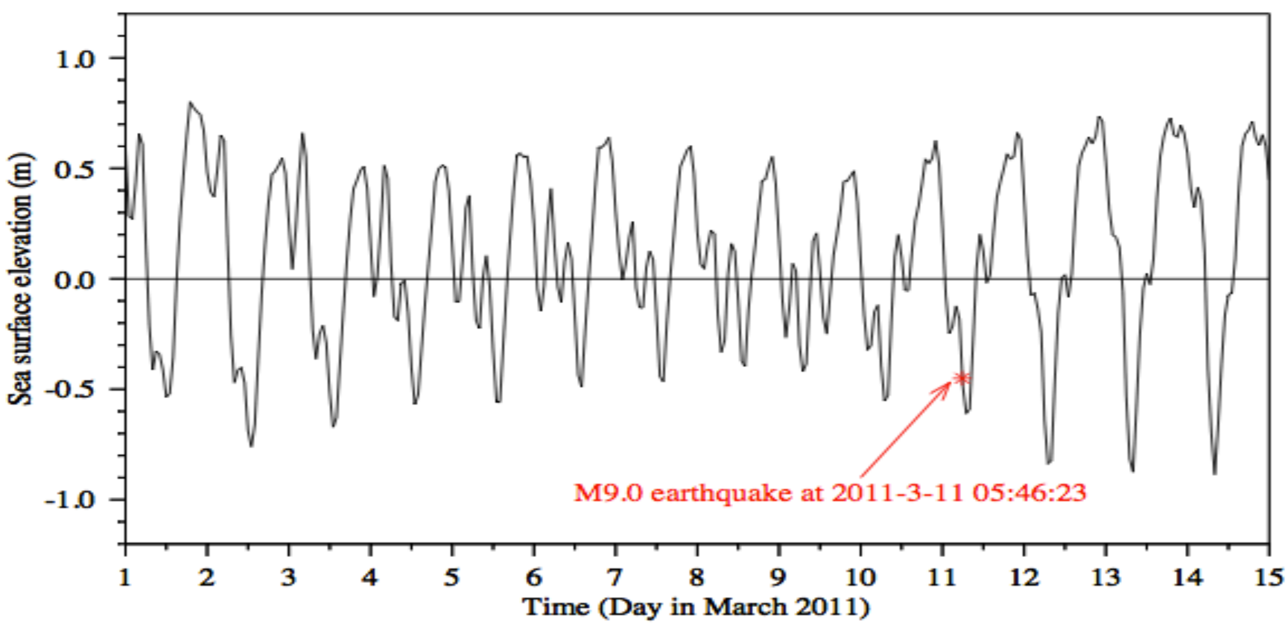


Fukushima Dai-ichi Nuclear Plant Facility



The wind velocity vectors at the 10-m height off Sendai, Japan





The sea level at the coast when the earthquake occurred

What do we need to address listed questions?

1. A sound earthquake model capable of reproducing the sea floor change caused by the earthquake?

2. A global-regional-coastal model system to resolve a) global ocean and regional circulation and b) coastal inundation. This model must includes a complete physics: realistic meteorological forcing, tides, and wave, etc.

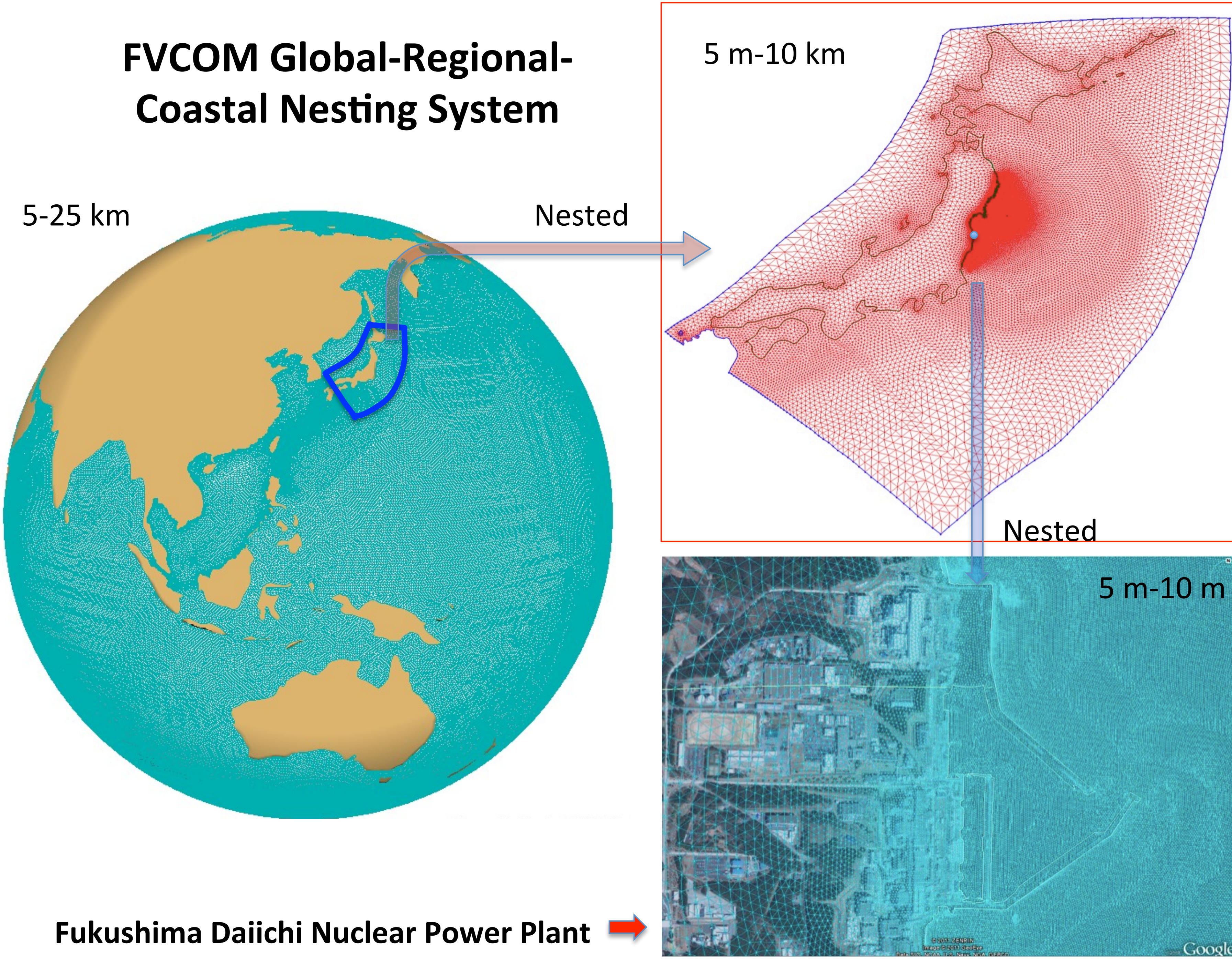
3. High-resolution bathymetric data for both ocean and lands.

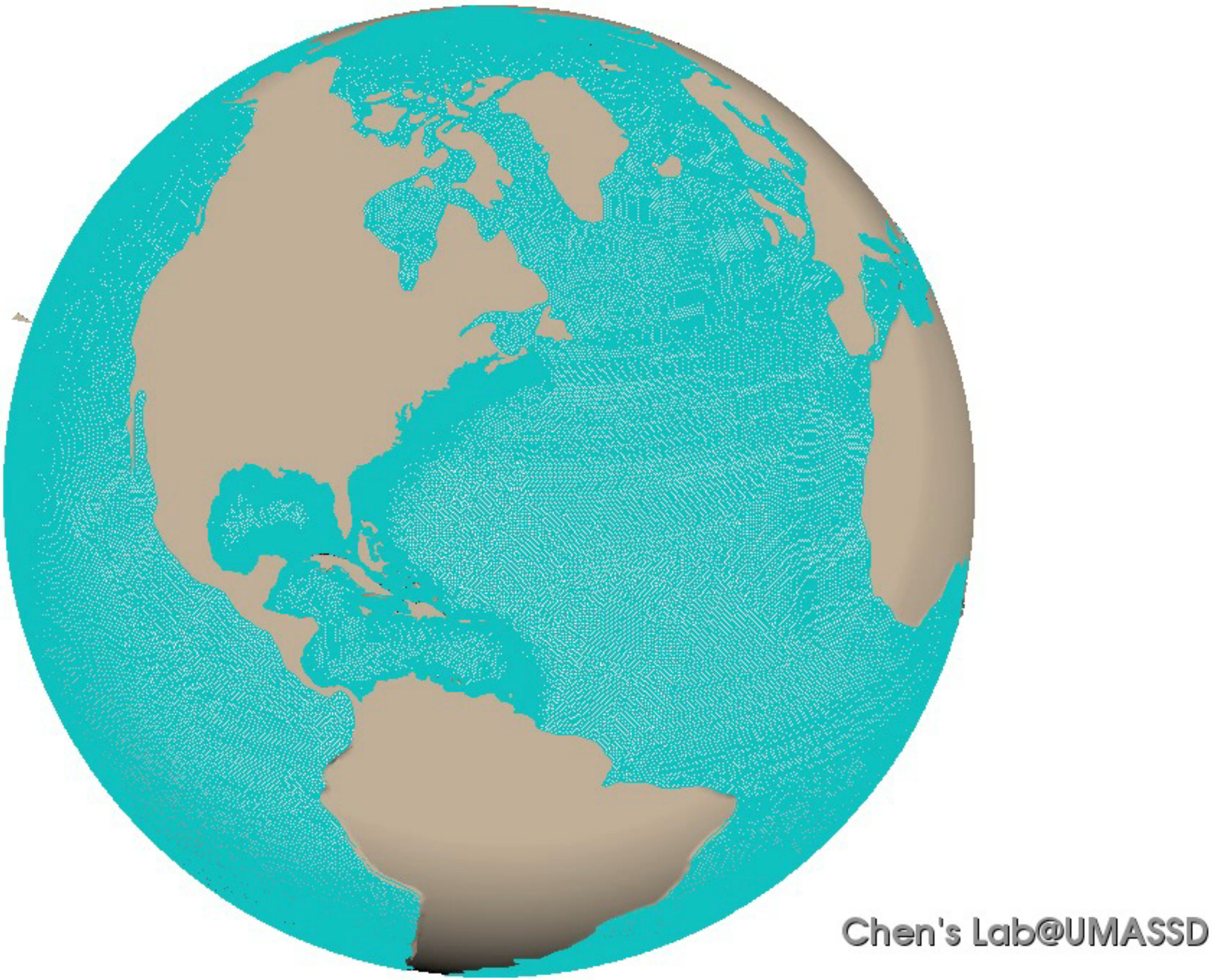
4. Detailed field measurements

In addition:

To resolve the geometry of Fukushima Daiichi Nuclear Plant, we need a resolution of ~ 5 m.

FVCOM Global-Regional-Coastal Nesting System




Chen's Lab@UMASSD


© 2011 ZENRIN
Image © 2011 GeoEye
Google

Approach

Step 1:

Run Global-FVCOM with the hindcast meteorological forcing, river discharges and tides (8 major tidal constituents) from January 1, 2011 to March 15, 2011. The experiments are made with inclusion of daily SSH and SST data assimilation.

Step 2:

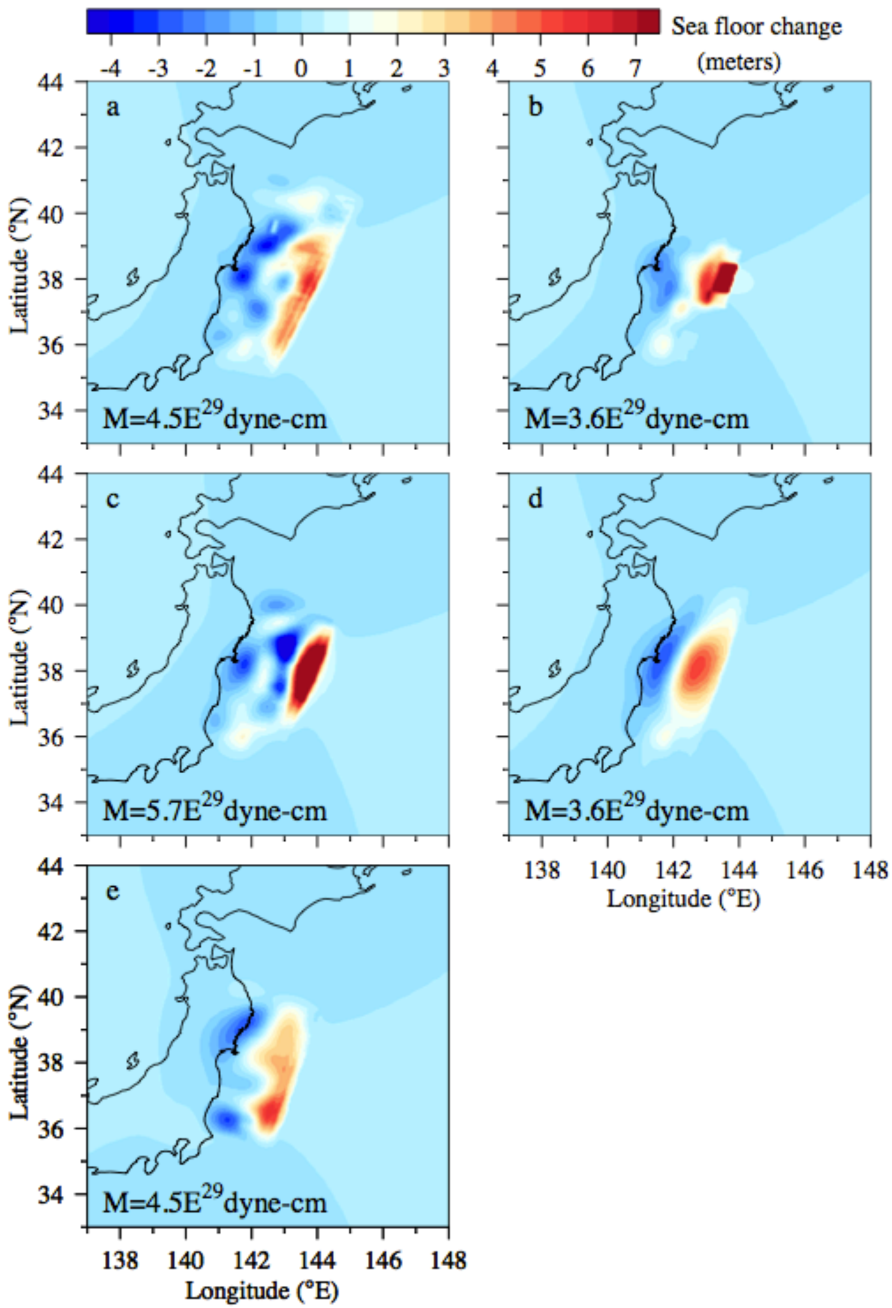
Re-run Global-FVCOM with a restart time at 00:00 GMT, March 11, 2011 and add the seafloor change at 5:46 GMT (the time when the earthquake occurred). A total of 6 earthquake models are considered.

Step 3:

Run the high-resolution FVCOM coastal inundation model (with a resolution up to 5 m) with the same meteorological forcing from Global-FVCOM and initial earthquake-induced sea level setup from the earthquake model.

Step 4:

Release tracers and track them in a 3-D high-resolution field.



Calculated bottom elevation and depression change caused by March 11 M=9 and M=7.9 quakes estimated by five seismic models:

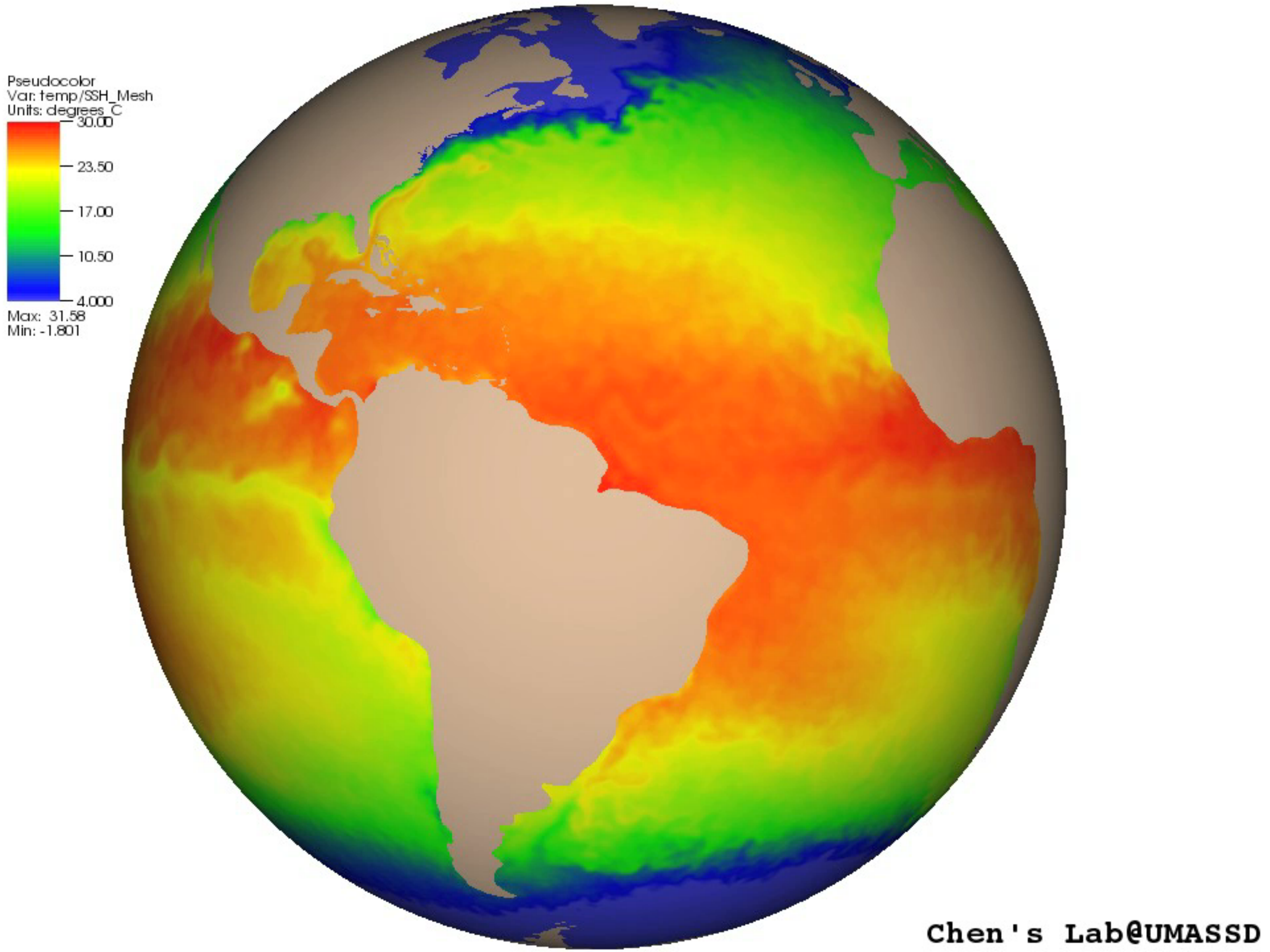
Case-a: *Wei and Sladen* (2011)
(with data sources from teleseismic P, SH and long period surface waves plus static GPS);

