海洋レーダ研究集会@九州大学応用力学研究所
2024/12/2-3

紀伊水道における海洋短波レーダーを利用した津波早期警報

Tsunami early warning using high-frequency ocean radar system in the Kii Channel, Japan

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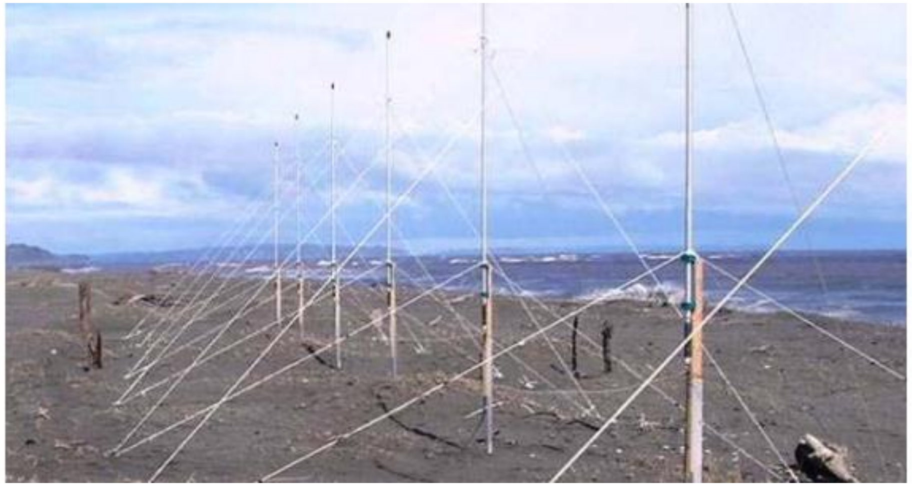
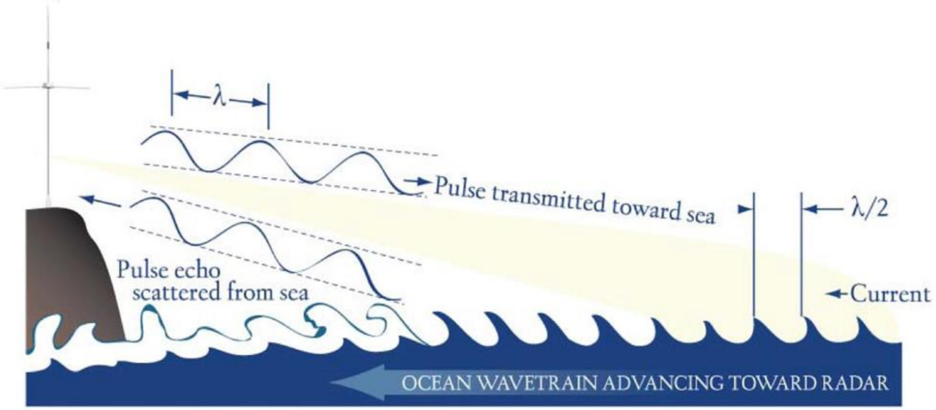
国立研究開発法人海洋研究開発機構