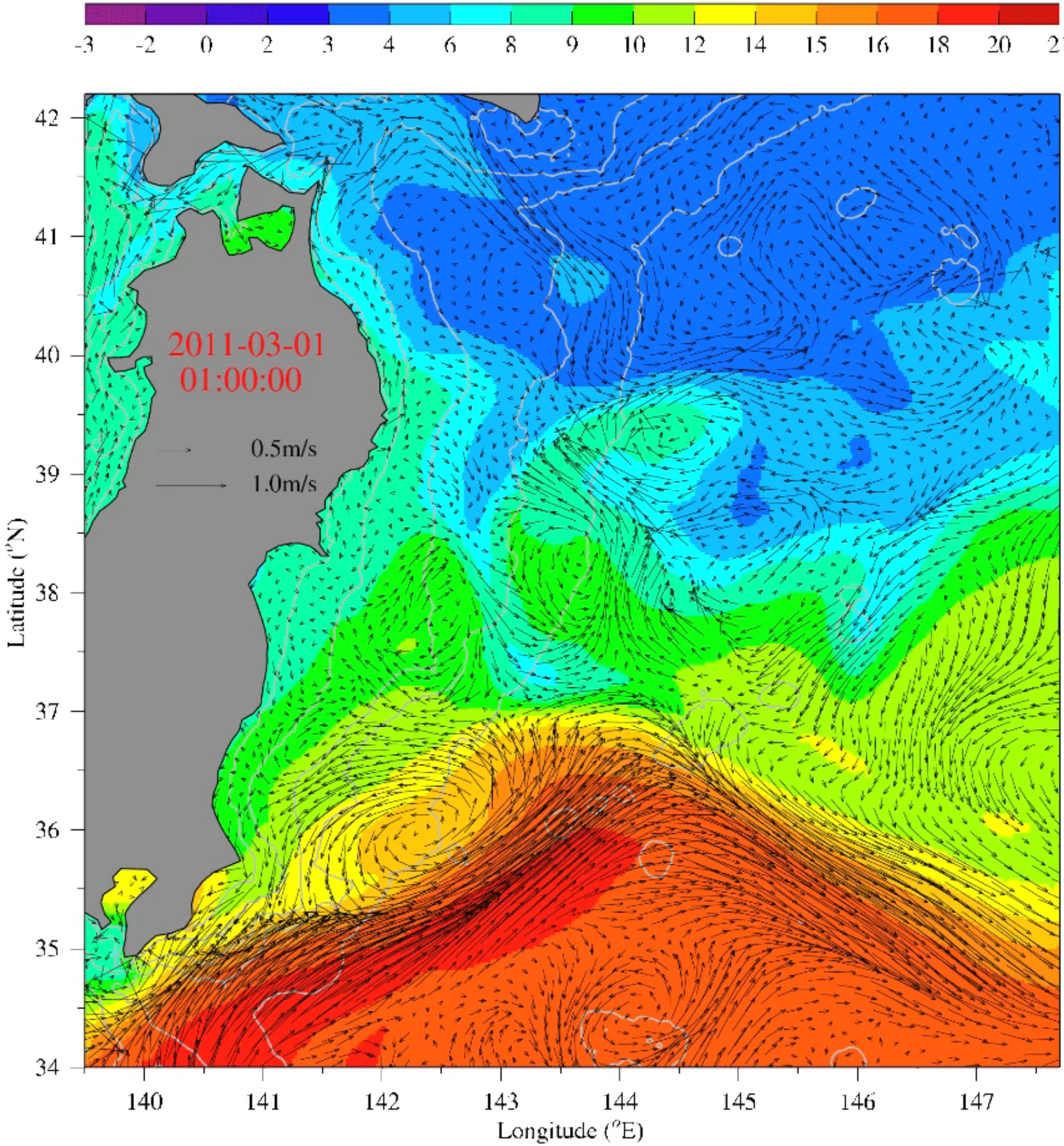
Case-b: *Fujii and Satake* (2011)
(with data sources from DART tsunamigrams and tidal guages);

Case-c: *Shao et al* (2011)
(with data sources from the same data source as *Wei and Slanden*'s except no GPS);

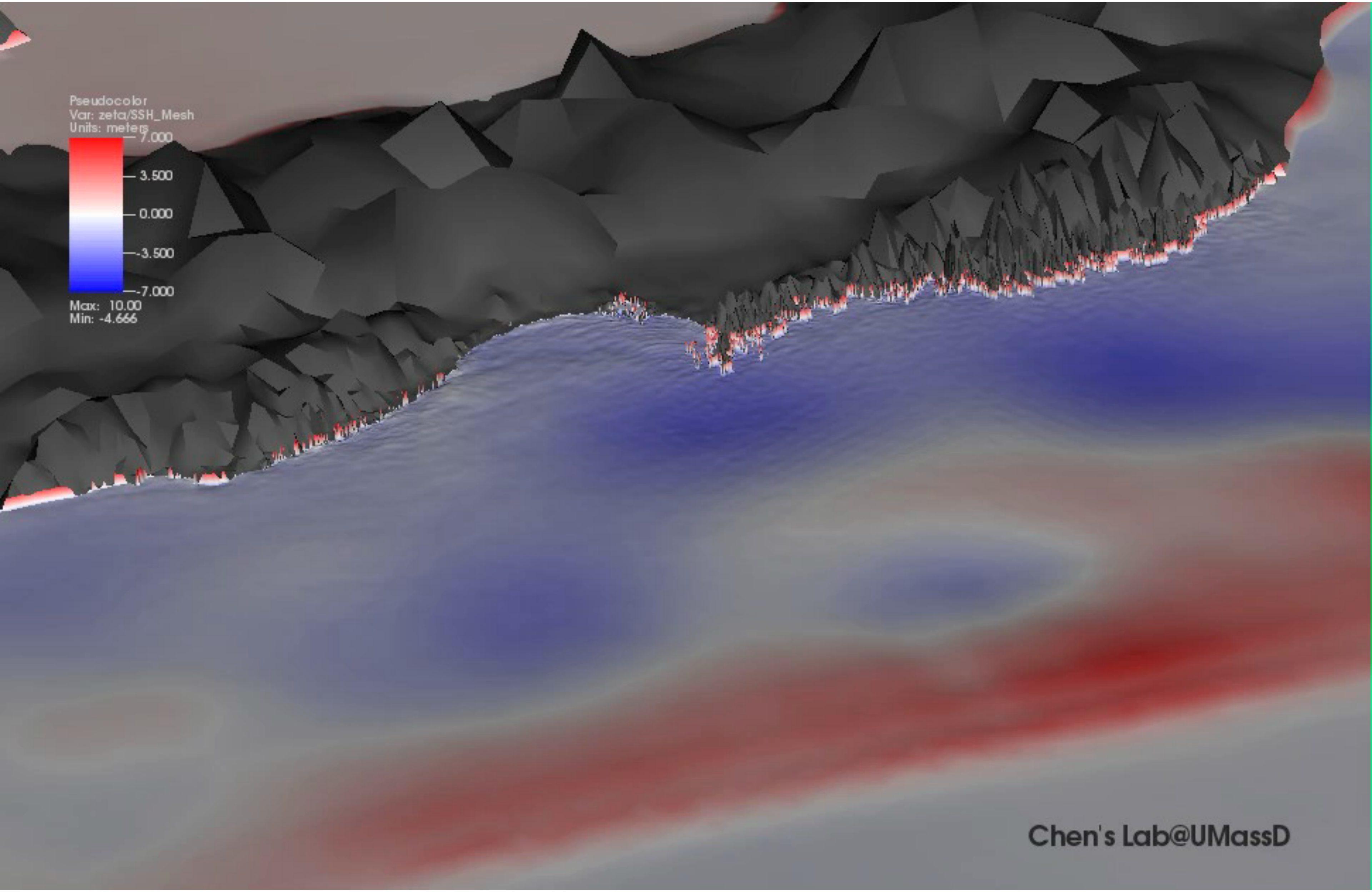
Case-d: *Pollitz and Burgmann* (2011)
(with data sources from static GPS and smoothed from 15,876 patches);

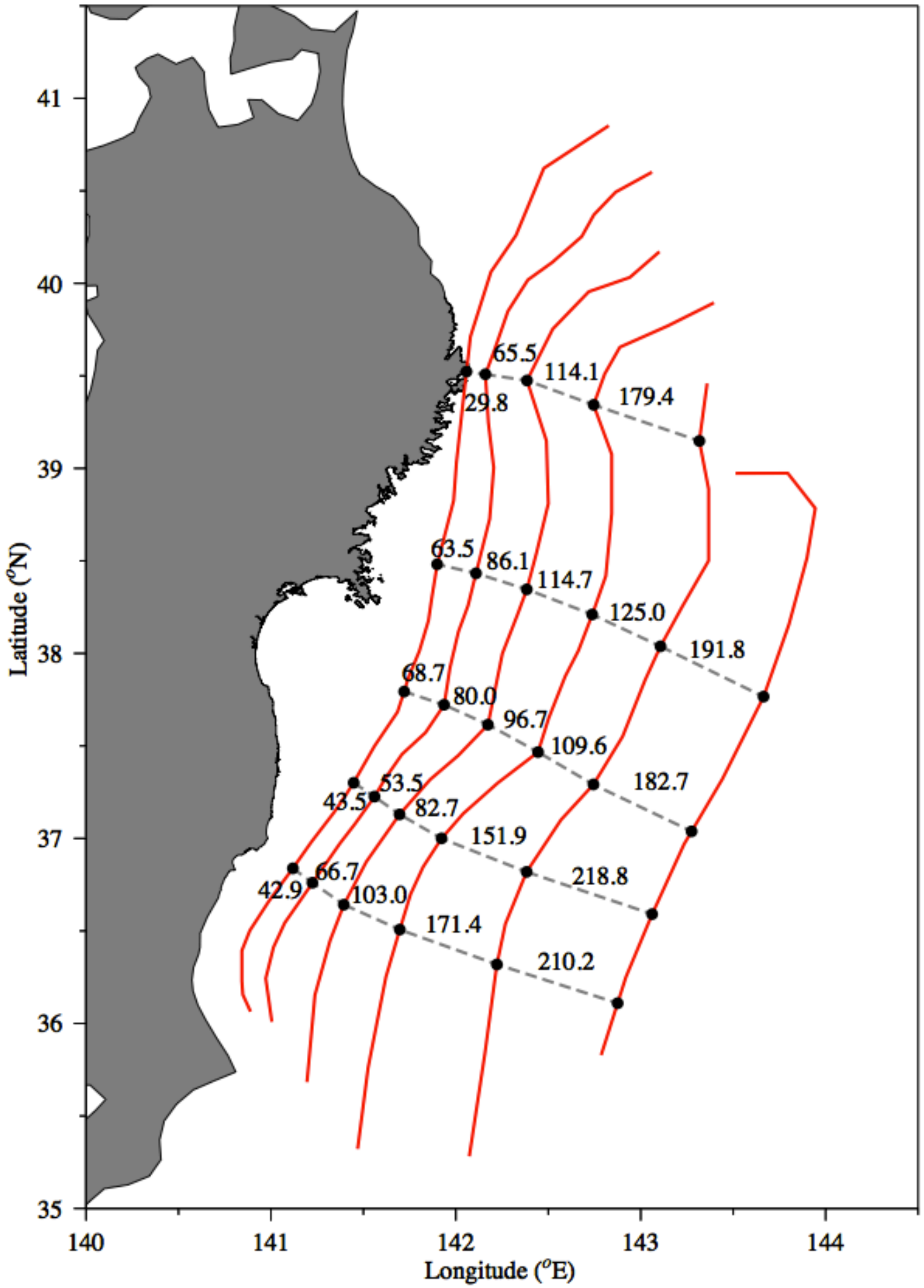
Case-e: *Yagi* (2011)
(with data sources from teleseismic body waves).


Pseudocolor
Var: temp/SSH_Mesh
Units: degrees_C
30.00
23.50
17.00
10.50
4.000
Max: 31.58
Min: -1.801
Chen's Lab@UMASSD



-3
-2
0
2
3
4
6
8
9
10
12
14
15
16
18
20
21
2011-03-01
01:00:00
0.5m/s
1.0m/s
42
41
40
39
38
37
36
35
34
Latitude (°N)
140
141
142
143
144
145
146
147
Longitude (°E)


Pseudocolor
Var: zeta/SSH_Mesh
Units: meters
7.000
3.500
0.000
-3.500
-7.000
Max: 10.00
Min: -4.666
Chen's Lab@UMassD



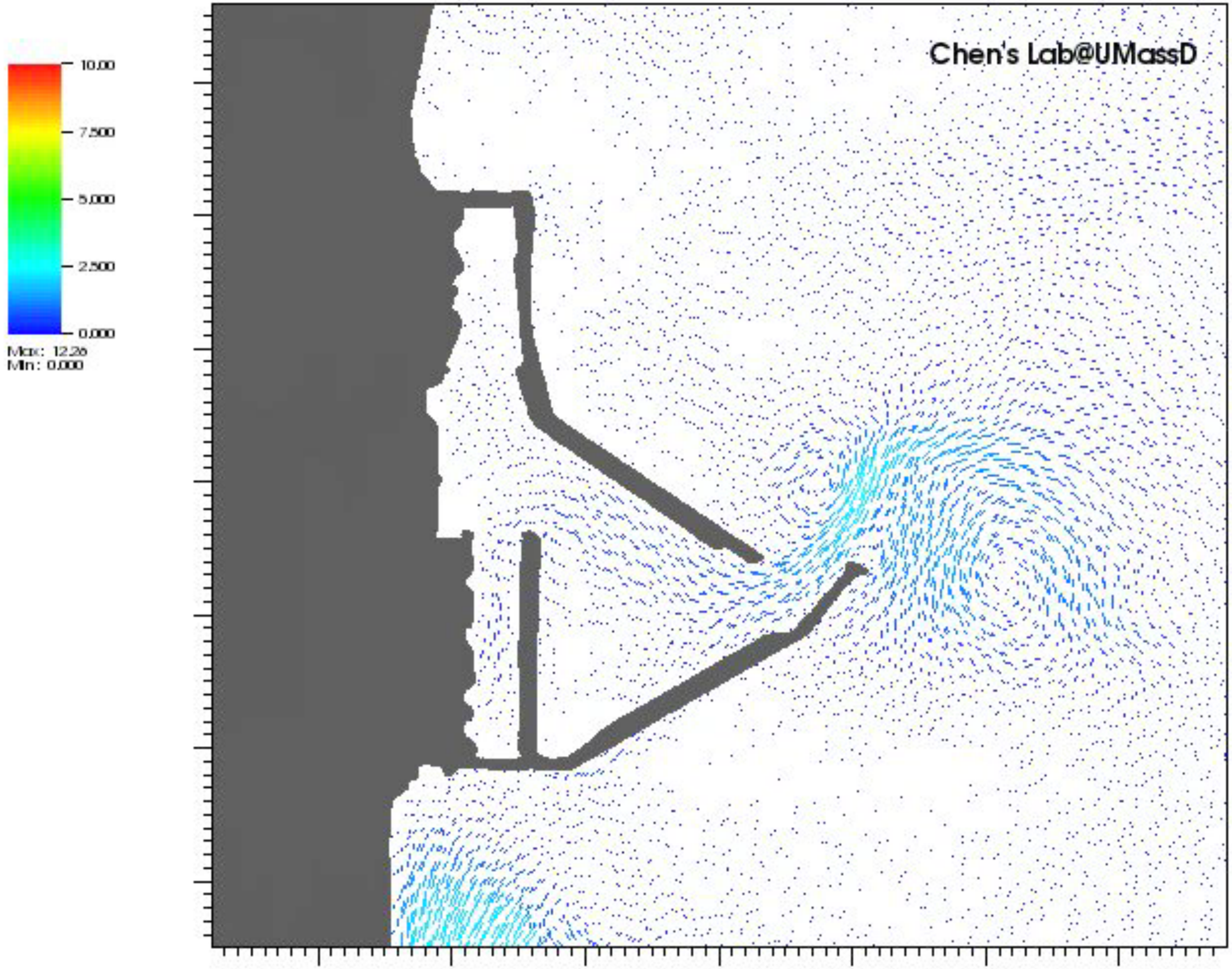
The propagation speed of the Tsunami Solitary Wave

Red line:

The location of the wave crest.

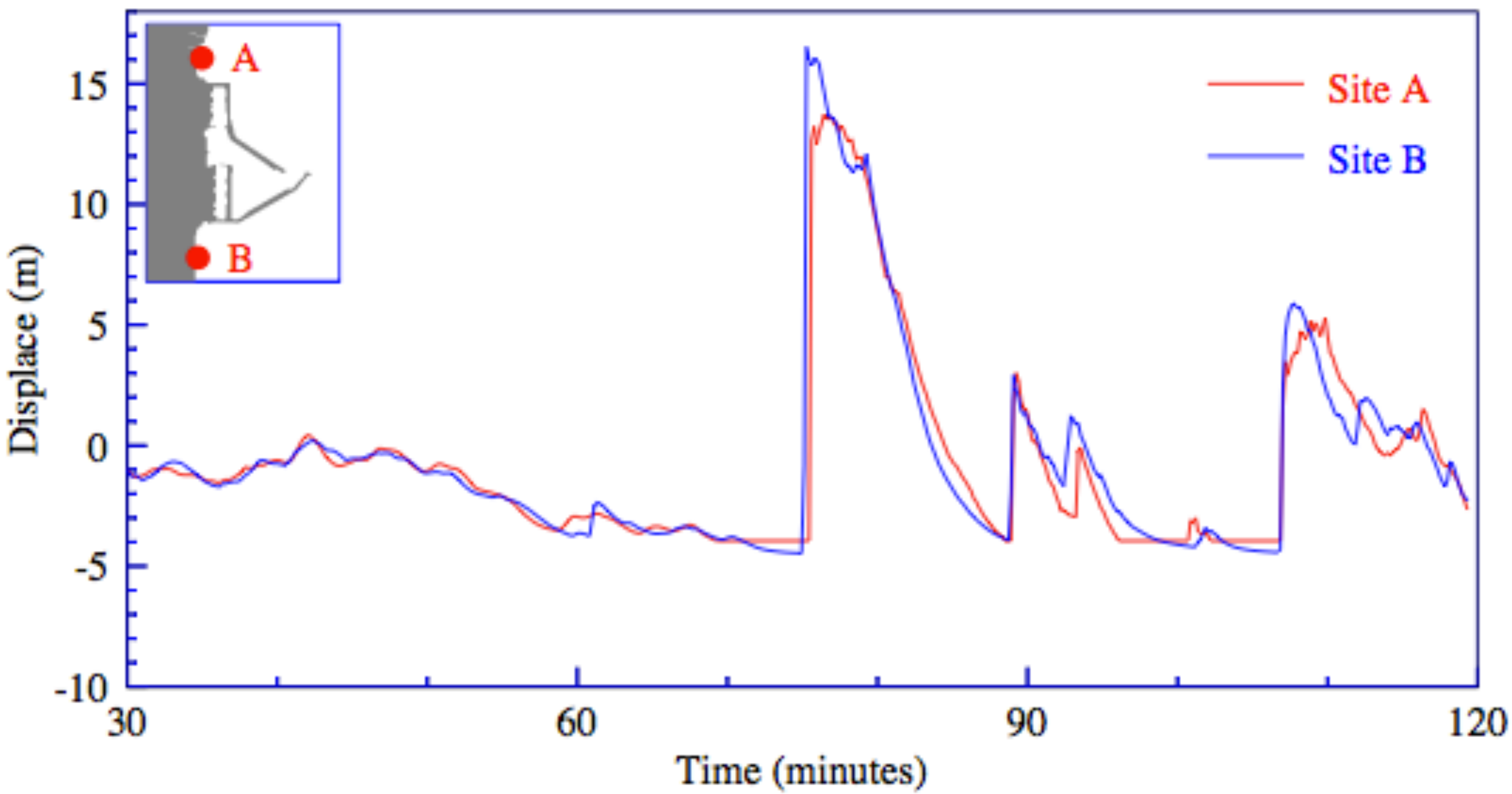
Number:

Propagation speed (m/s)



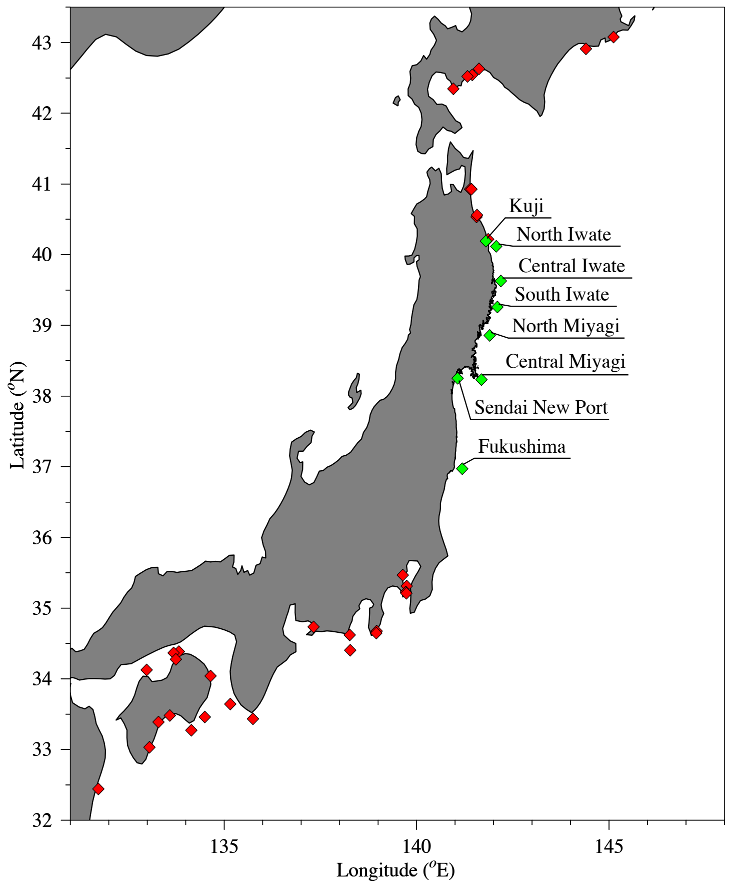
10.00
7.500
5.000
2.500
0.000
Max: 12.26
Min: 0.000
Chen's Lab@UMassD

Tsunami-derived water levels

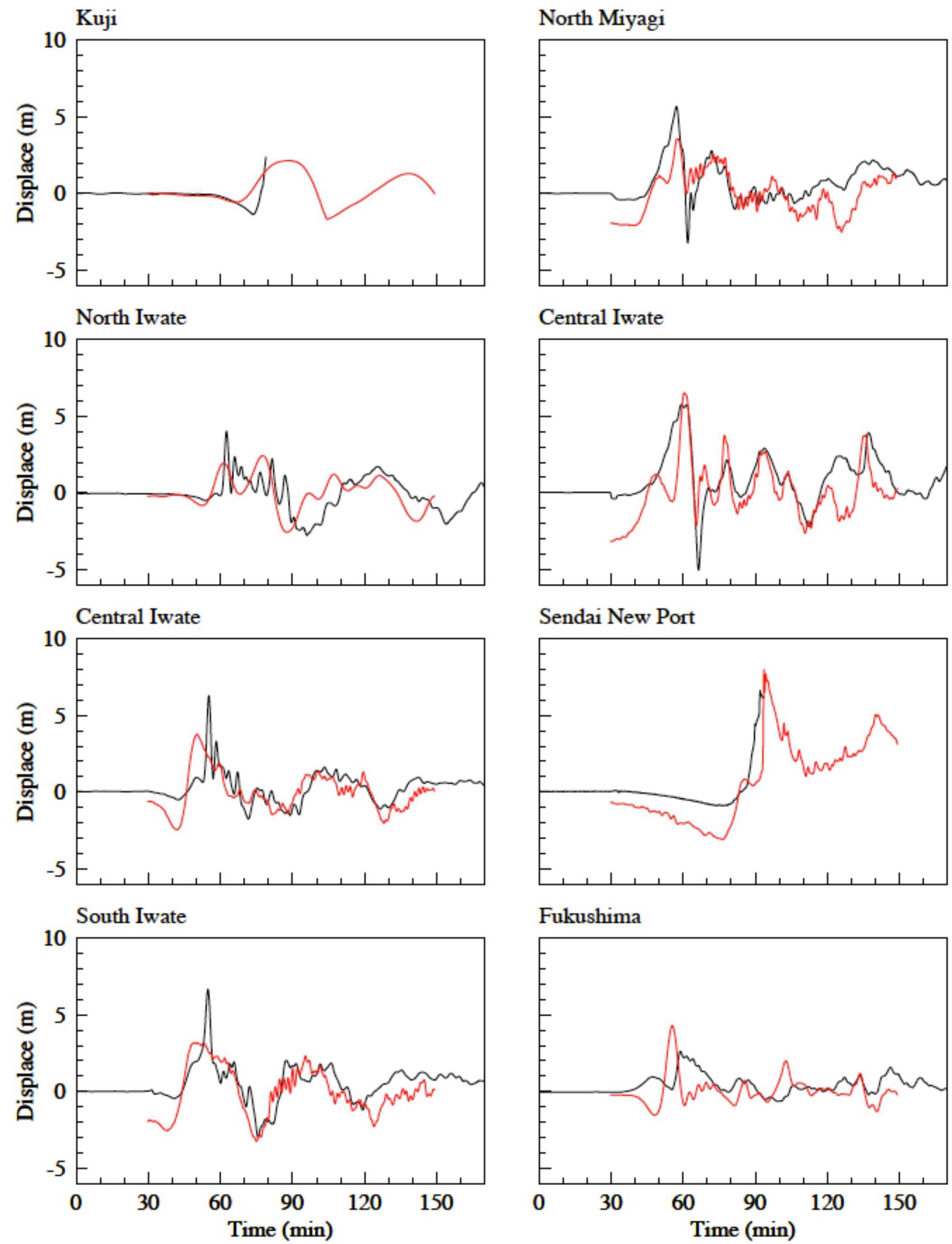


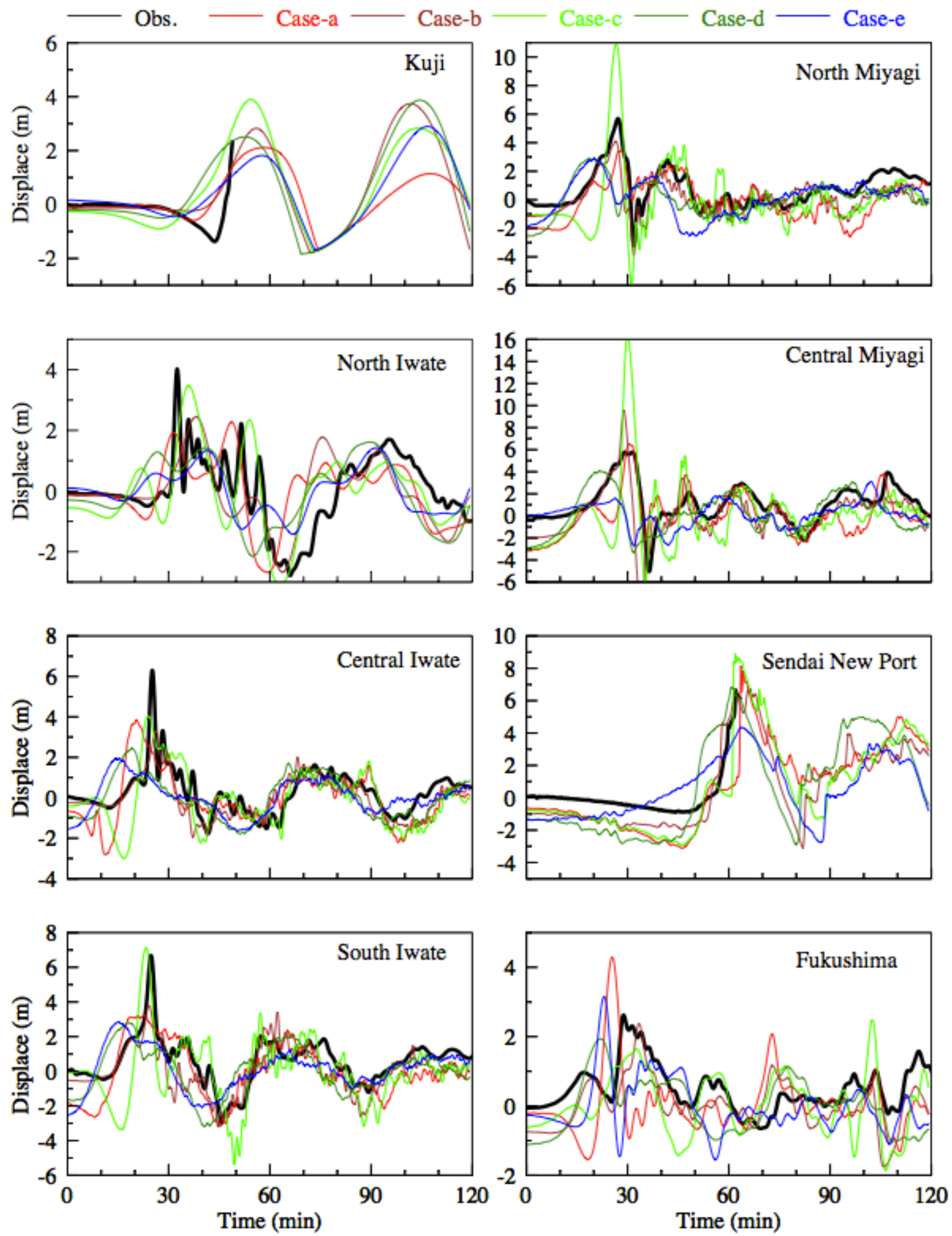
Photos of strong vortex during 2011 event provided by Kyeong Ok Kim at KORDI, South Korea.

Time series comparisons

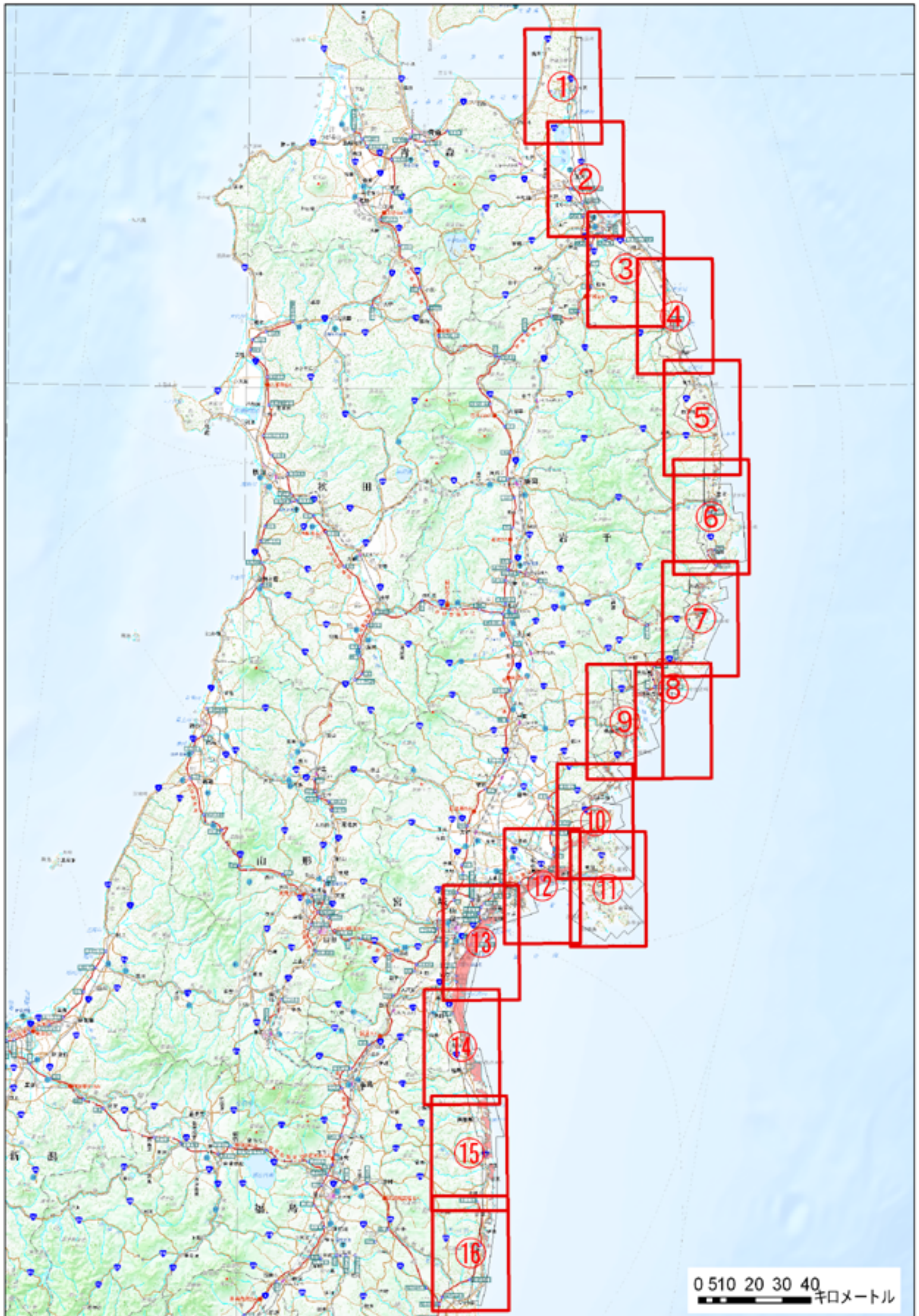


For case-a



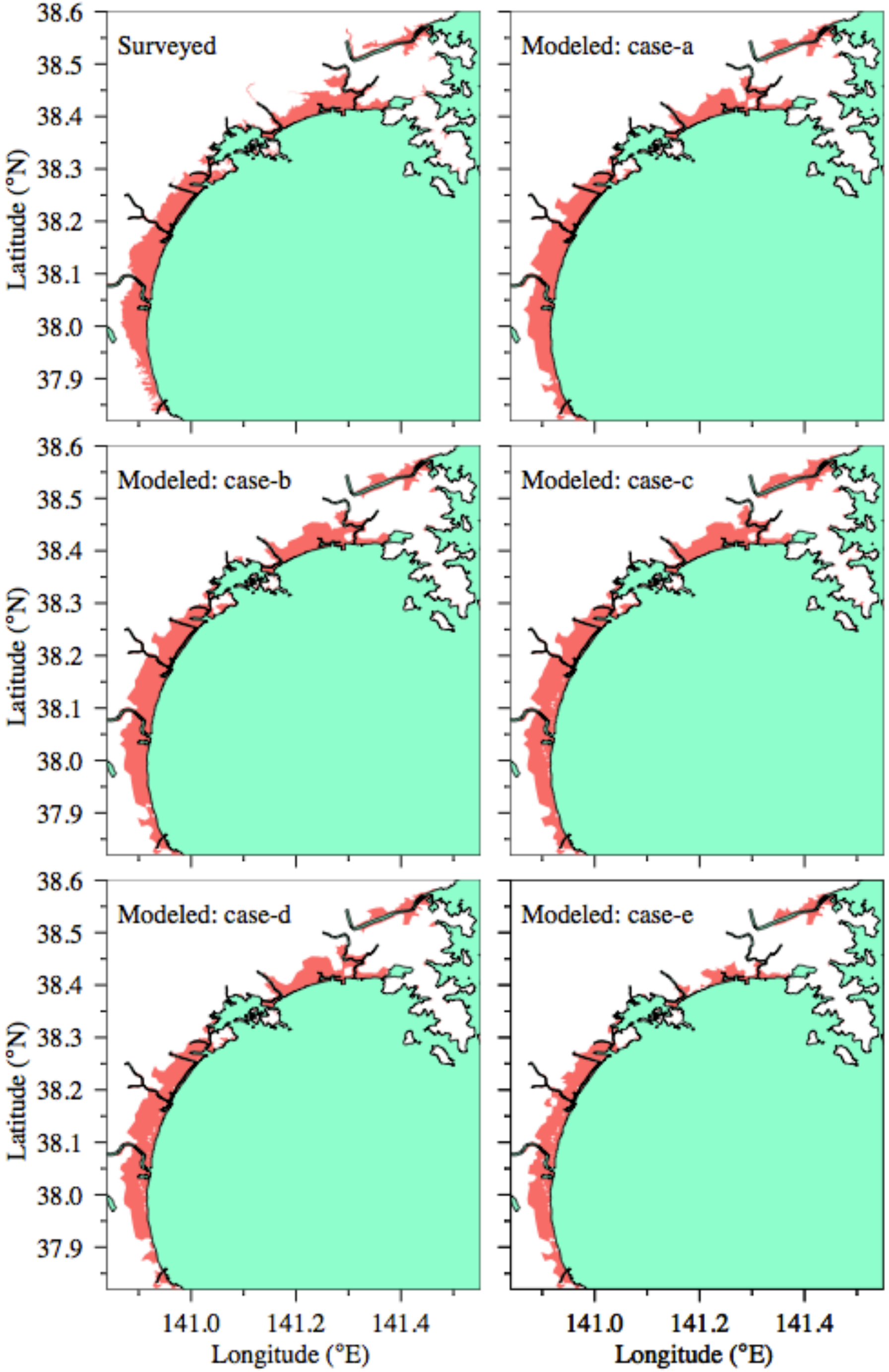


Obs.
Case-a
Case-b
Case-c
Case-d
Case-e
Kuji
North Miyagi
North Iwate
Central Miyagi
Central Iwate
Sendai New Port
South Iwate
Fukushima
Displace (m)
Time (min)

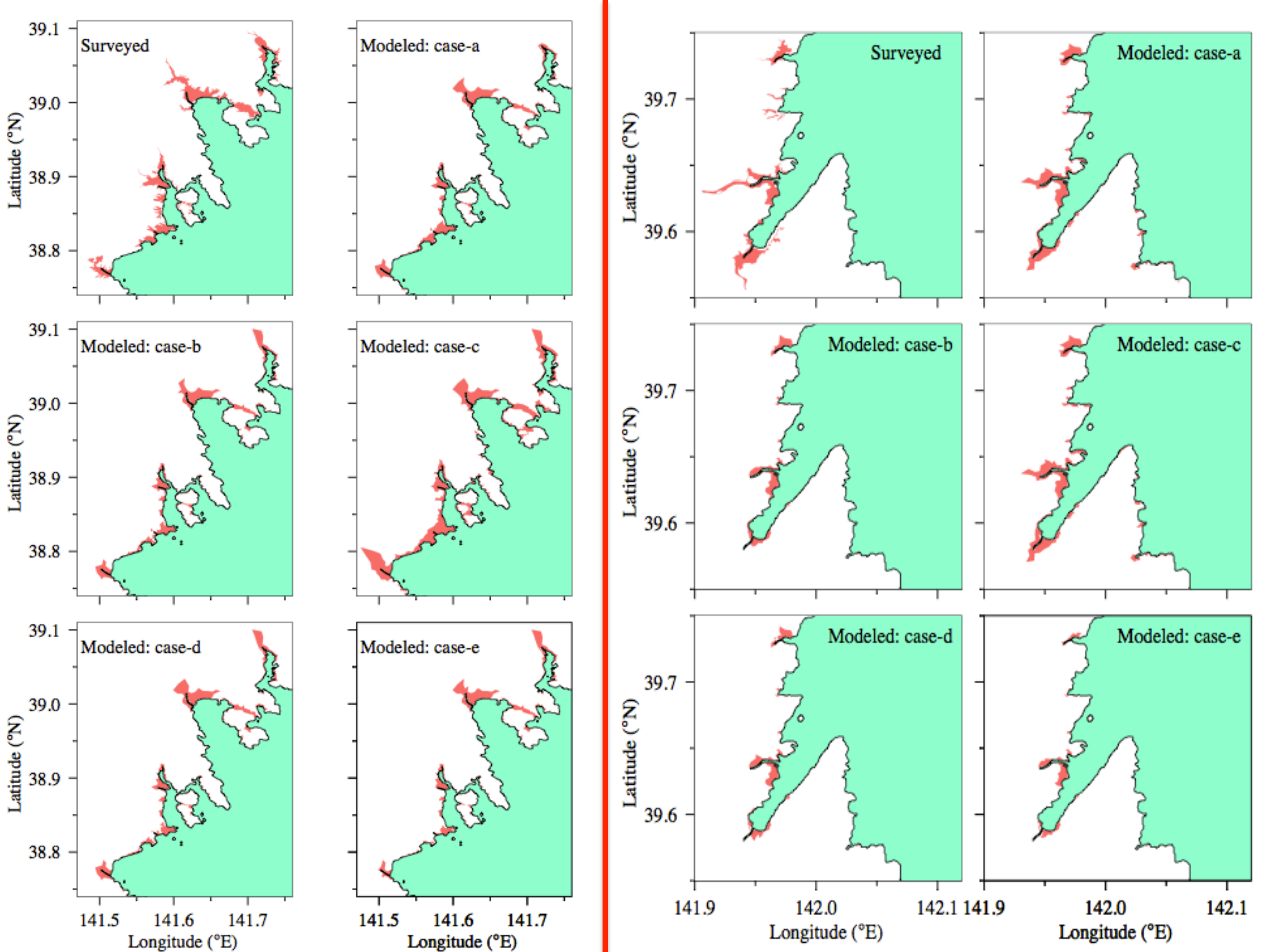


Survey regions of the Tsunami inundation area by Japanese survey teams.