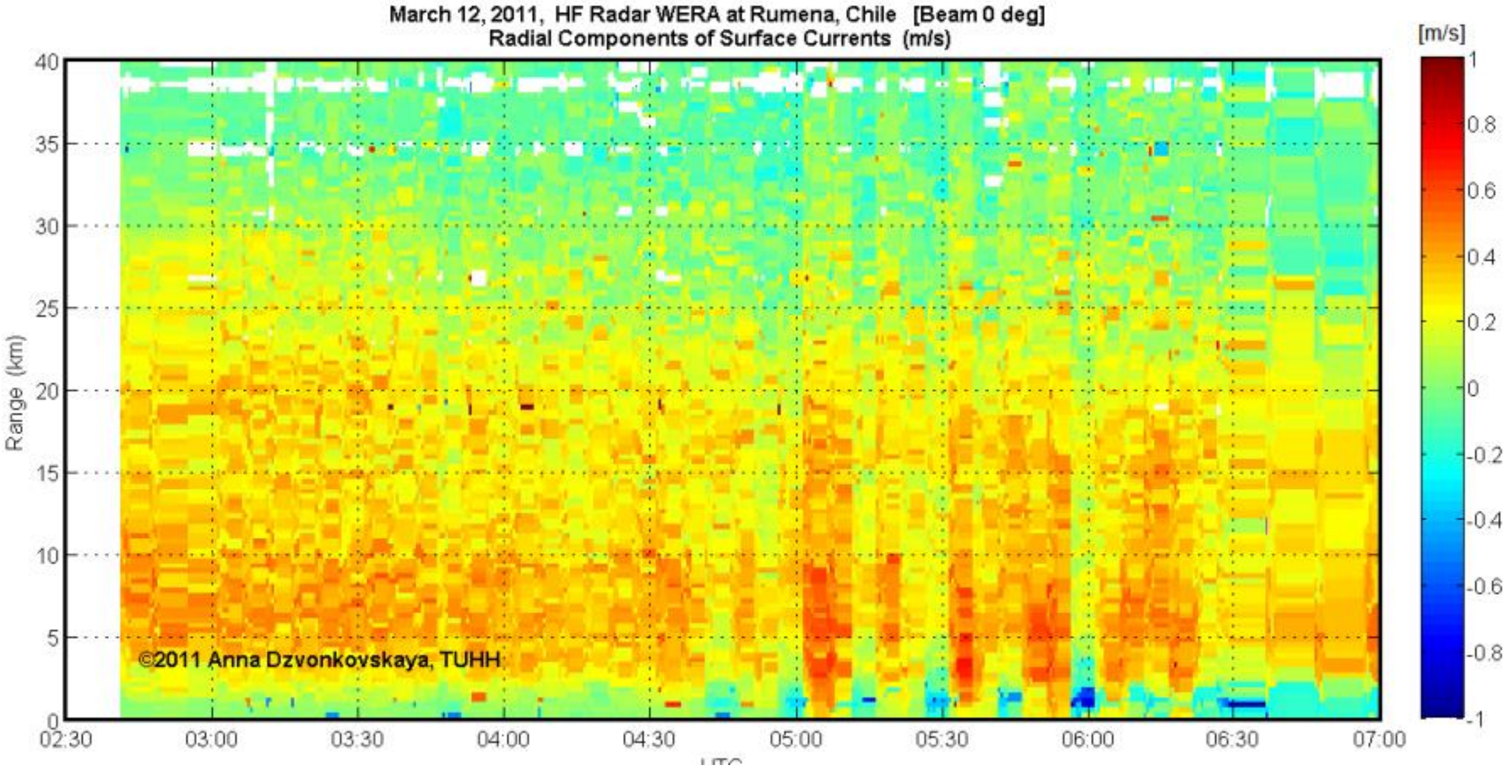
1. はじめに

High-frequency (HF) ocean radar

Example: HF radar in Chile observed the tsunami of the 2011 Tohoku earthquake.