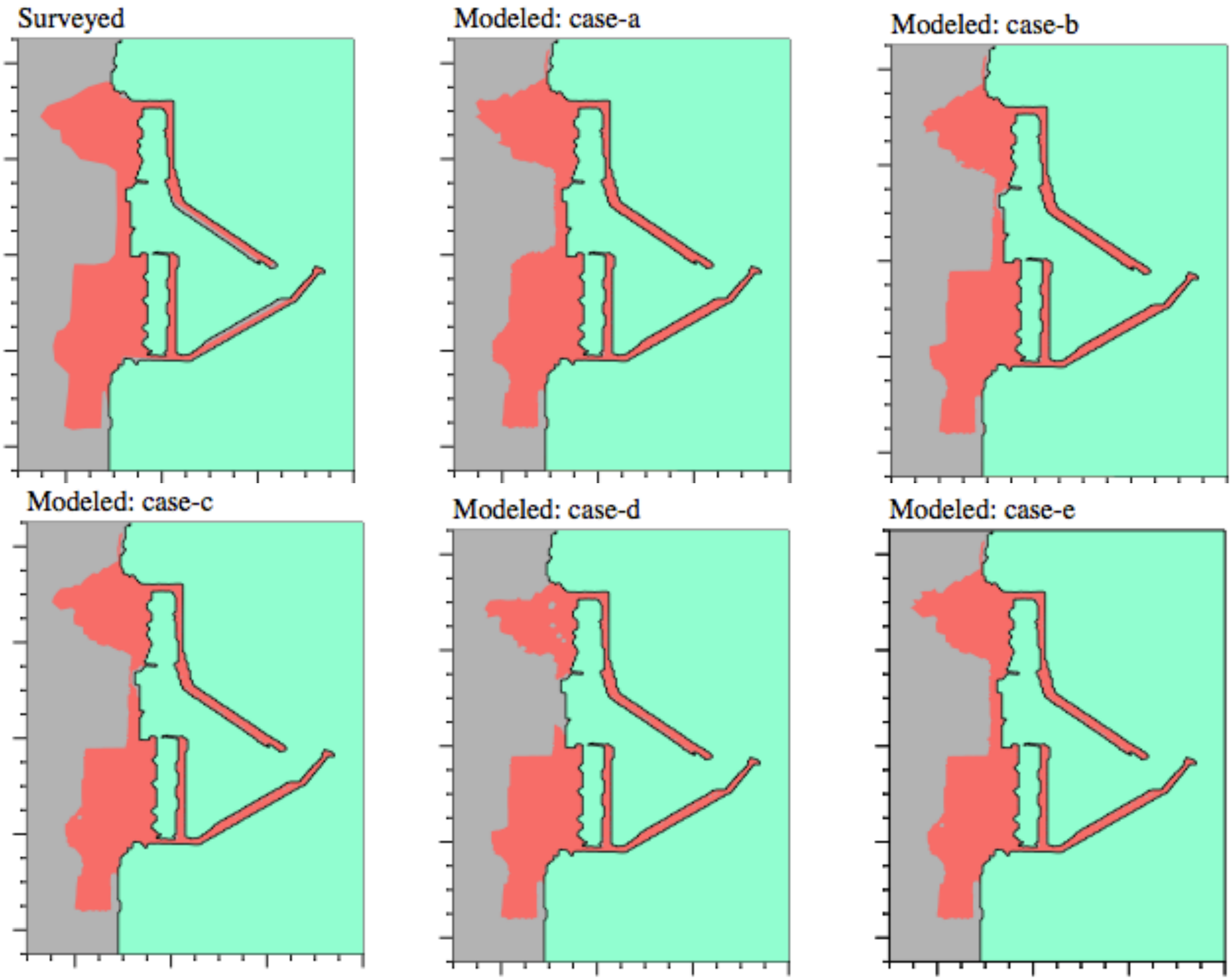
Total: 16 regions



Types	Inundated area (km^2)
Measured	32.89
Case-a	26.99
Case-b	28.94
Case-c	30.94
Case-d	26.87
Case-e	20.39



Surveyed
Modeled: case-a
Modeled: case-b
Modeled: case-c
Modeled: case-d
Modeled: case-e
Latitude (°N)
Longitude (°E)
39.1
39.0
38.9
38.8
141.5
141.6
141.7
39.7
39.6
141.9
142.0
142.1


Surveyed
Modeled: case-a
Modeled: case-b
Modeled: case-c
Modeled: case-d
Modeled: case-e

Questions:

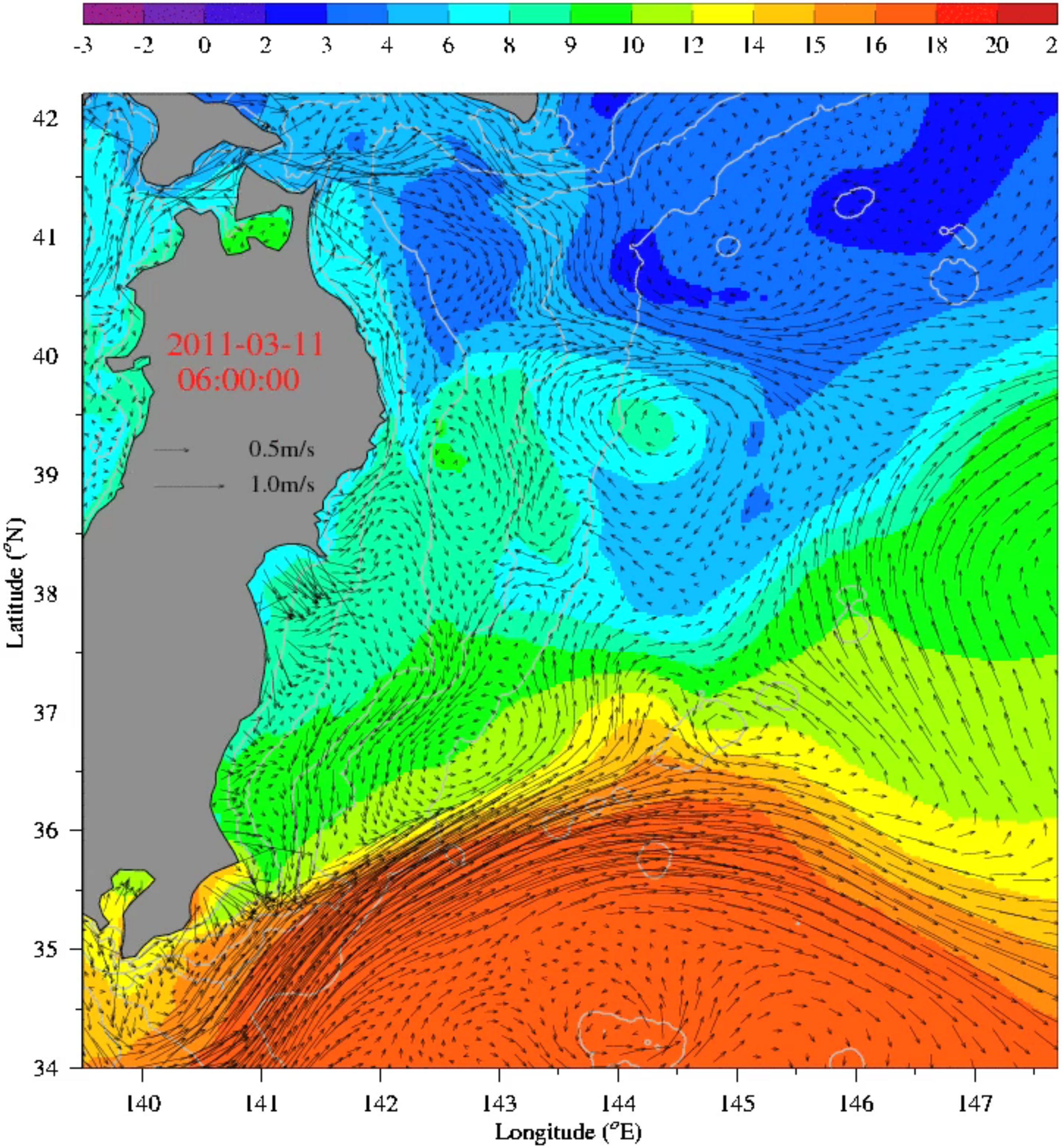
- **How could we track the CS-137 spreading?**
- **How are the results sensitive to model resolution?**

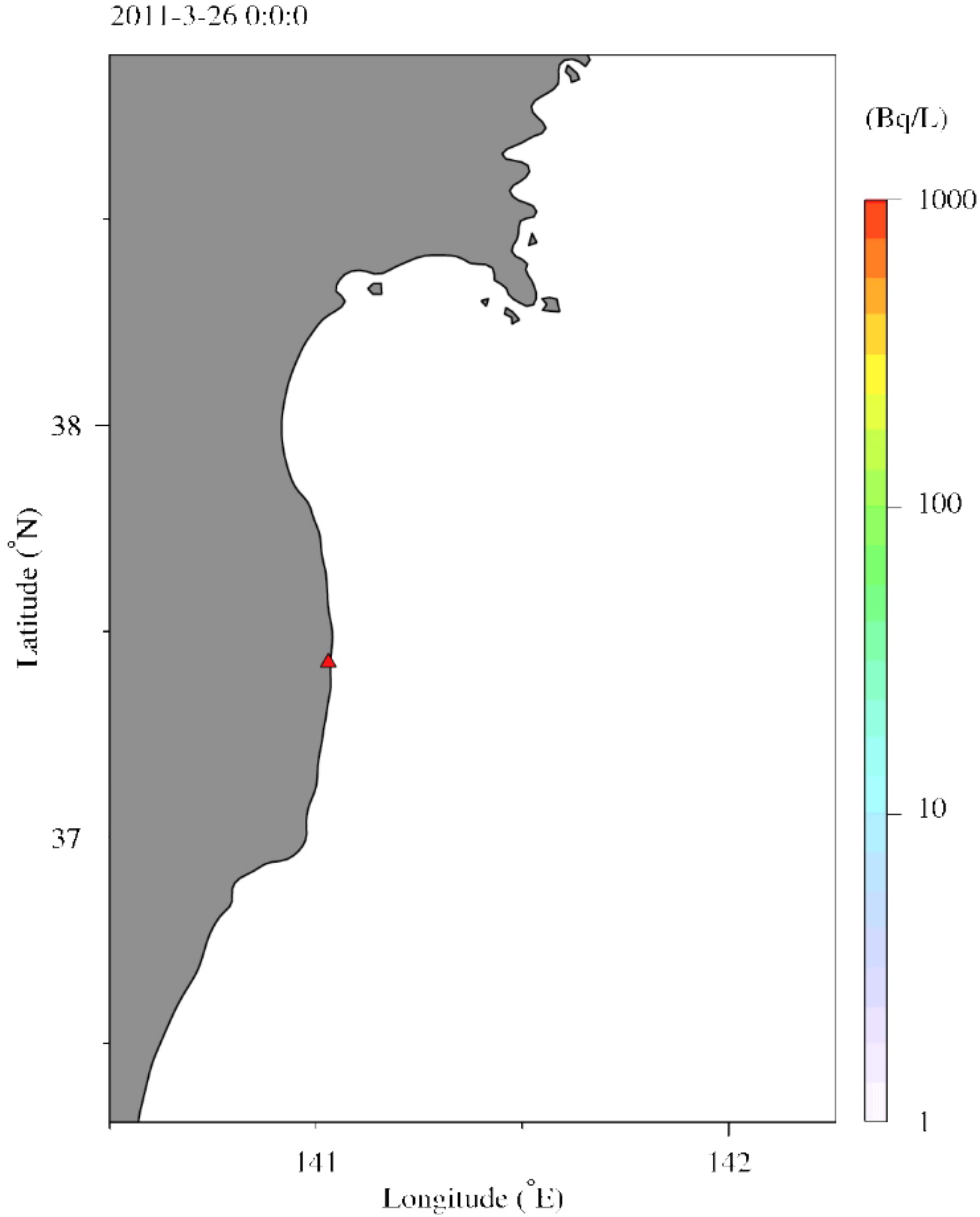
The movement of the center of the dye patch is controlled by

$$\frac{dx_c(t)}{dt} = \frac{1}{\hat{C}}\left[\int\int_A \bar{C}(\bar{u}h)dxdy + \int\int_A h\overline{c'u'}dxdy + \int\int_A xh\bar{C}_o dxdy\right]$$

$$\frac{dy_c(t)}{dt} = \frac{1}{\hat{C}}\left[\int\int_A \bar{C}(\bar{v}h)dxdy + \int\int_A h\overline{c'v'}dxdy + \int\int_A yh\bar{C}_o dxdy\right]$$

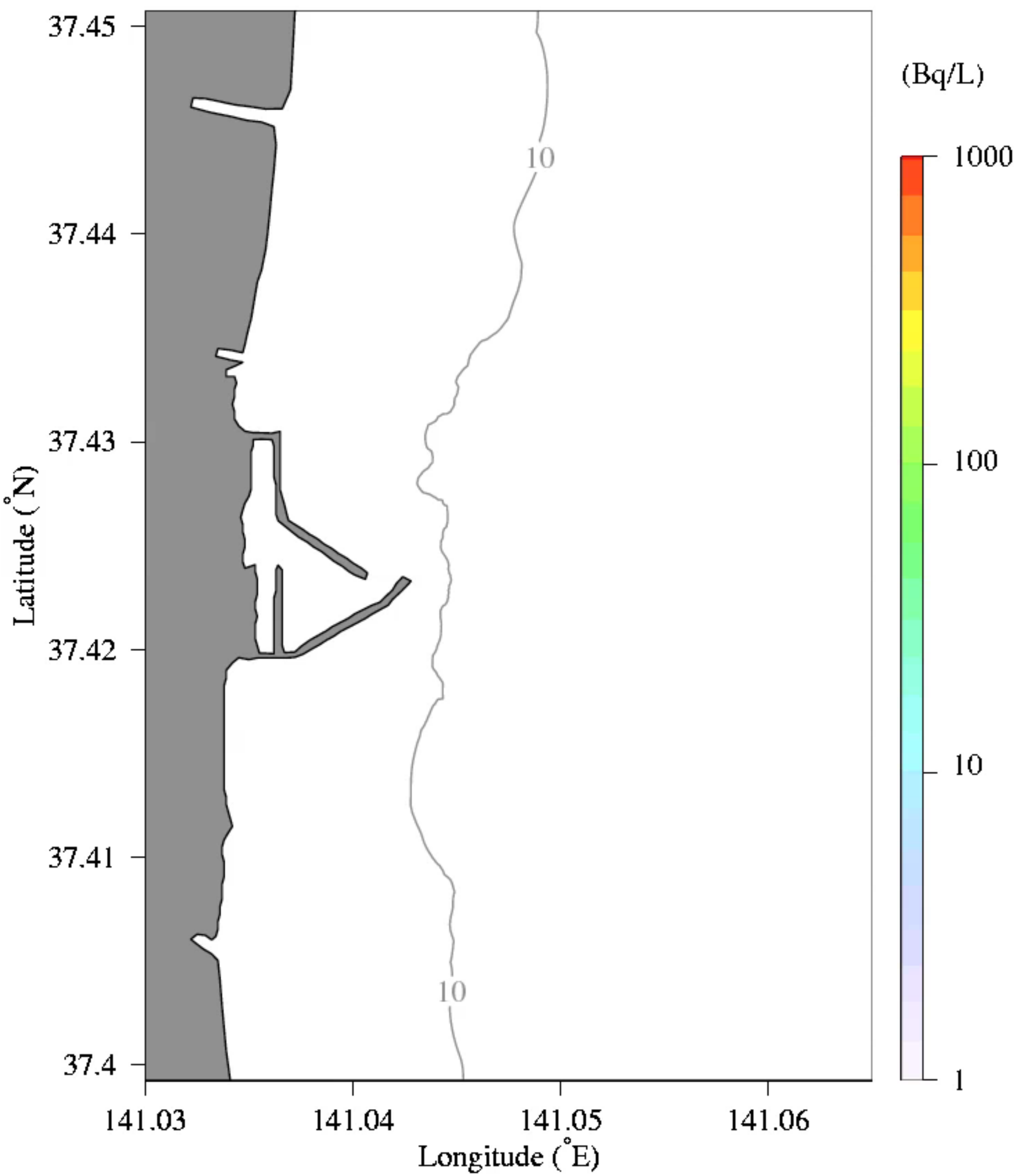
Chen et al. (2008): A model-dye comparison experiment in the tidal mixing front zone on the southern flank of Georges Bank, JGR-Ocean, 113, C02005


-3 -2 0 2 3 4 6 8 9 10 12 14 15 16 18 20 21
2011-03-11
06:00:00
0.5m/s
1.0m/s
Latitude (^{o}N)
42
41
40
39
38
37
36
35
34
140 141 142 143 144 145 146 147
Longitude (^{o}E)

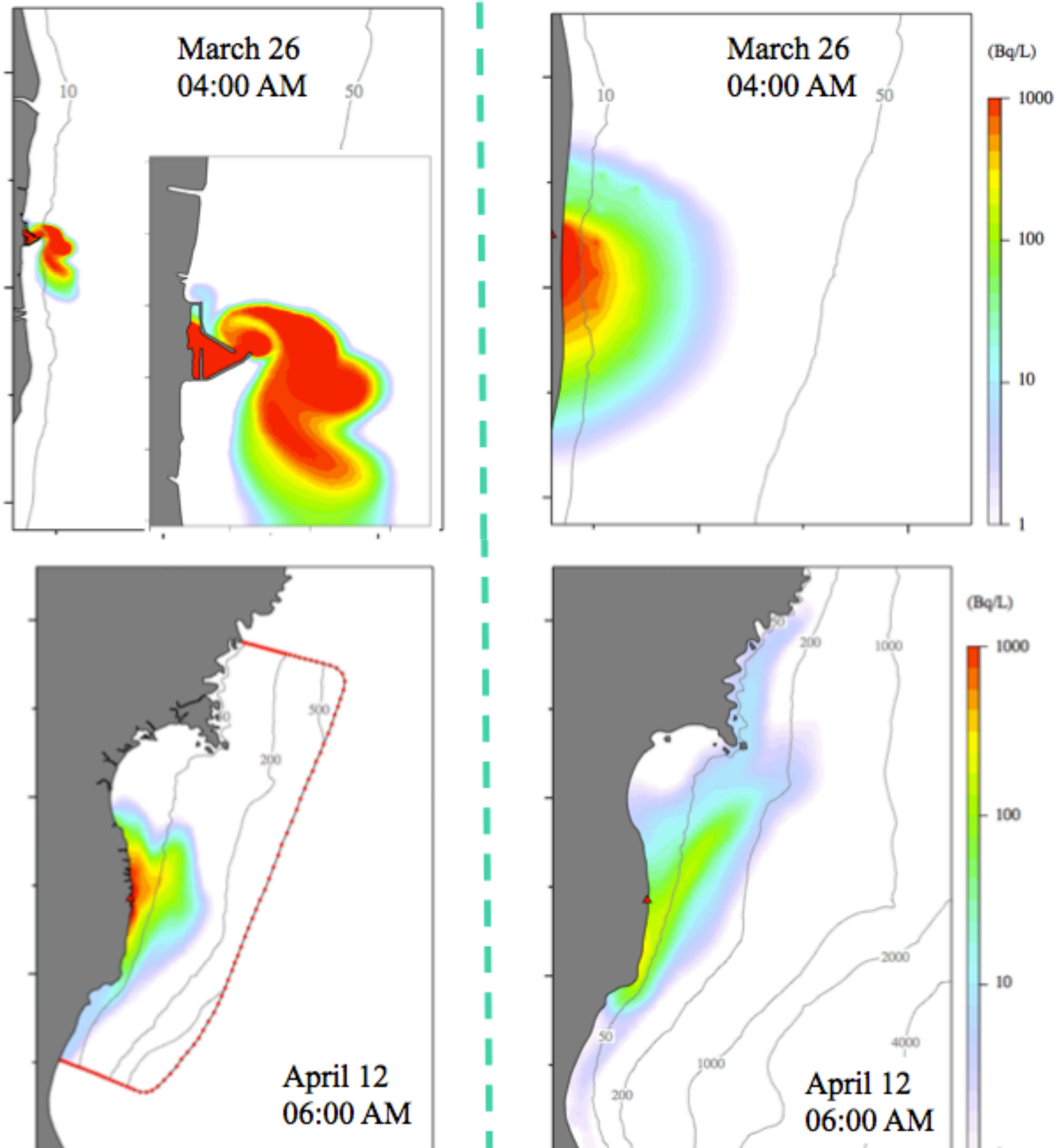


2011-3-26 0:0:0
(Bq/L)
1000
100
10
1
38
37
Latitude (°N)
141
142
Longitude (°E)

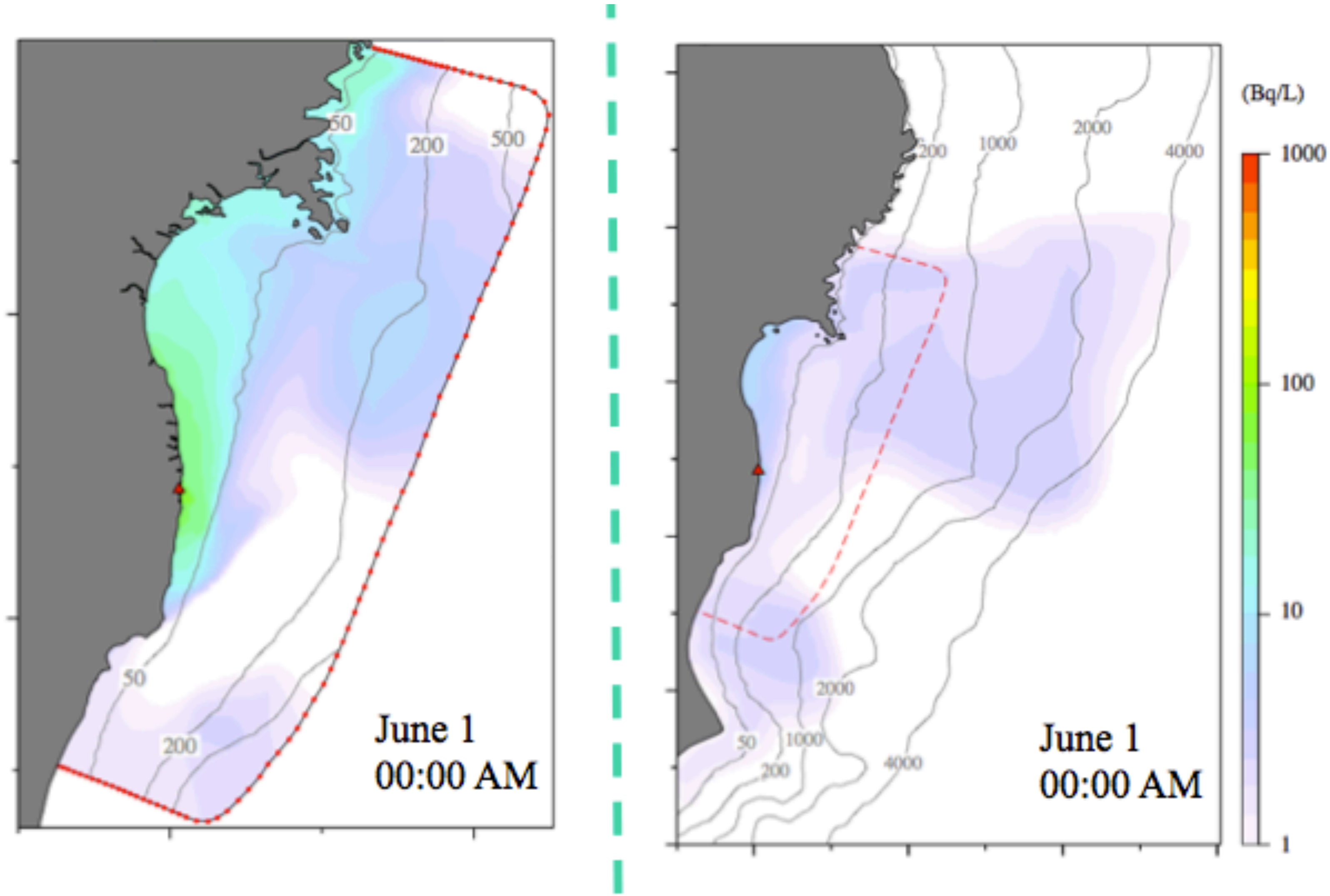
2011-3-26 0:0:0



(Bq/L)
1000
100
10
1
10
10
37.45
37.44
37.43
37.42
37.41
37.4
Latitude (˚N)
141.03
141.04
141.05
141.06
Longitude (˚E)

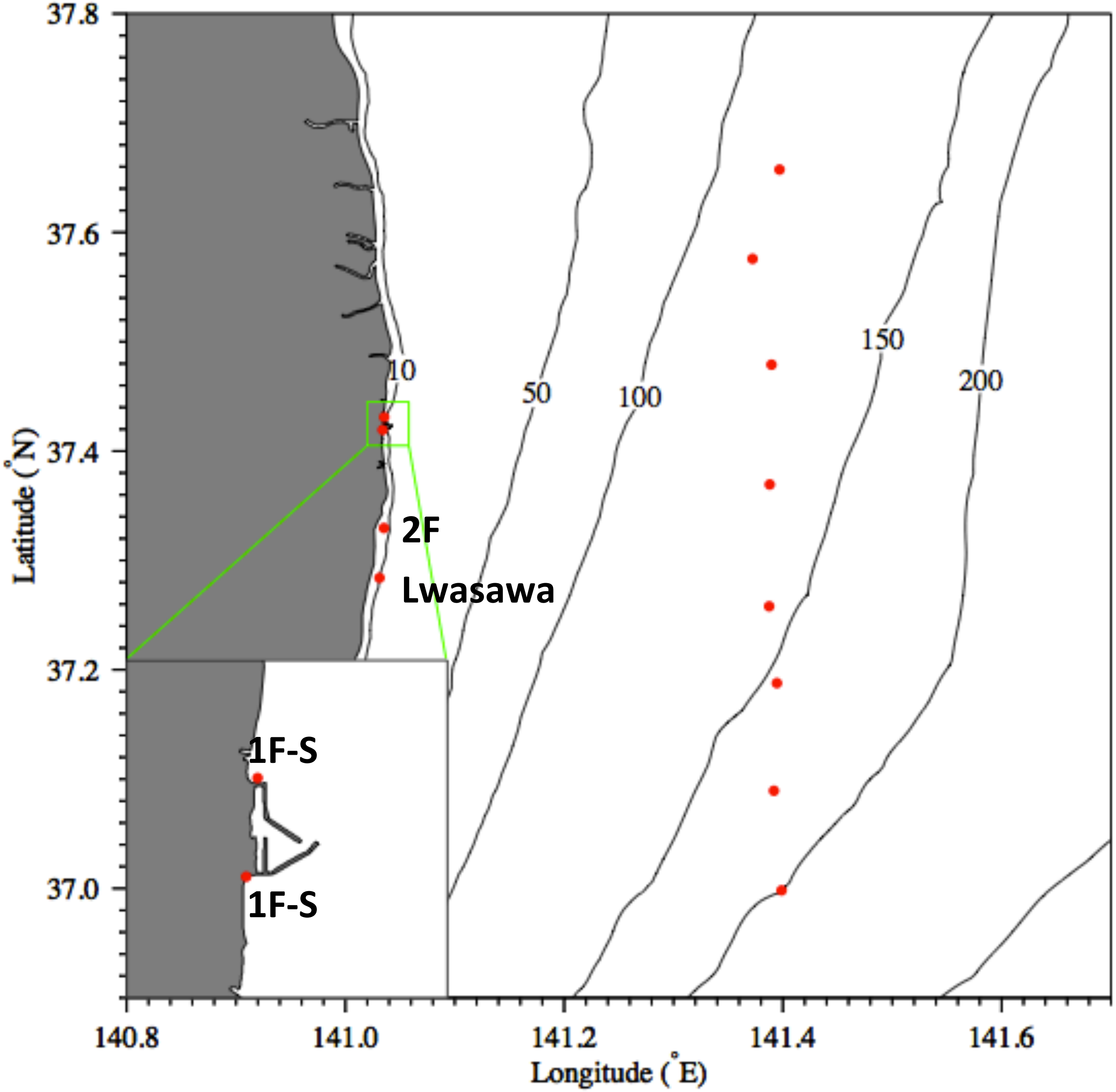


March 26
04:00 AM
10
50
March 26
04:00 AM
10
50
(Bq/L)
1000
100
10
1
April 12
06:00 AM
200
500
April 12
06:00 AM
200
1000
2000
4000
50
(Bq/L)
1000
100
10
1

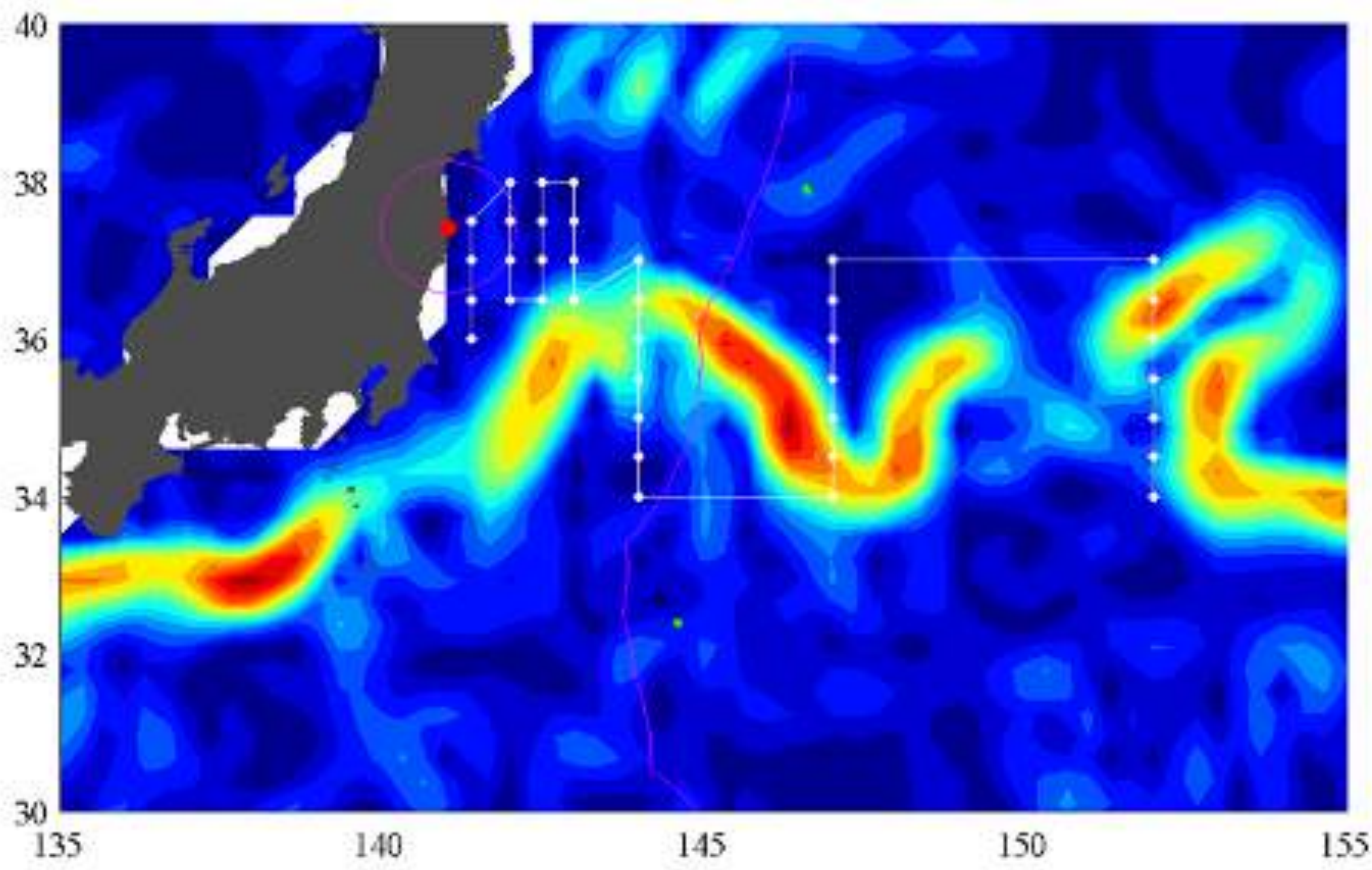


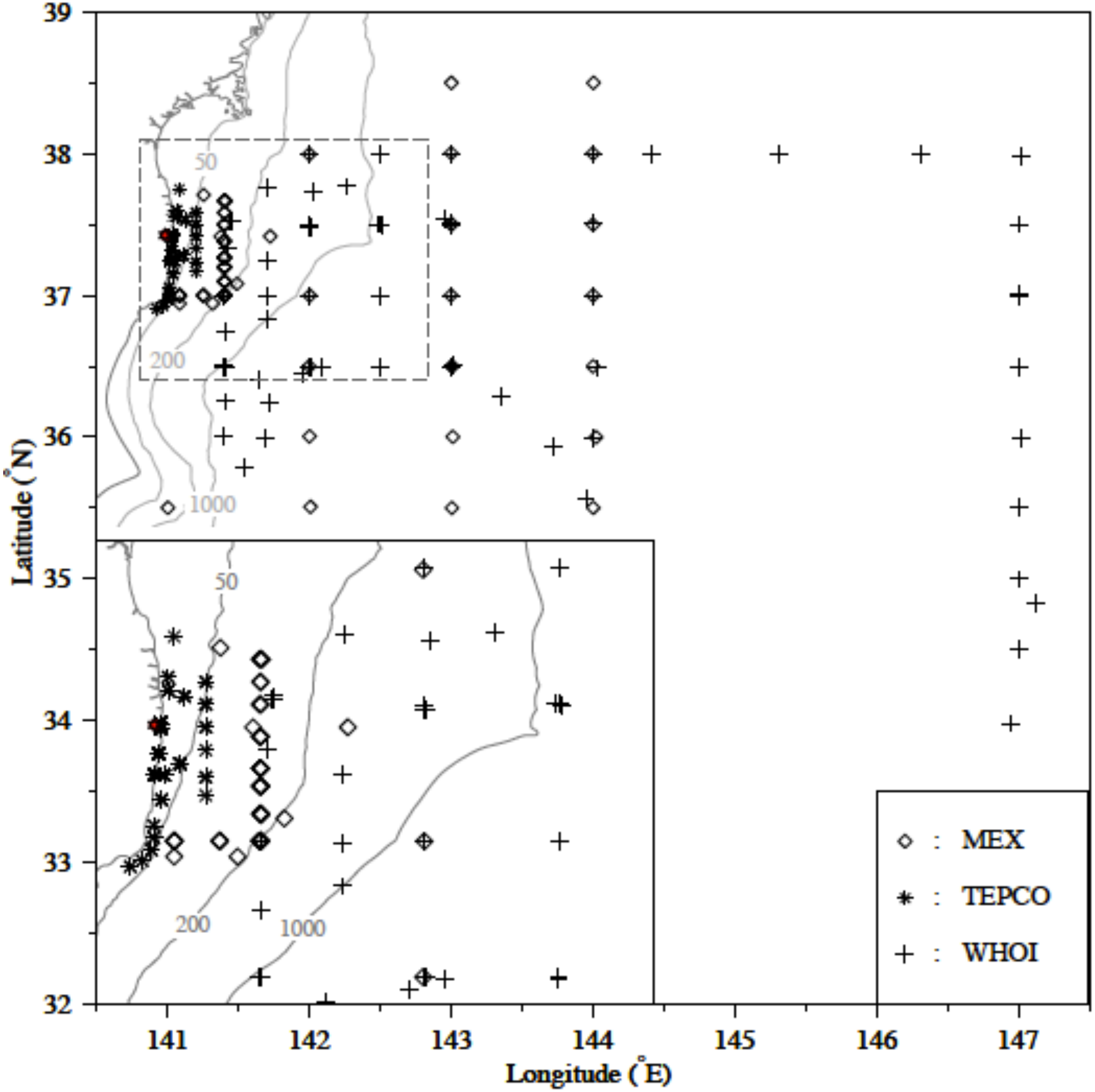
50
200
500
50
200
June 1
00:00 AM
200
1000
2000
4000
2000
50
1000
200
4000
June 1
00:00 AM
(Bq/L)
1000
100
10
1