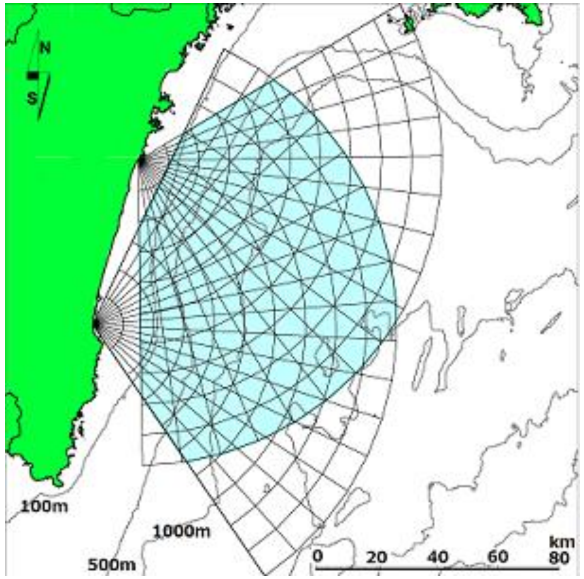


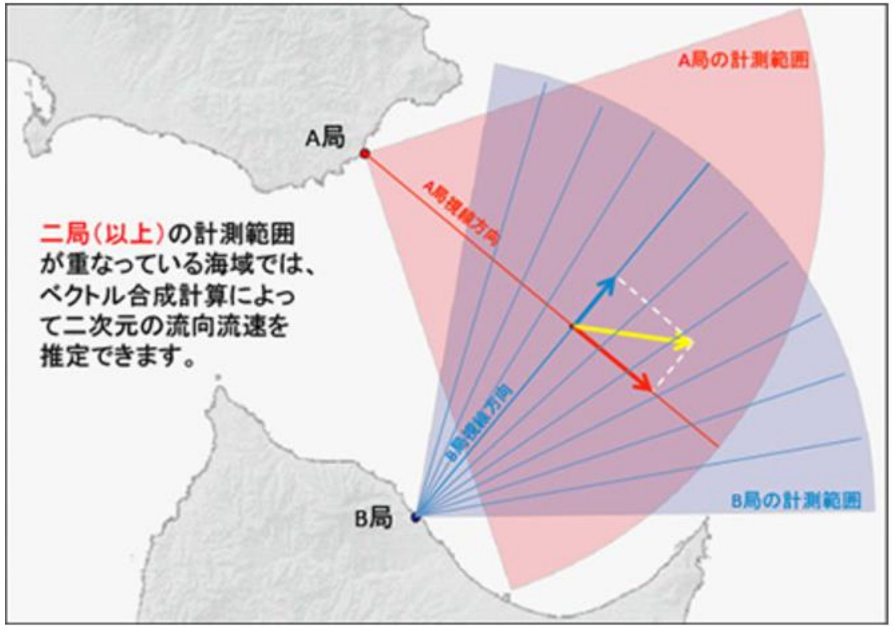


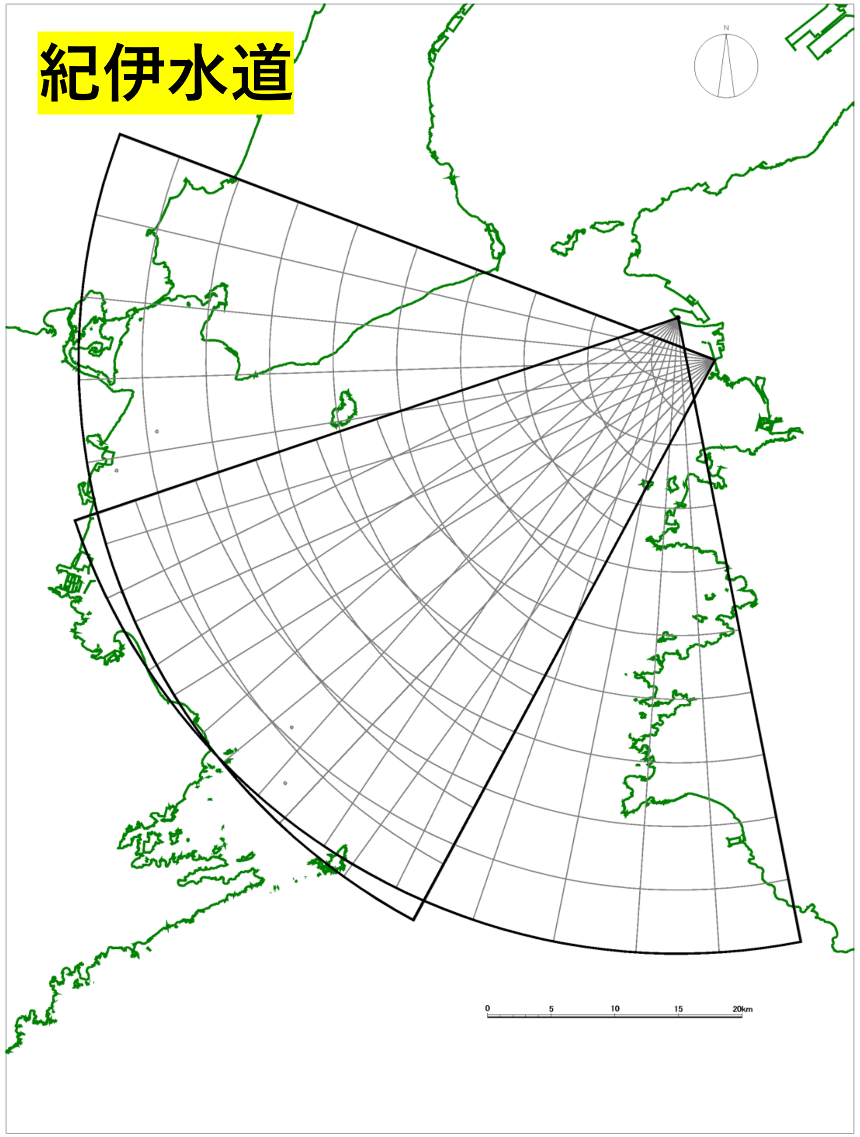


(Dzvonkovskaya et al., 2011; Roarty et al., 2019)

HF radar in Japan







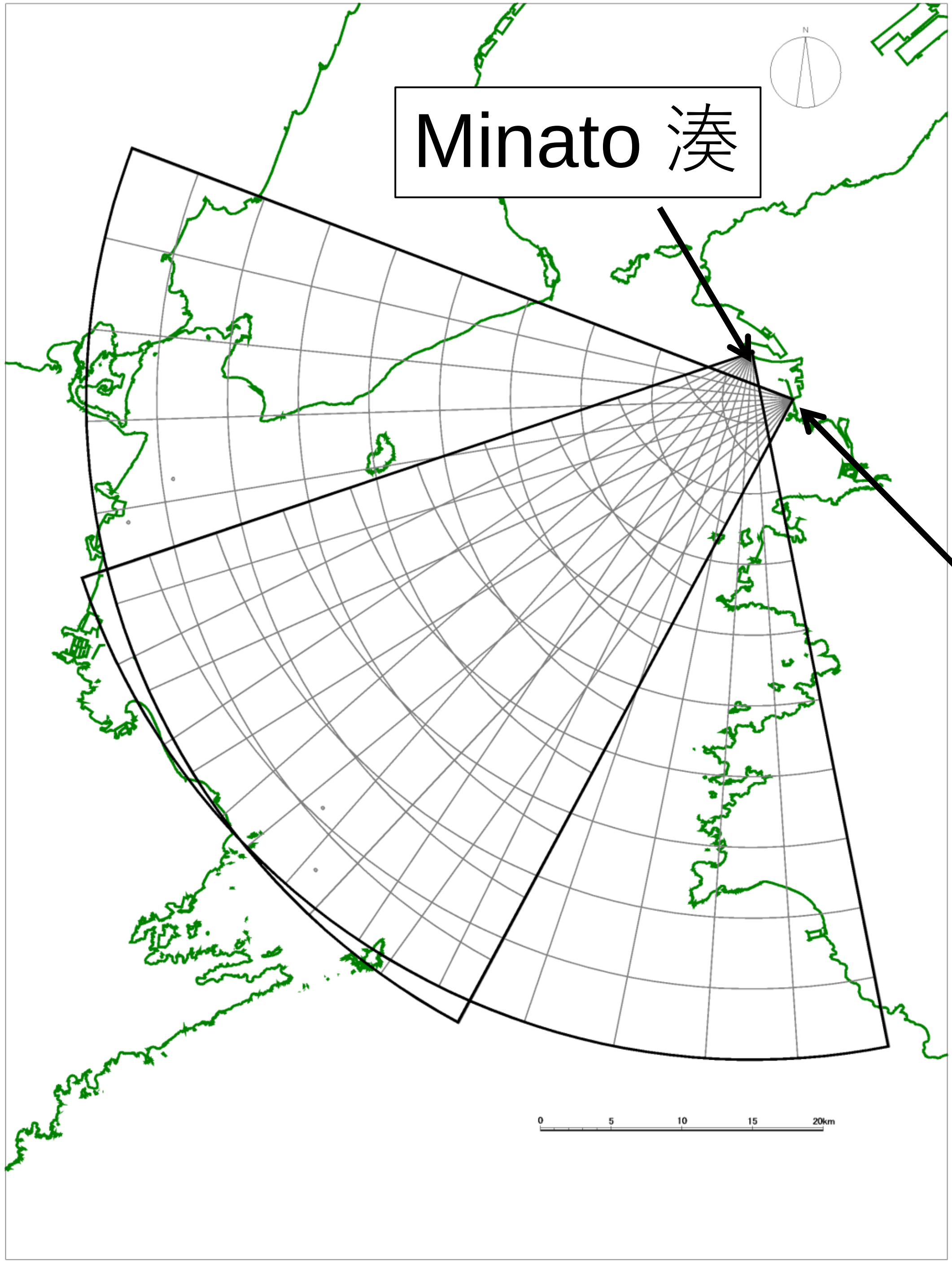
(Figure Source: JAMSTEC, MLIT, Miyazaki Prefecture)

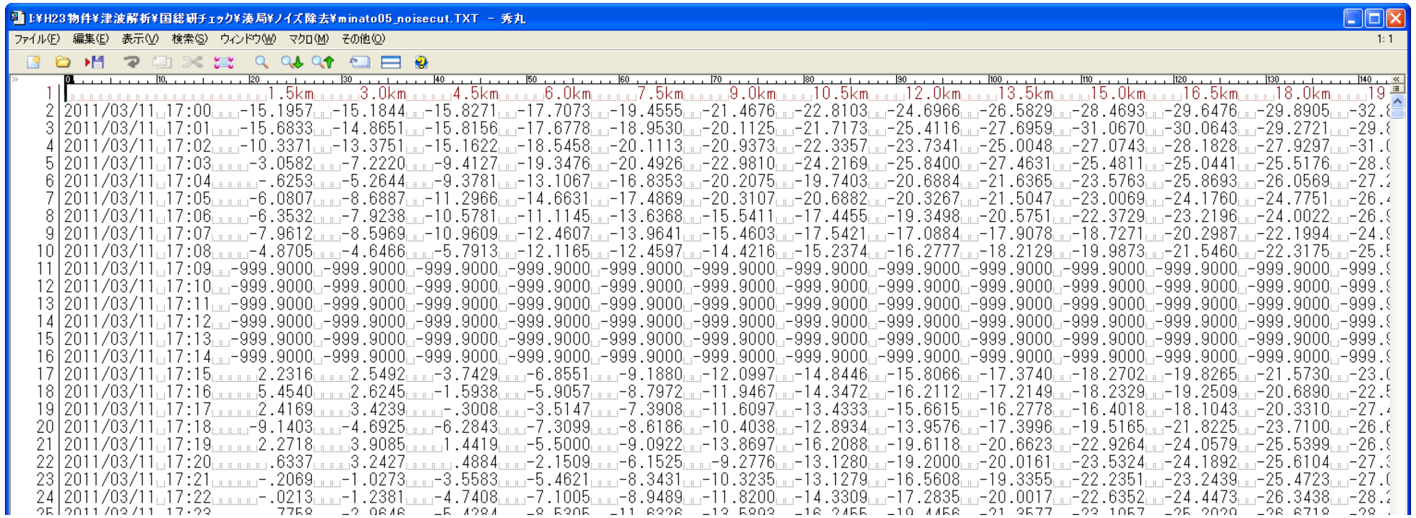
2. データ解析

2011 Tohoku Tsunami

- Generated by the M9 Tohoku Earthquake on March 11, 2011
- Arrived in Kii Channel approximately 3 hours after the earthquake

(Figure Source: The New York Times)





I:¥H23物件¥津波解析¥国総研チェック¥湊局¥ノイズ除去¥minato05_noisecut.TXT - 秀丸

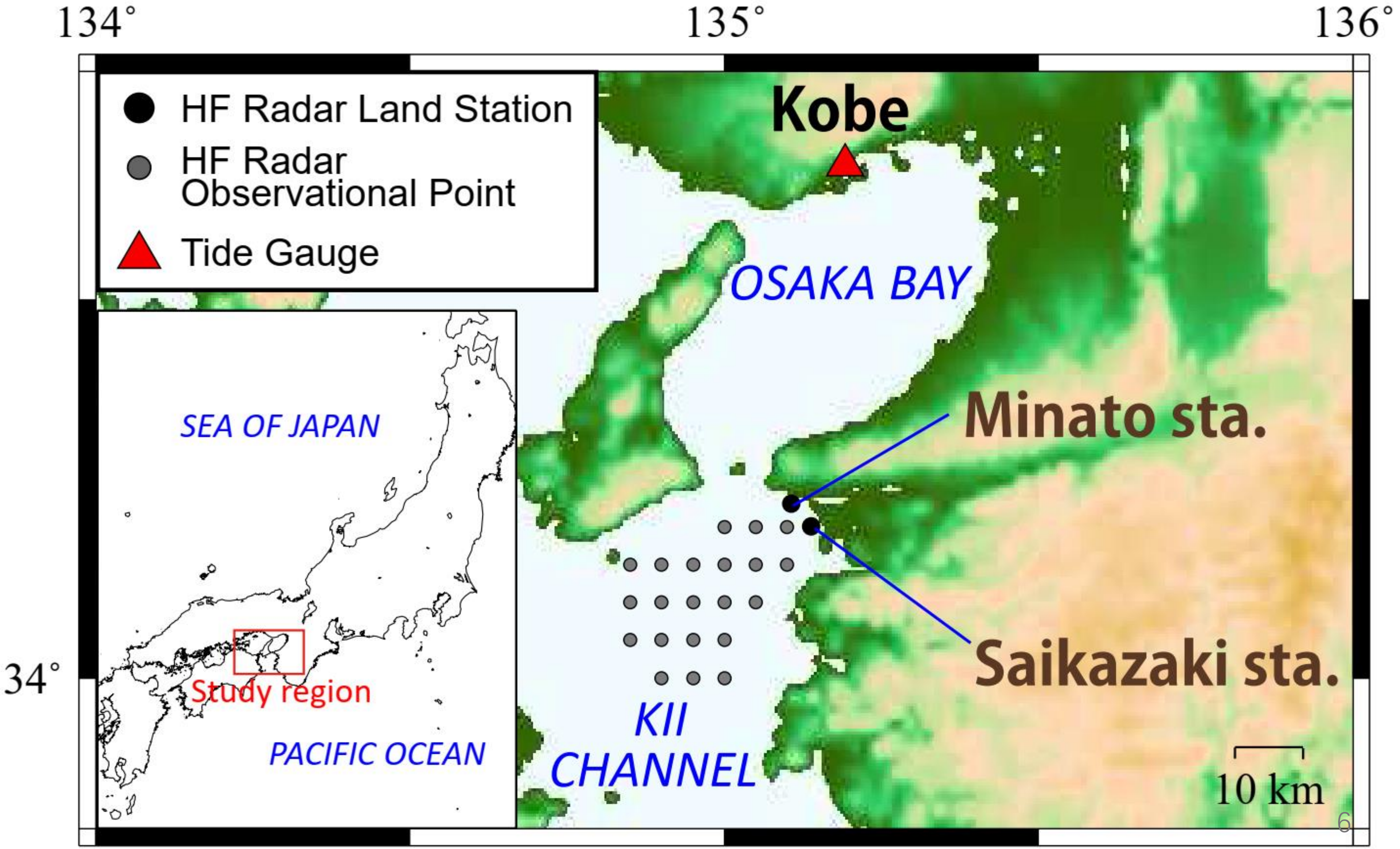
ファイル(F) 編集(E) 表示(V) 検索(S) ウィンドウ(W) マクロ(M) その他(O)