Cs-137 Spreading Experiments

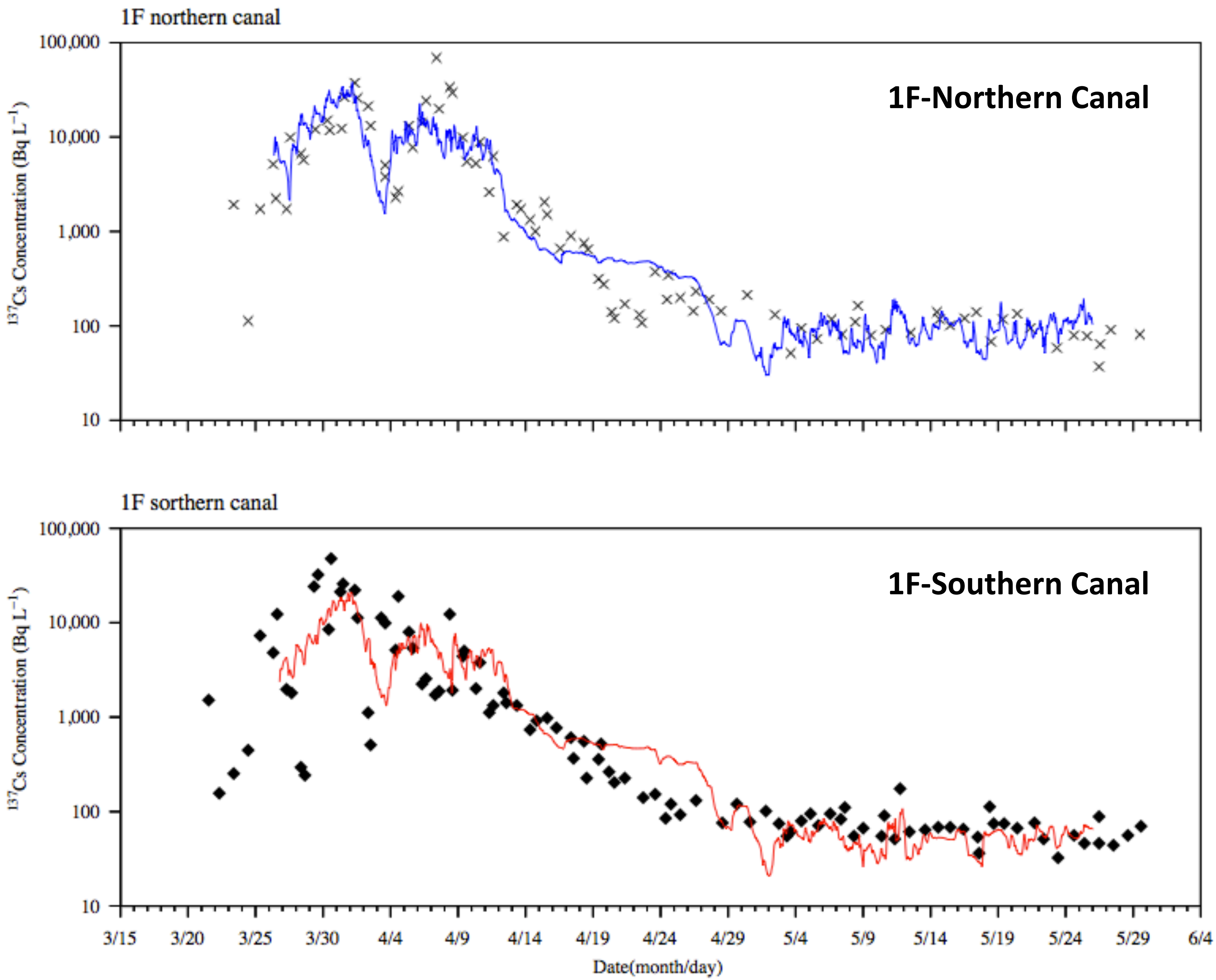


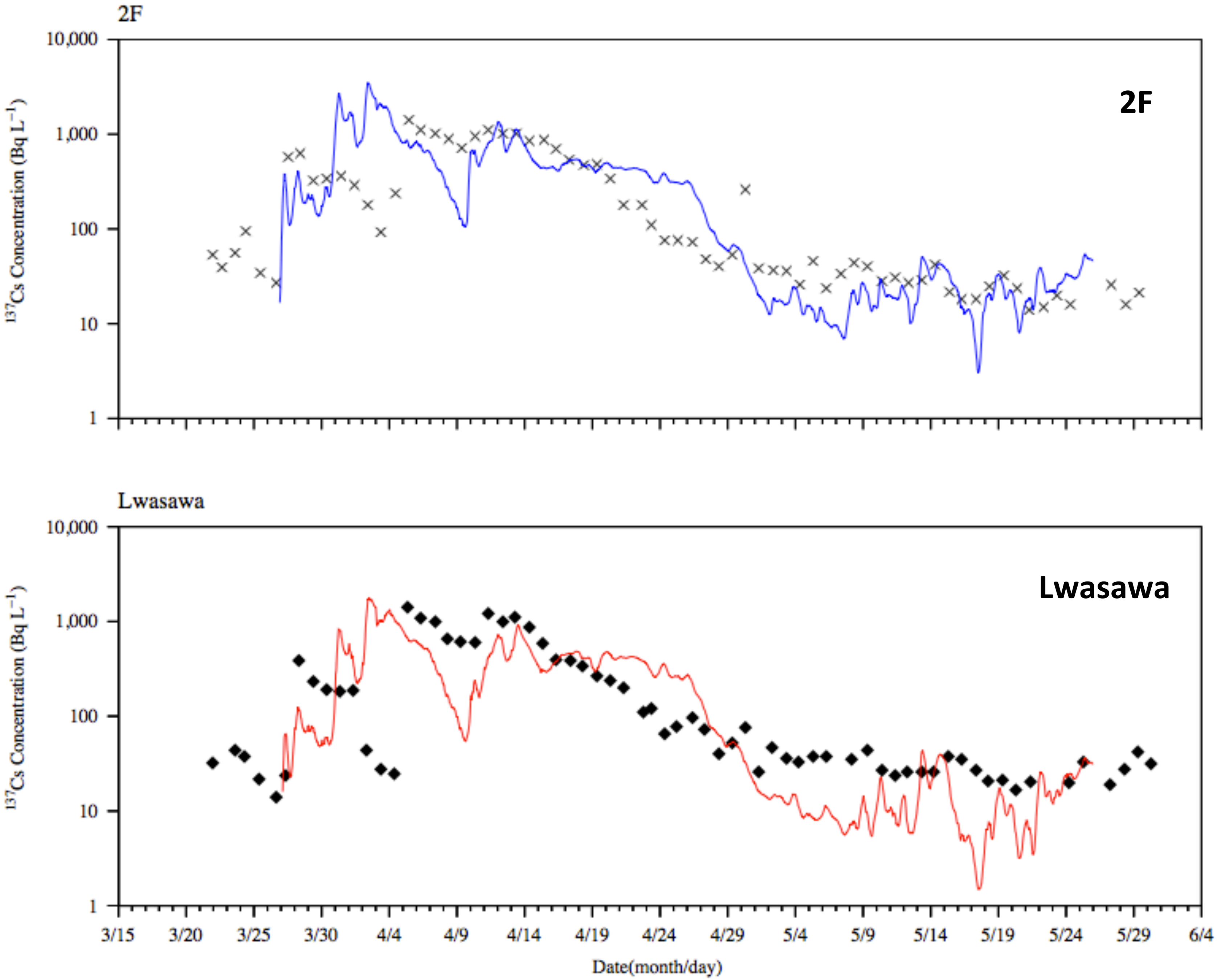
The WHOI Field Measurement Program in June 2011



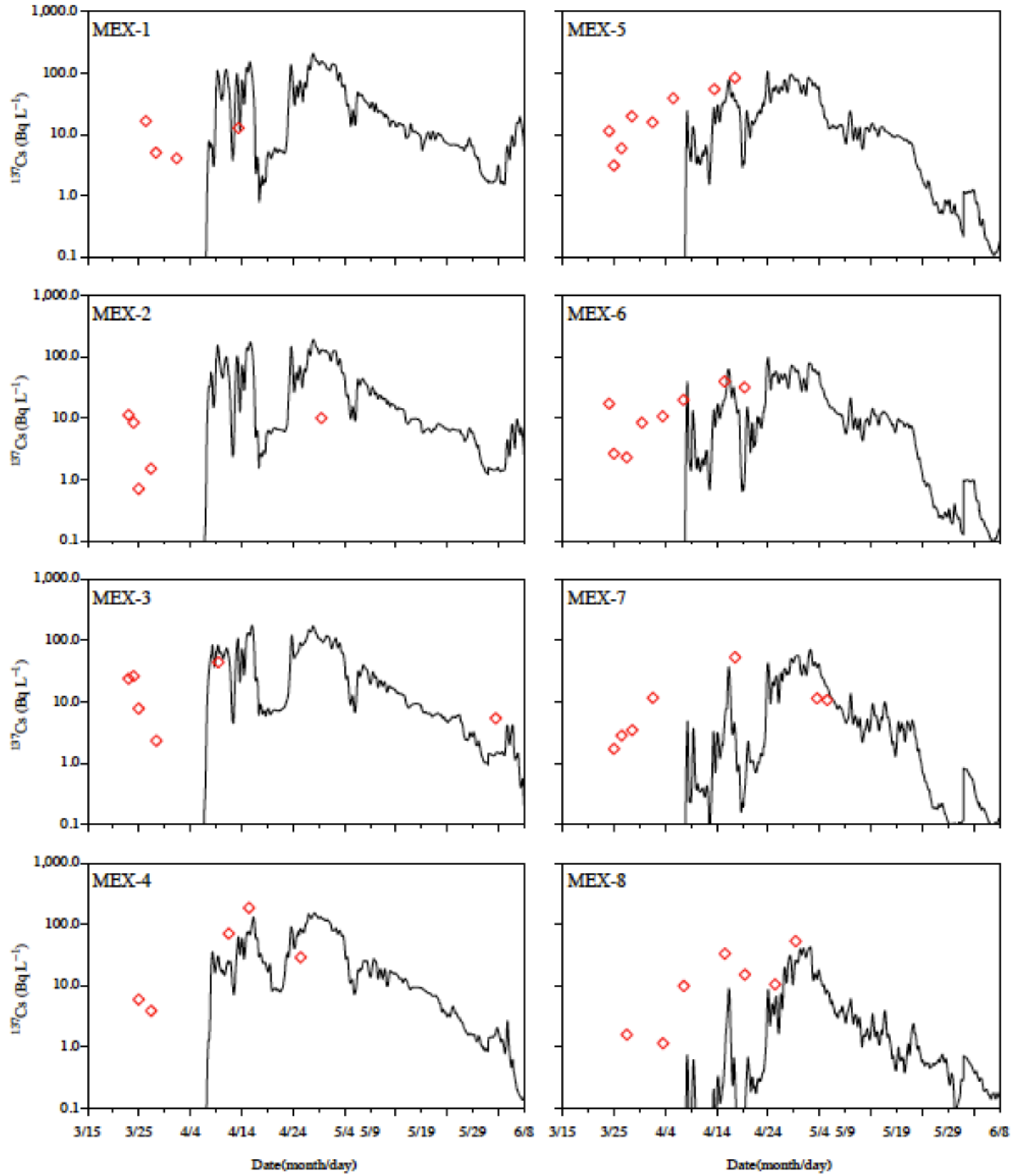


39
38
37
36
35
34
33
32
Latitude (°N)
141
142
143
144
145
146
147
Longitude (°E)
50
200
1000
50
200
1000
◇ : MEX
✱ : TEPCO
+ : WHOI


1F northern canal
1F-Northern Canal
100,000
10,000
1,000
100
10
^{137}Cs Concentration (Bq L^{-1})
1F sorthern canal
1F-Southern Canal
100,000
10,000
1,000
100
10
^{137}Cs Concentration (Bq L^{-1})
3/15
3/20
3/25
3/30
4/4
4/9
4/14
4/19
4/24
4/29
5/4
5/9
5/14
5/19
5/24
5/29
6/4
Date(month/day)

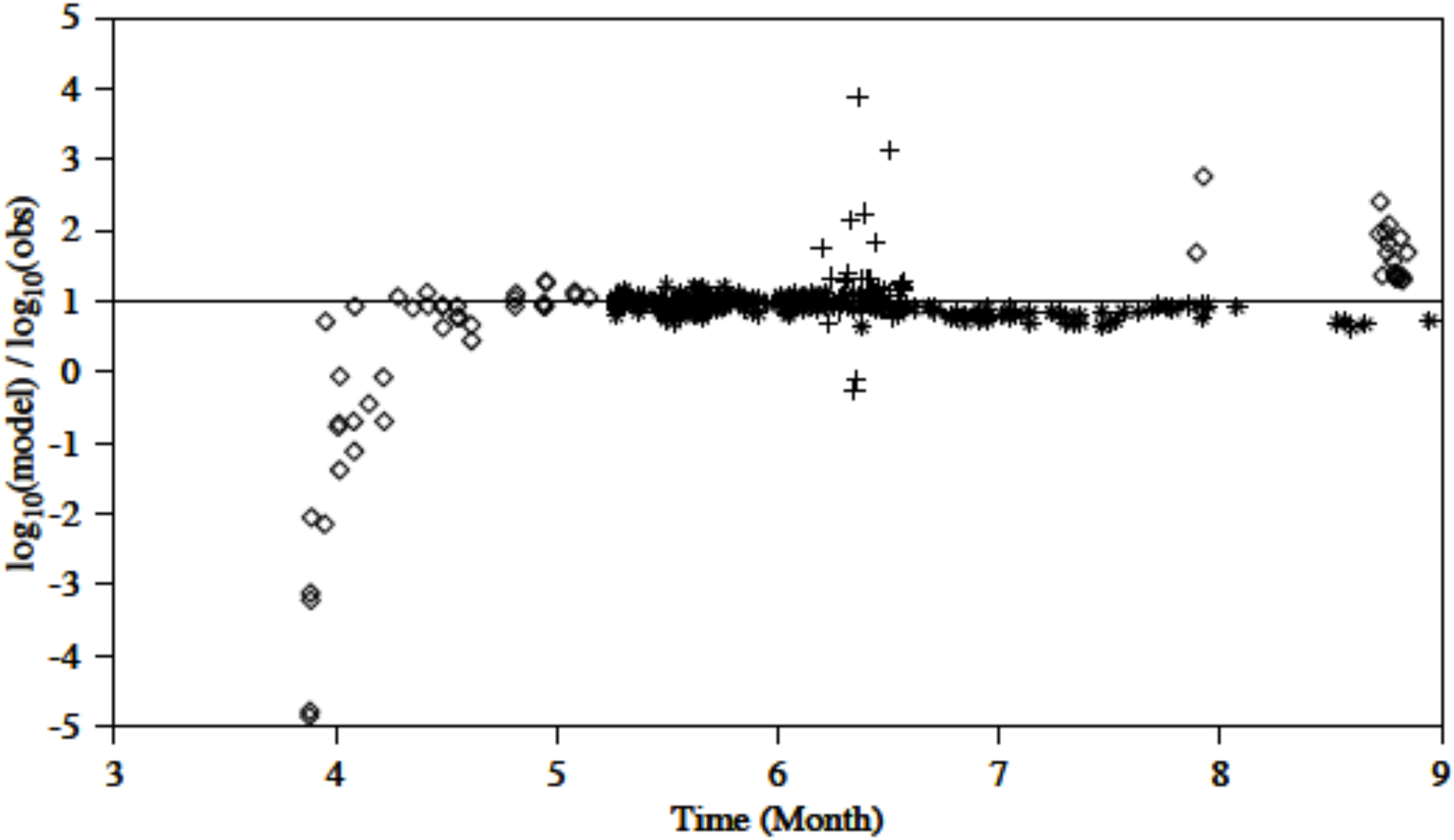


2F
2F
10,000
1,000
100
10
1
^{137}Cs Concentration (Bq L^{-1})
Lwasawa
Lwasawa
10,000
1,000
100
10
1
^{137}Cs Concentration (Bq L^{-1})
3/15
3/20
3/25
3/30
4/4
4/9
4/14
4/19
4/24
4/29
5/4
5/9
5/14
5/19
5/24
5/29
6/4
Date(month/day)

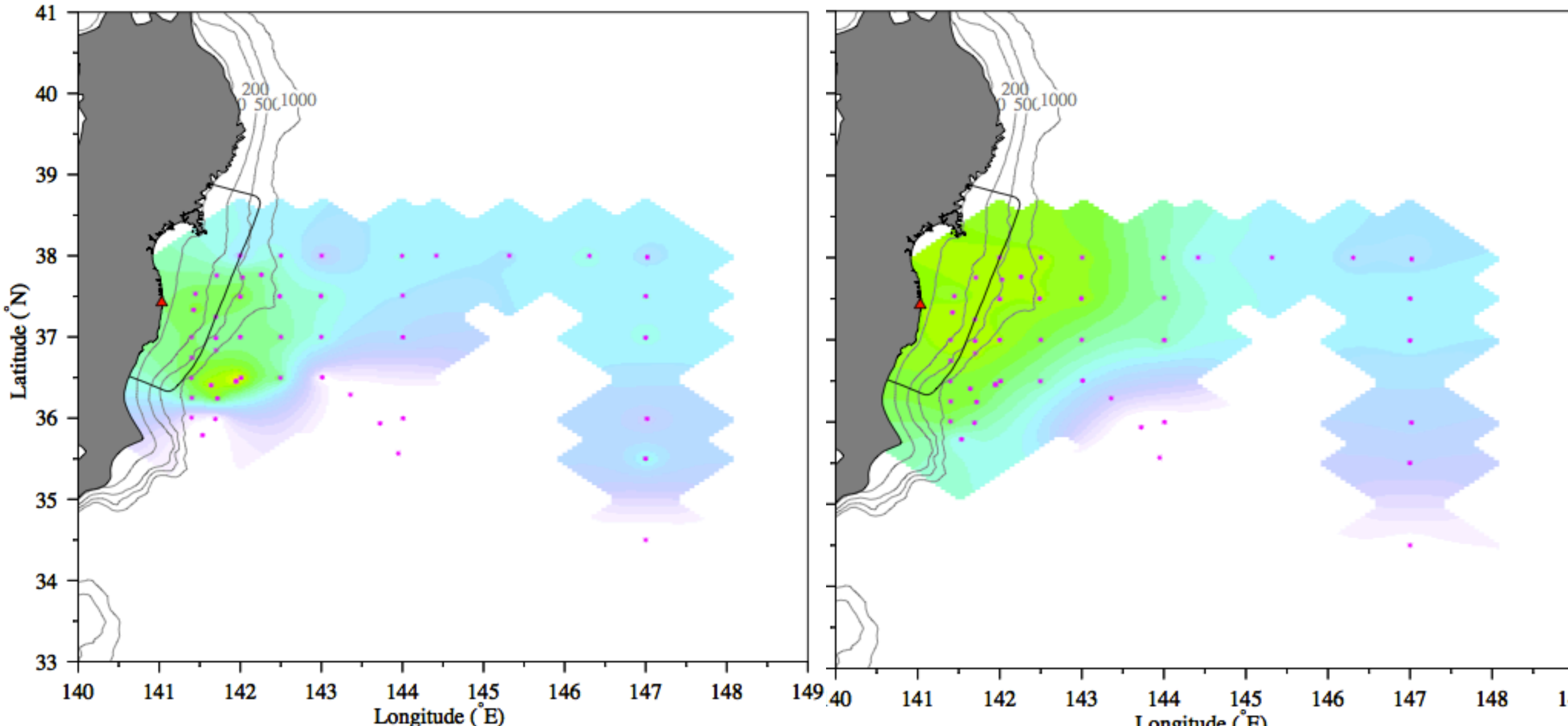


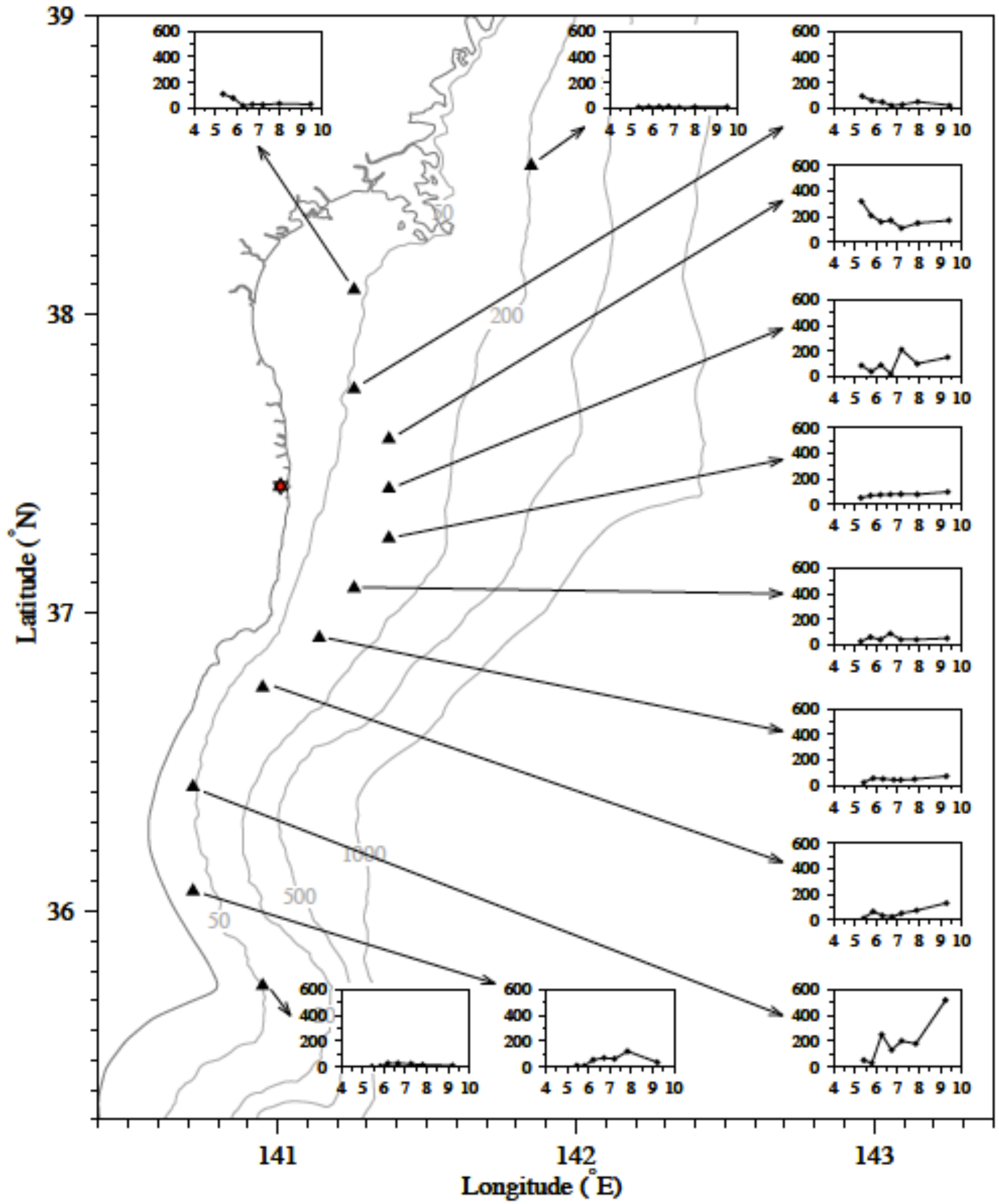
MEX-1
MEX-2
MEX-3
MEX-4
MEX-5
MEX-6
MEX-7
MEX-8
1,000.0
100.0
10.0
1.0
0.1
^{137}Cs (Bq L^{-1})
3/15
3/25
4/4
4/14
4/24
5/4
5/9
5/19
5/29
6/8
Date(month/day)

Model-data comparisons

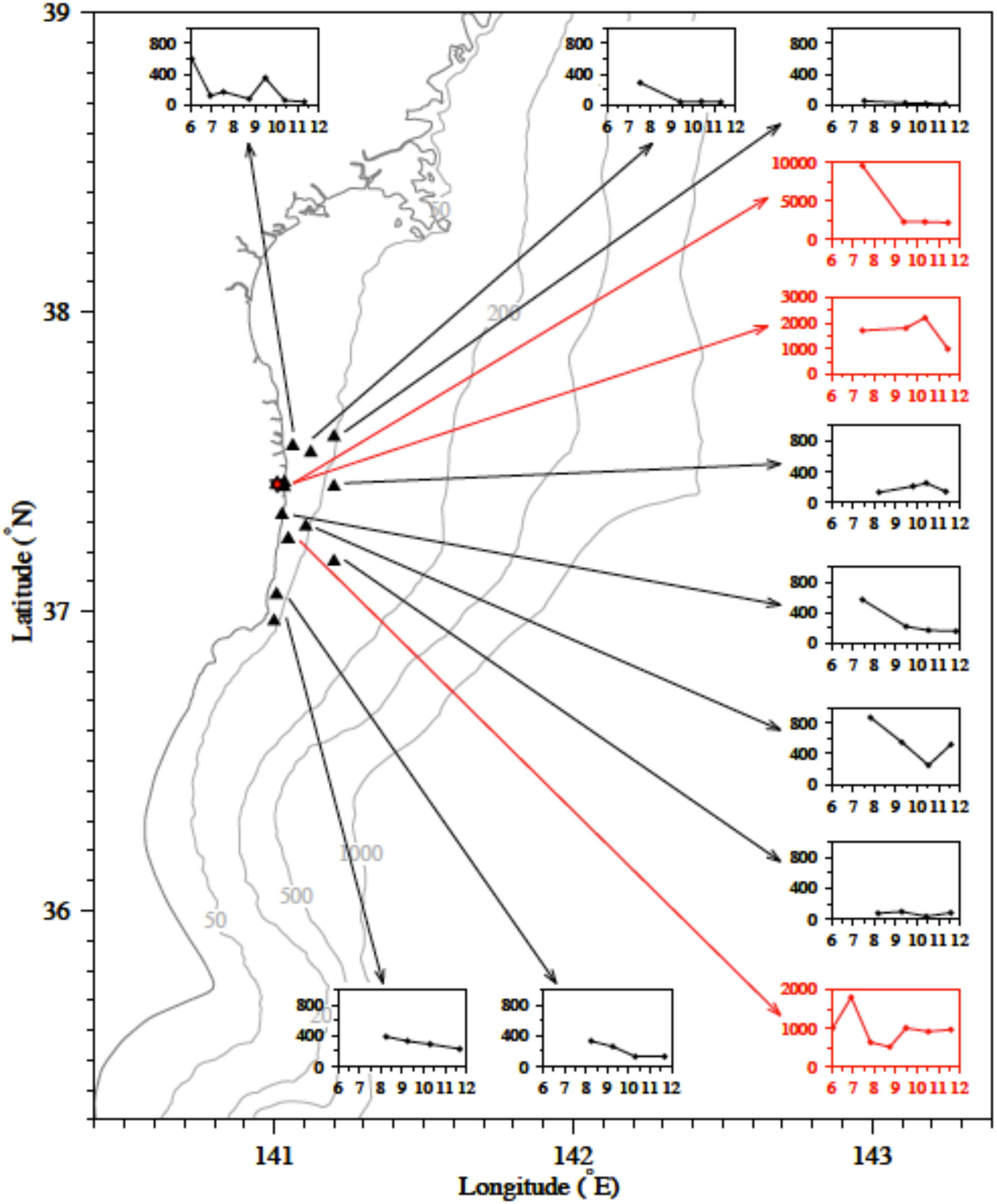


Cs-137 Distribution in June, 2011





Time series of the Cs-137 concentration in the sediment over the shelf.



Time series of the Cs-137 concentration in the sediment at near-shore stations

Do we need to include the non-hydrostatic dynamics?

~1 ~1000 km

Hydrostatic

$$\frac{\text{Surface elevation}}{\text{Local water depth}} = \frac{\zeta}{H} << 1$$

Large-scale motion in which the vertical motion is at least one order of magnitude smaller than the horizontal motion.

Vertical convection, over-turning, and high frequency internal waves are not resolved.

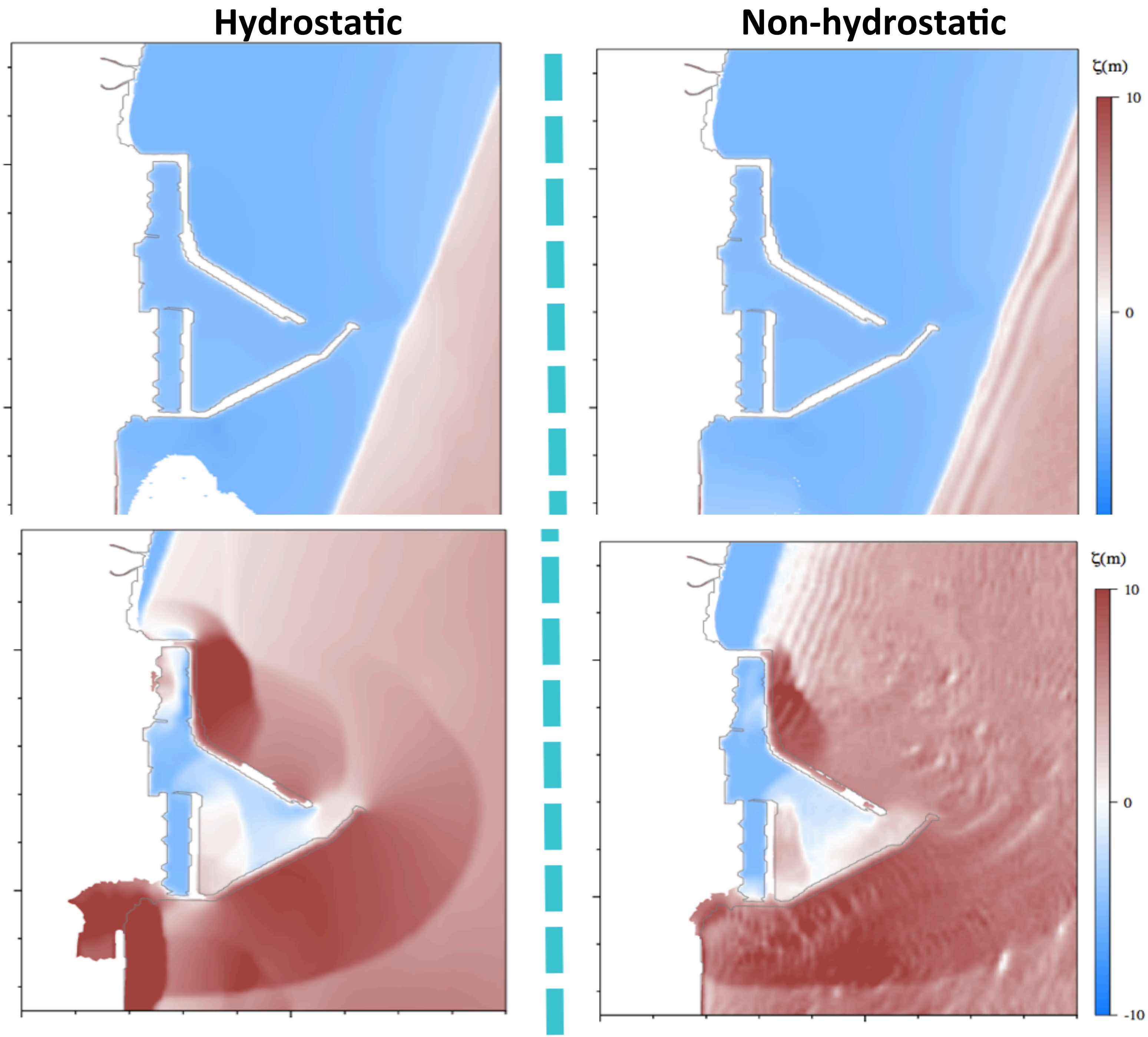
~ a few meters

Non-hydrostatic

$$\frac{\text{Surface elevation}}{\text{Local water depth}} = \frac{\zeta}{H} \sim 1$$

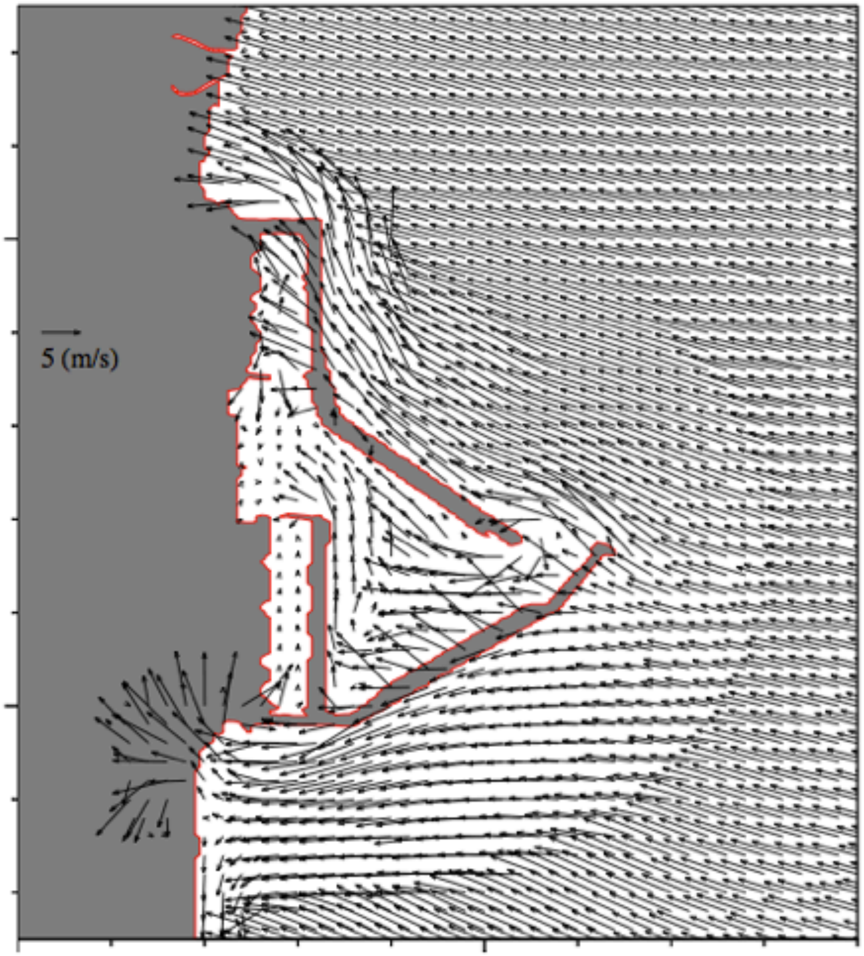
Small-scale motion in which vertical motion is the same order of the horizontal motion.

Vertical convection, over-turning, and high frequency internal waves can be resolved.

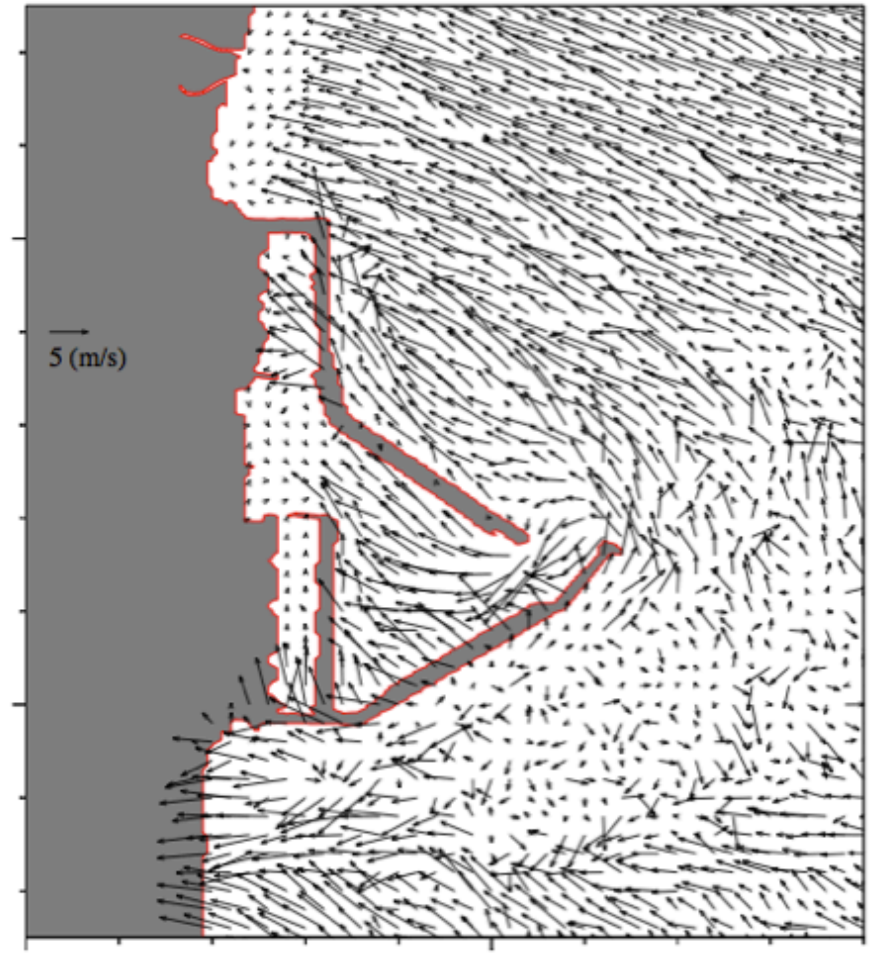


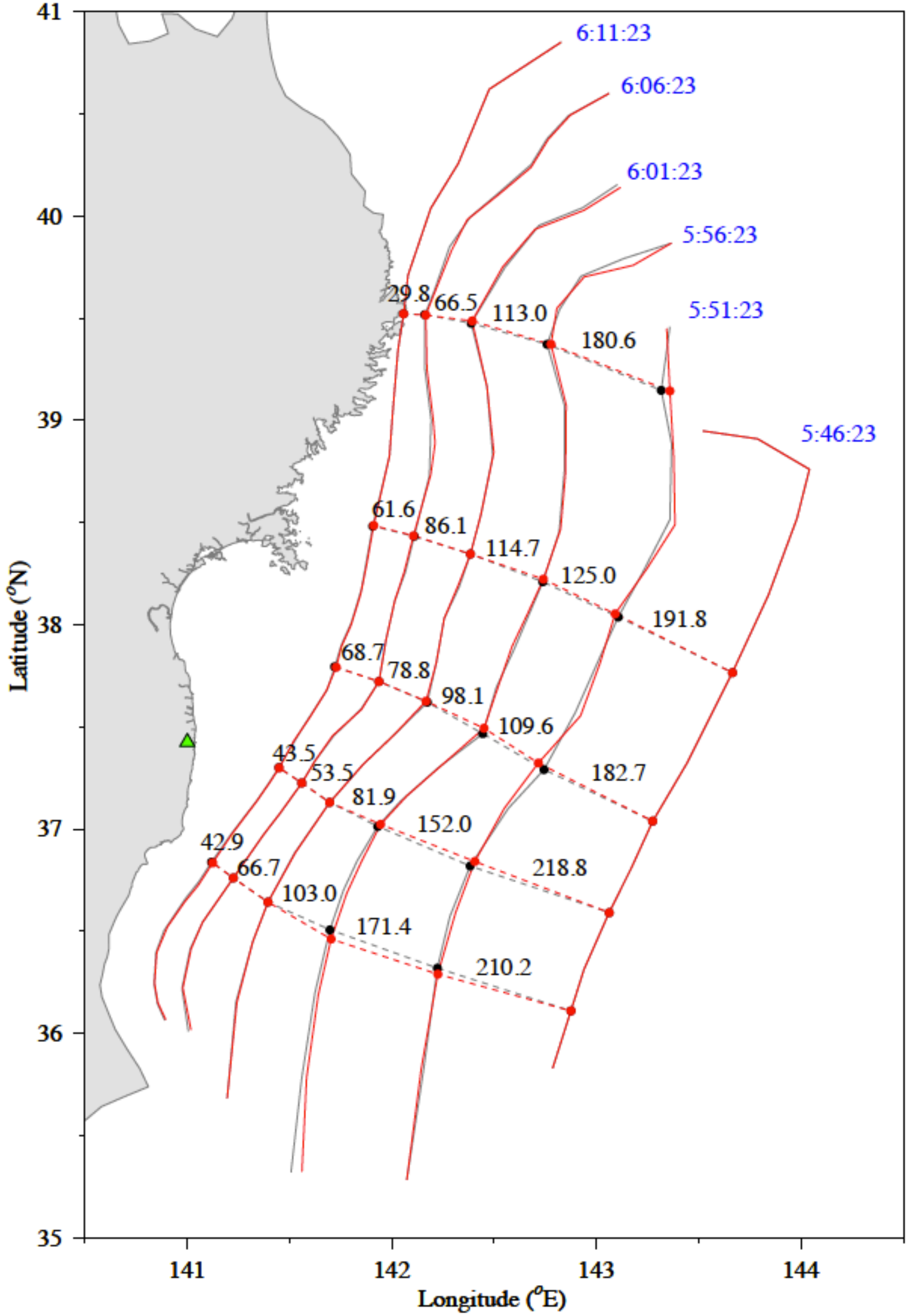
Hydrostatic
Non-hydrostatic
ζ(m)
10
0
ζ(m)
10
0
-10