		1.5km	3.0km	4.5km	6.0km	7.5km	9.0km	10.5km	12.0km	13.5km	15.0km	16.5km	18.0km	19…
2	2011/03/11 17:00	-15.1957	-15.1844	-15.8271	-17.7073	-19.4555	-21.4676	-22.8103	-24.6966	-26.5829	-28.4693	-29.6476	-29.8905	-32.8
3	2011/03/11 17:01	-15.6833	-14.8651	-15.8156	-17.6778	-18.9530	-20.1125	-21.7173	-25.4116	-27.6959	-31.0670	-30.0643	-29.2721	-29.8
4	2011/03/11 17:02	-10.3371	-13.3751	-15.1622	-18.5458	-20.1113	-20.9373	-22.3357	-23.7341	-25.0048	-27.0743	-28.1828	-27.9297	-31.0
5	2011/03/11 17:03	-3.0582	-7.2220	-9.4127	-19.3476	-20.4926	-22.9810	-24.2169	-25.8400	-27.4631	-25.4811	-25.0441	-25.5176	-28.9
6	2011/03/11 17:04	-.6253	-5.2644	-9.3781	-13.1067	-16.8353	-20.2075	-19.7403	-20.6884	-21.6365	-23.5763	-25.8693	-26.0569	-27.2
7	2011/03/11 17:05	-6.0807	-8.6887	-11.2966	-14.6631	-17.4869	-20.3107	-20.6882	-20.3267	-21.5047	-23.0069	-24.1760	-24.7751	-26.4
8	2011/03/11 17:06	-6.3532	-7.9238	-10.5781	-11.1145	-13.6368	-15.5411	-17.4455	-19.3498	-20.5751	-22.3729	-23.2196	-24.0022	-26.9
9	2011/03/11 17:07	-7.9612	-8.5969	-10.9609	-12.4607	-13.9641	-15.4603	-17.5421	-17.0884	-17.9078	-18.7271	-20.2987	-22.1994	-24.9
10	2011/03/11 17:08	-4.8705	-4.6466	-5.7913	-12.1165	-12.4597	-14.4216	-15.2374	-16.2777	-18.2129	-19.9873	-21.5460	-22.3175	-25.5
11	2011/03/11 17:09	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9
12	2011/03/11 17:10	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9
13	2011/03/11 17:11	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9
14	2011/03/11 17:12	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9
15	2011/03/11 17:13	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9
16	2011/03/11 17:14	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9000	-999.9
17	2011/03/11 17:15	2.2316	2.5492	-3.7429	-6.8551	-9.1880	-12.0997	-14.8446	-15.8066	-17.3740	-18.2702	-19.8265	-21.5730	-23.0
18	2011/03/11 17:16	5.4540	2.6245	-1.5938	-5.9057	-8.7972	-11.9467	-14.3472	-16.2112	-17.2149	-18.2329	-19.2509	-20.6890	-22.5
19	2011/03/11 17:17	2.4169	3.4239	-.3008	-3.5147	-7.3908	-11.6097	-13.4333	-15.6615	-16.2778	-16.4018	-18.1043	-20.3310	-27.4
20	2011/03/11 17:18	-9.1403	-4.6925	-6.2843	-7.3099	-8.6186	-10.4038	-12.8934	-13.9576	-17.3996	-19.5165	-21.8225	-23.7100	-26.6
21	2011/03/11 17:19	2.2718	3.9085	1.4419	-5.5000	-9.0922	-13.8697	-16.2088	-19.6118	-20.6623	-22.9264	-24.0579	-25.5399	-26.9
22	2011/03/11 17:20	.6337	3.2427	.4884	-2.1509	-6.1525	-9.2776	-13.1280	-19.2000	-20.0161	-23.5324	-24.1892	-25.6104	-27.3
23	2011/03/11 17:21	-.2069	-1.0273	-3.5583	-5.4621	-8.3431	-10.3235	-13.1279	-16.5608	-19.3355	-22.2351	-23.2439	-25.4723	-27.0
24	2011/03/11 17:22	-.0213	-1.2381	-4.7408	-7.1005	-8.9489	-11.8200	-14.3309	-17.2835	-20.0017	-22.6352	-24.4473	-26.3438	-28.2

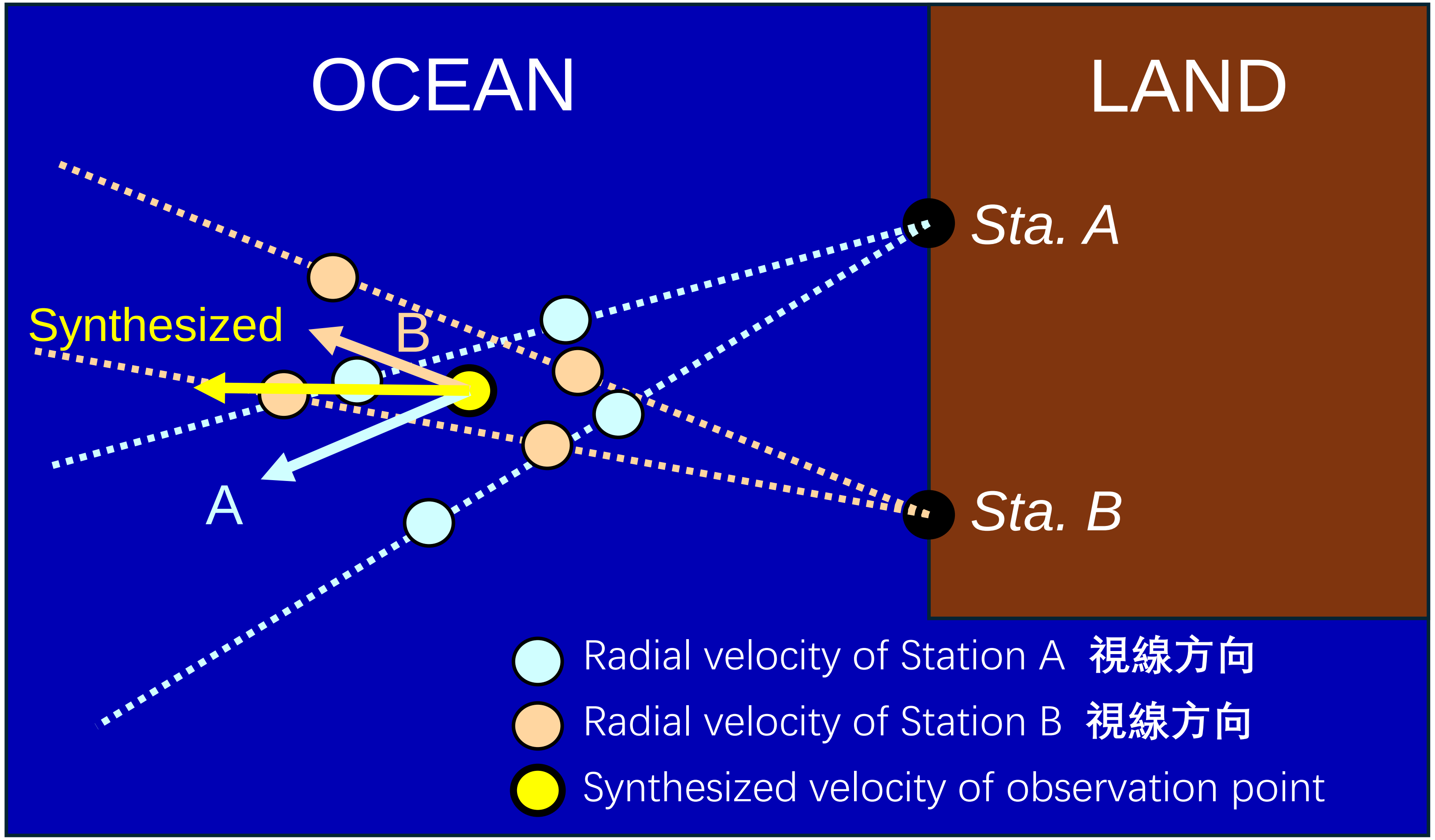
観測データ＠湊　（処理前）

The tsunamis of the 2011 Tohoku earthquake was observed by high-frequency radar system in Kii Channel.

Sampling rate: 1 min


134°
135°
136°
34°
HF Radar Land Station
HF Radar Observational Point
Tide Gauge
Kobe
OSAKA BAY
Minato sta.
Saikazaki sta.
SEA OF JAPAN
Study region
PACIFIC OCEAN
KII CHANNEL
10 km

Vector Synthesis of Surface Vector



- At least **two** land stations are required for vector synthesis
- It is necessary to install the beams of the two stations to be close to **90 degrees**

Beam direction (radial velocity) -> NS/EW direction

Vector Synthesis of Surface Vector

$$\begin{bmatrix} sin\theta_1 & cos\theta_1 \\ sin\theta_2 & cos\theta_2 \\ & \vdots \\ sin\theta_N & cos\theta_N \end{bmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \begin{bmatrix} U_{r1} \\ U_{r2} \\ \vdots \\ U_{rN} \end{bmatrix}$$