Hydrostatic



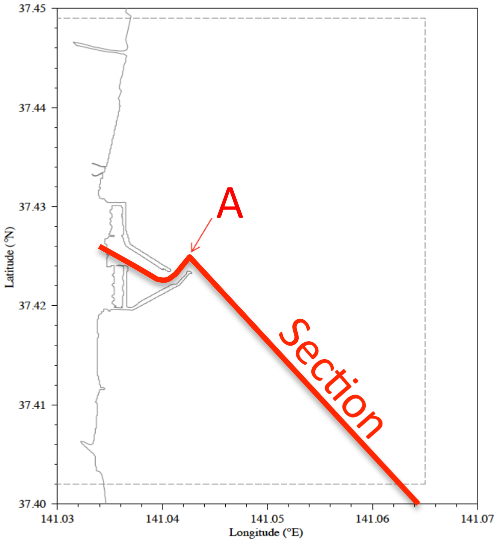
Non-Hydrostatic

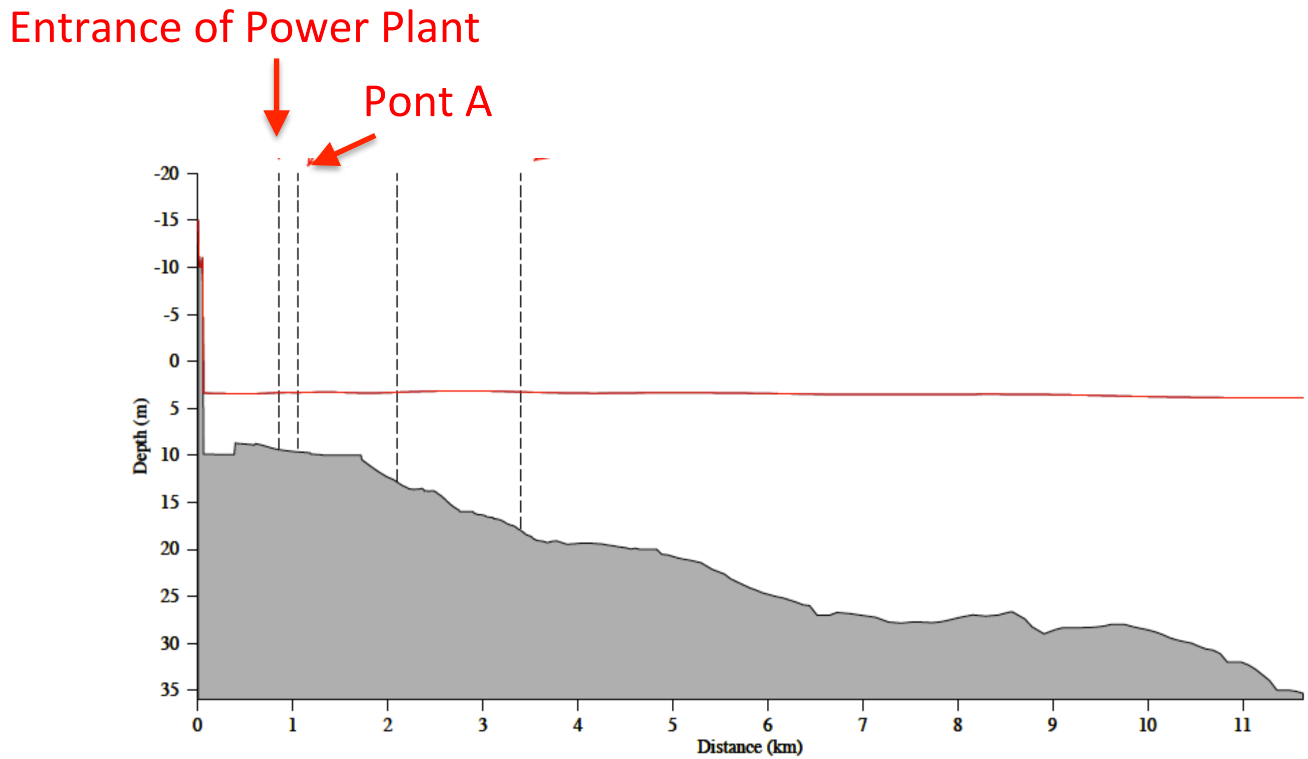




Red: Non-hydrostatic

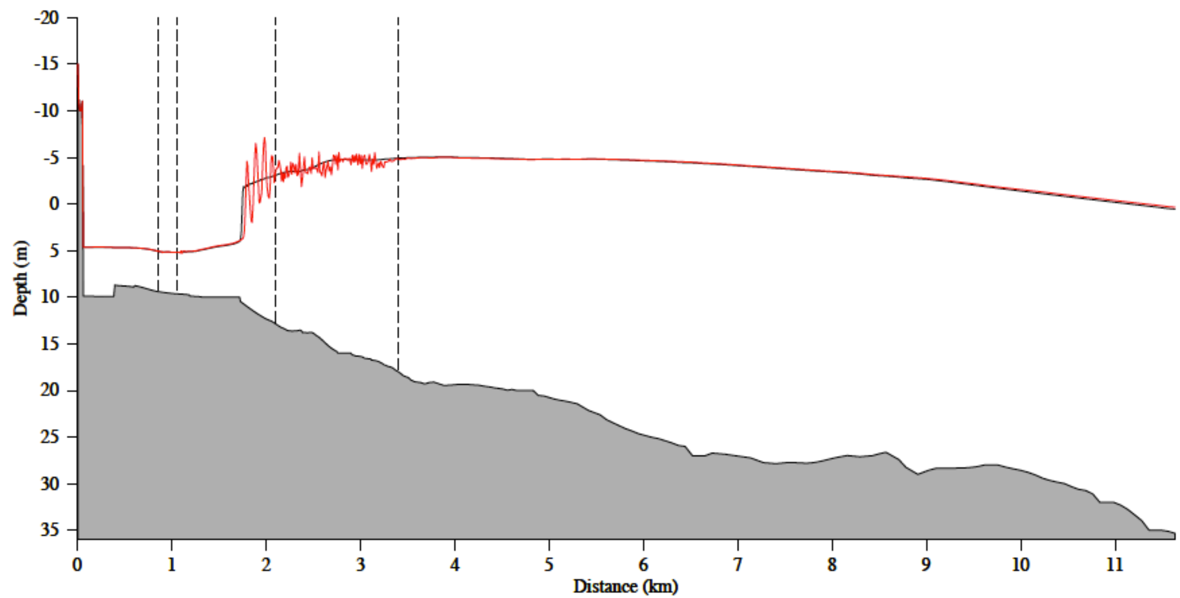
Black: Hydrostatic





Red: Non-hydrostatic

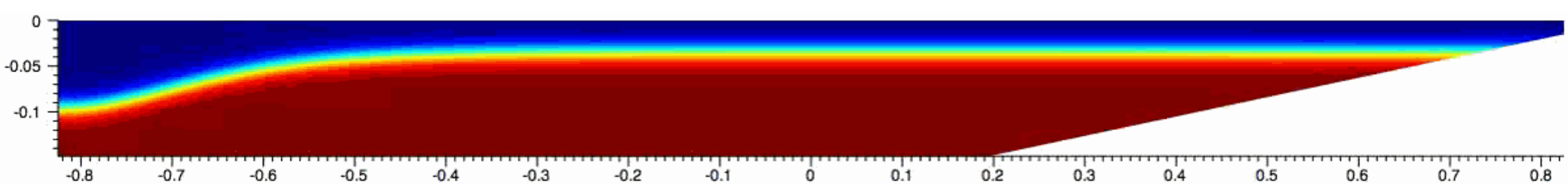
Black: Hydrostatic

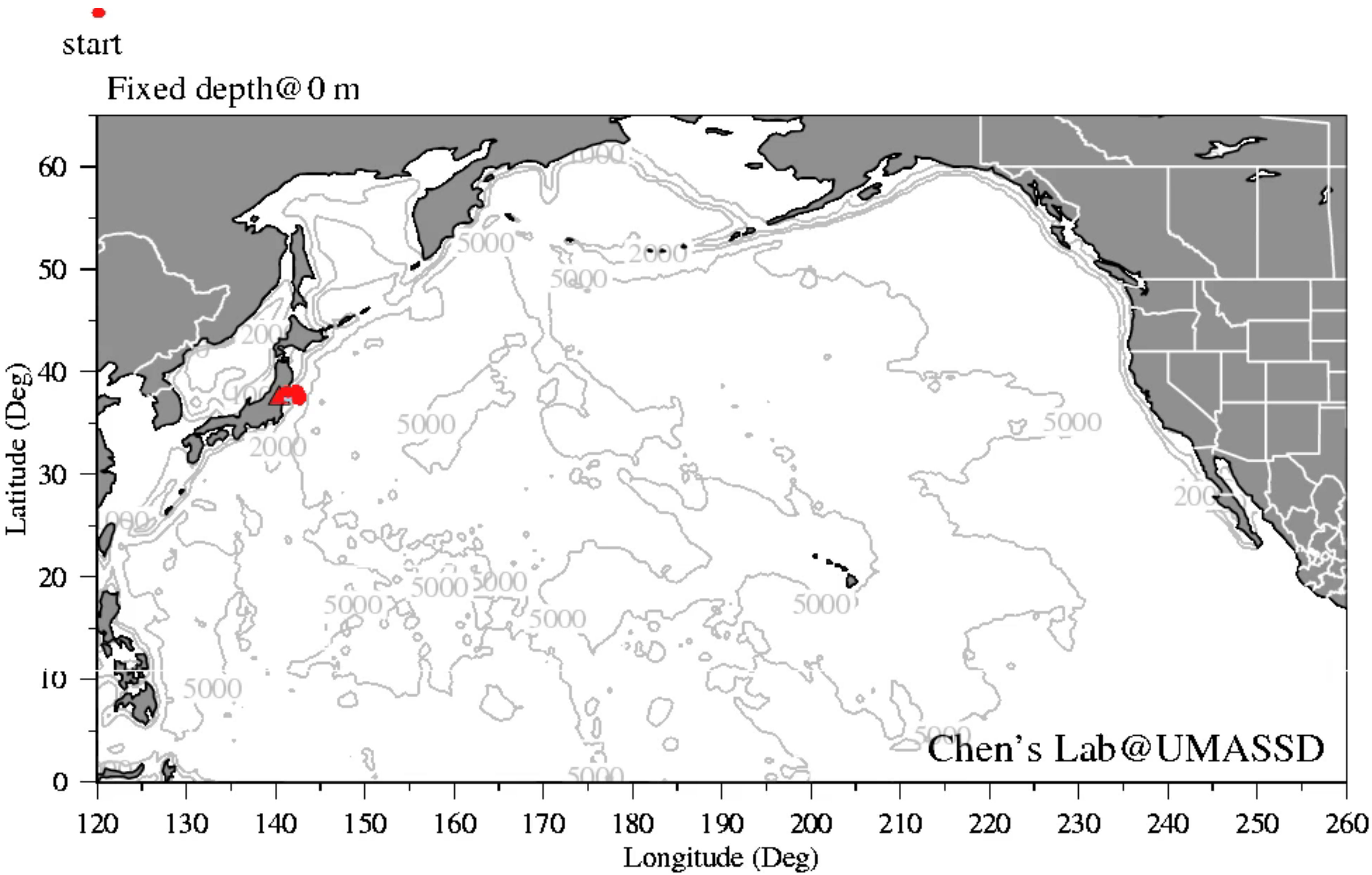


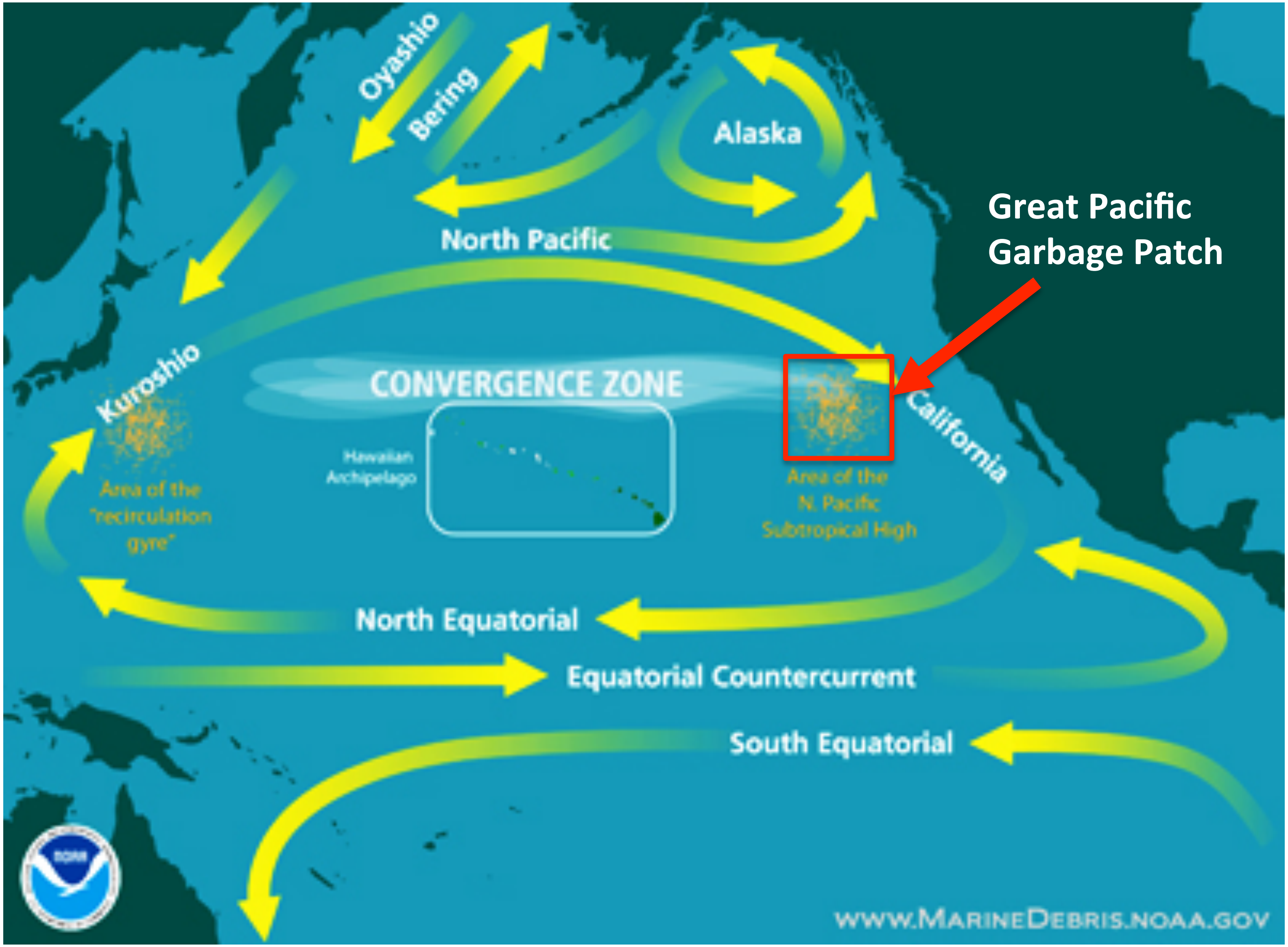
Summary

1. The global-regional-coastal FVCOM system is suitable for the Tsunami inundation simulation;

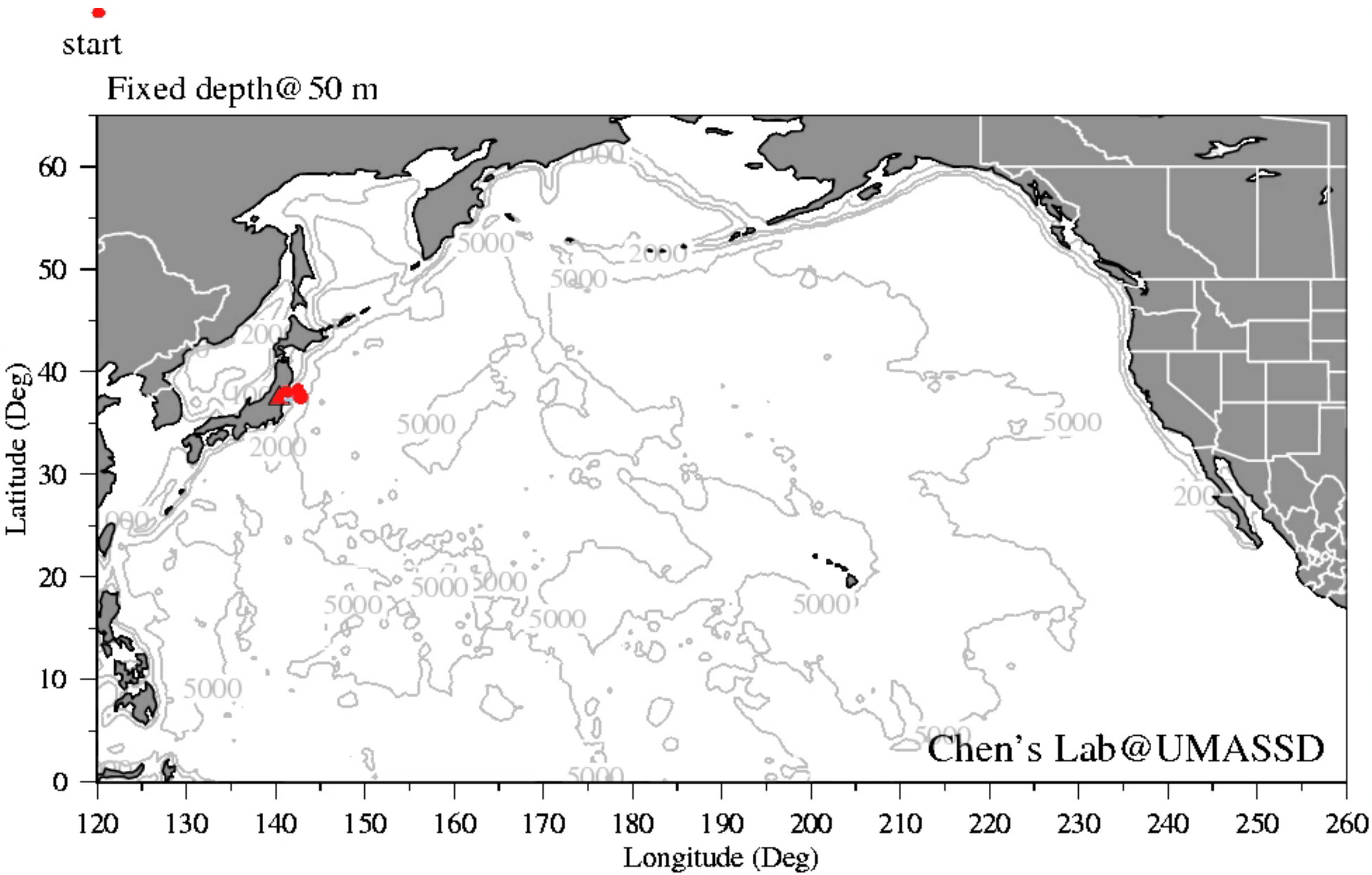
2. The impact of radionuclides on the Pacific Ocean needs to be assessed with attentions to the multi-scale ocean processes along the Japan's coast;




start
Fixed depth@ 0 m
Latitude (Deg)
Longitude (Deg)
0
10
20
30
40
50
60
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
5000
2000
Chen's Lab@UMASSD



http://marinedebris.noaa.gov/info/patch.html#lit



start
Fixed depth@ 50 m
Latitude (Deg)
Longitude (Deg)
0
10
20
30
40
50
60
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
1000
2000
5000
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