i: Number of HF radar land station

θ_i: Azimuth of the grid

U_{ri}: Velocity in the beam direction

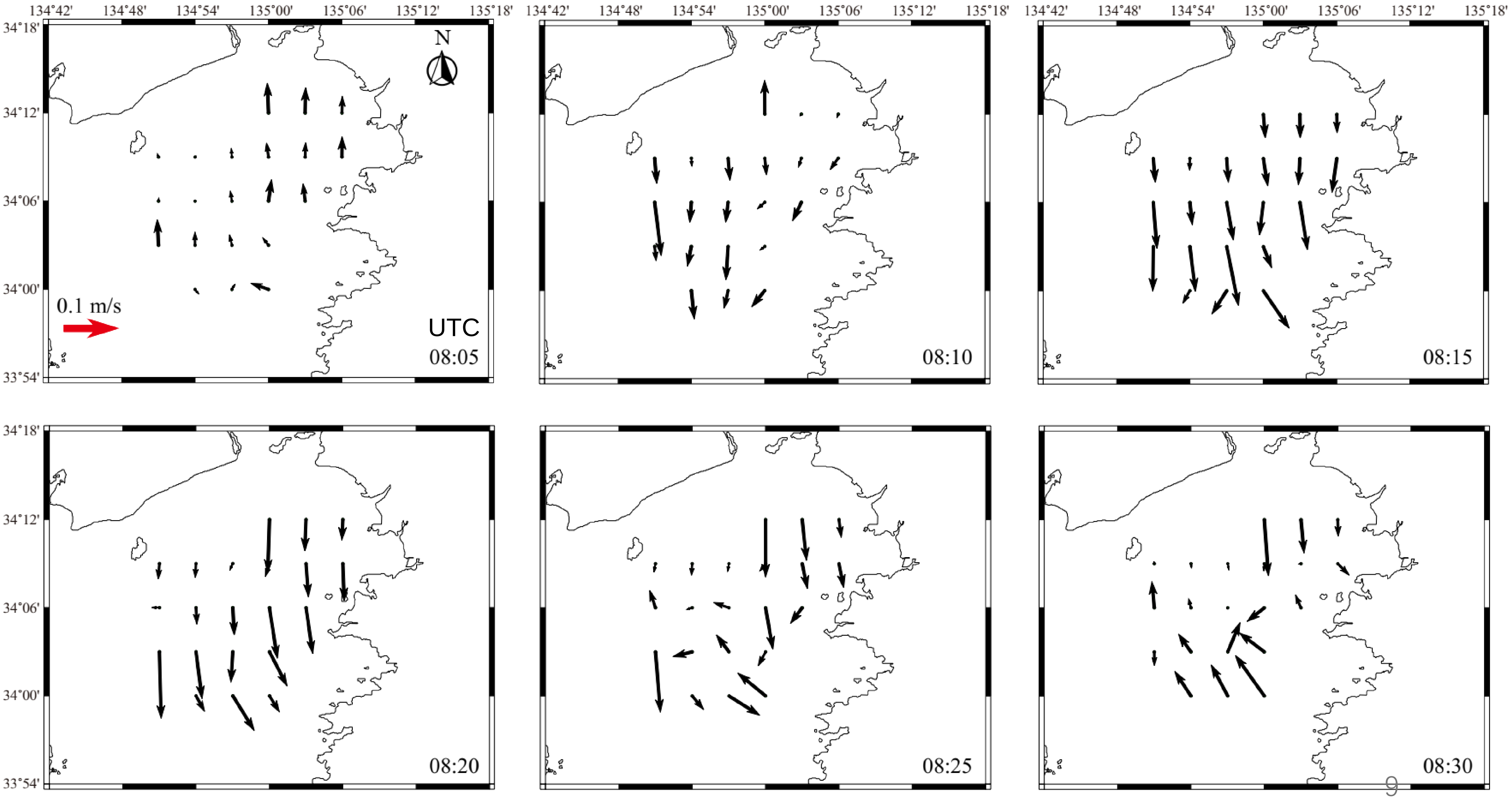
u, v: Velocity in the EW/NS direction

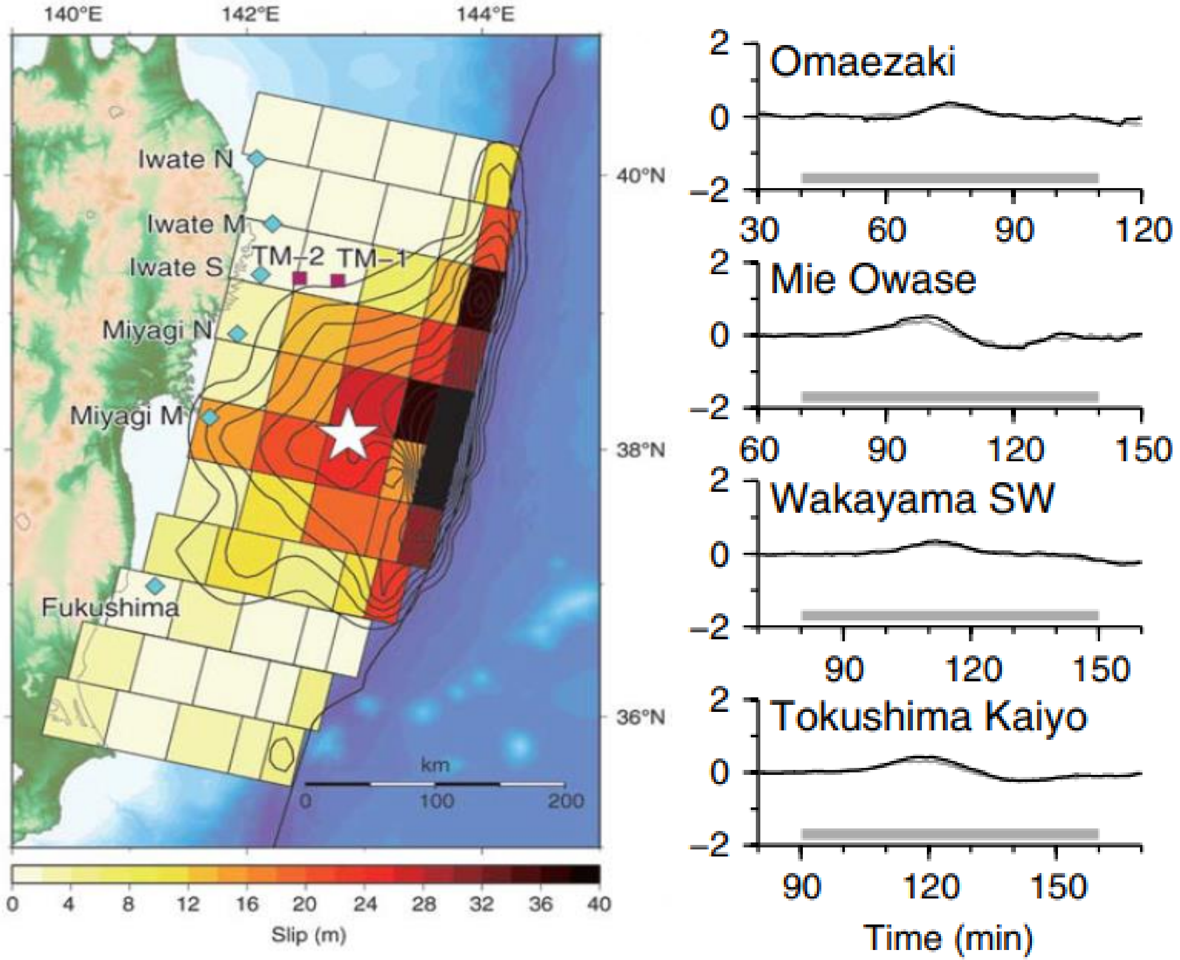
When N > 2:

$$\sum_{i=1}^{N} (U_{ri} - \widehat{U}_{r1})^2 / \sigma_i^2 \rightarrow min$$

When N = 2 (in this study):

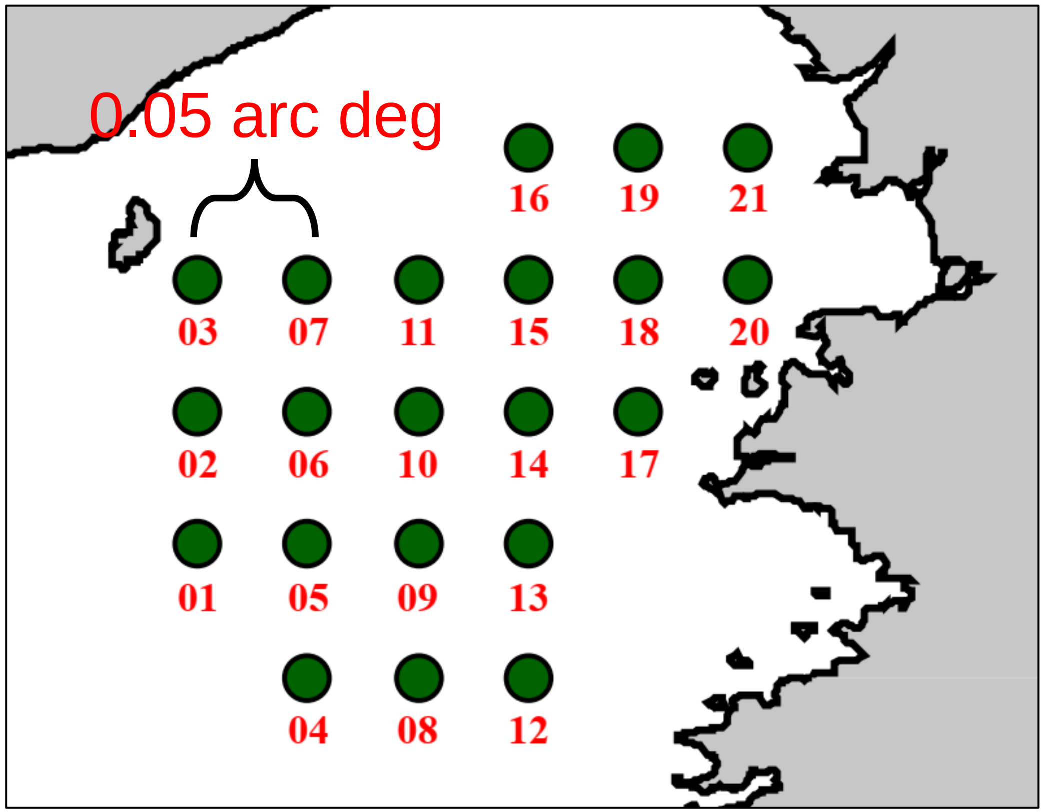
$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{bmatrix} sin\theta_1 & cos\theta_1 \\ sin\theta_2 & cos\theta_2 \end{bmatrix}^{-1} \begin{bmatrix} U_{r1} \\ U_{r2} \end{bmatrix}$$


134°42'
134°48'
134°54'
135°00'
135°06'
135°12'
135°18'
34°18'
34°12'
34°06'
34°00'
33°54'
N
0.1 m/s
UTC
08:05
08:10
08:15
08:20
08:25
08:30



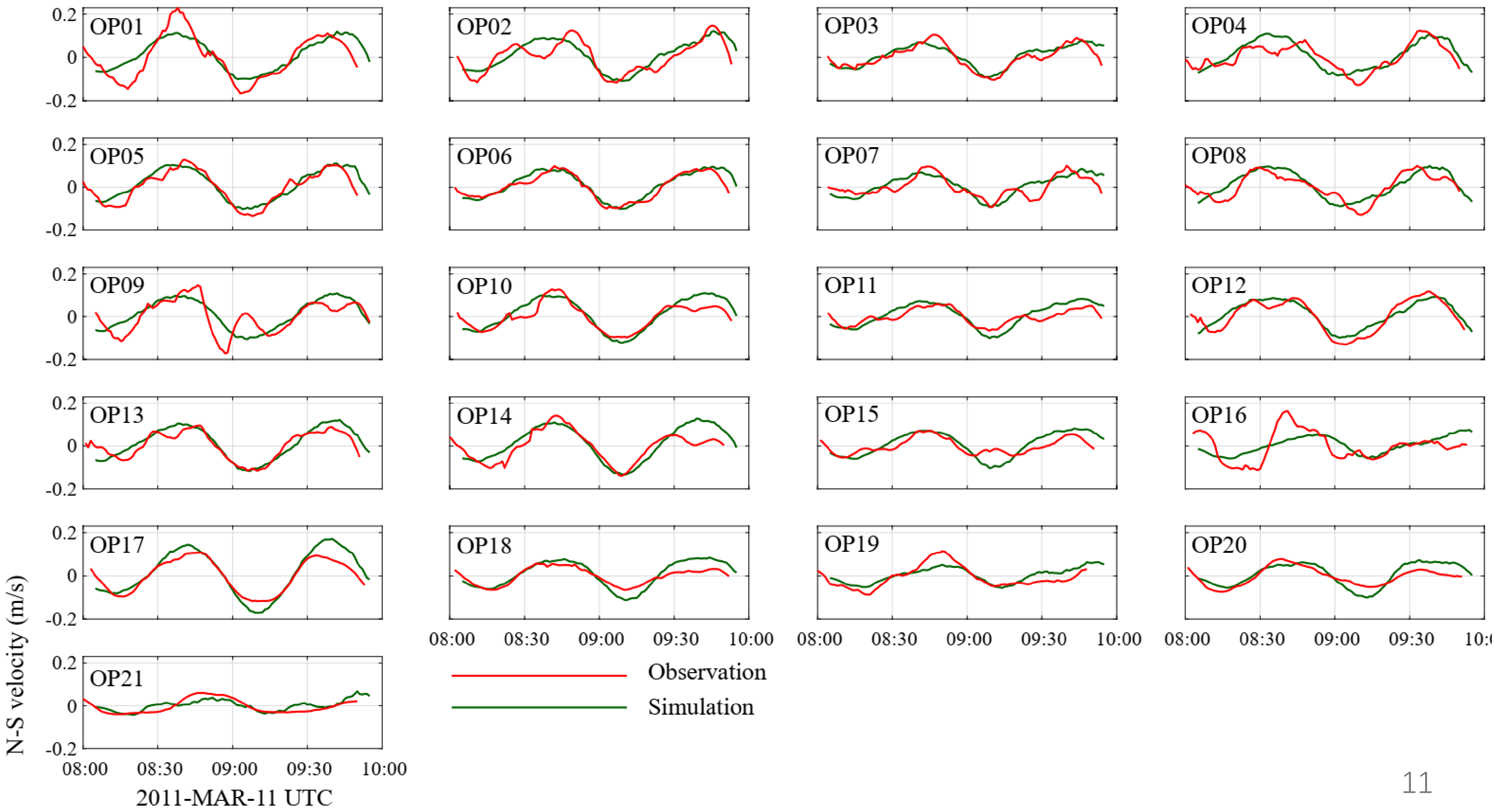
Satake et al. (2013)

Location of Observational Point (OP)

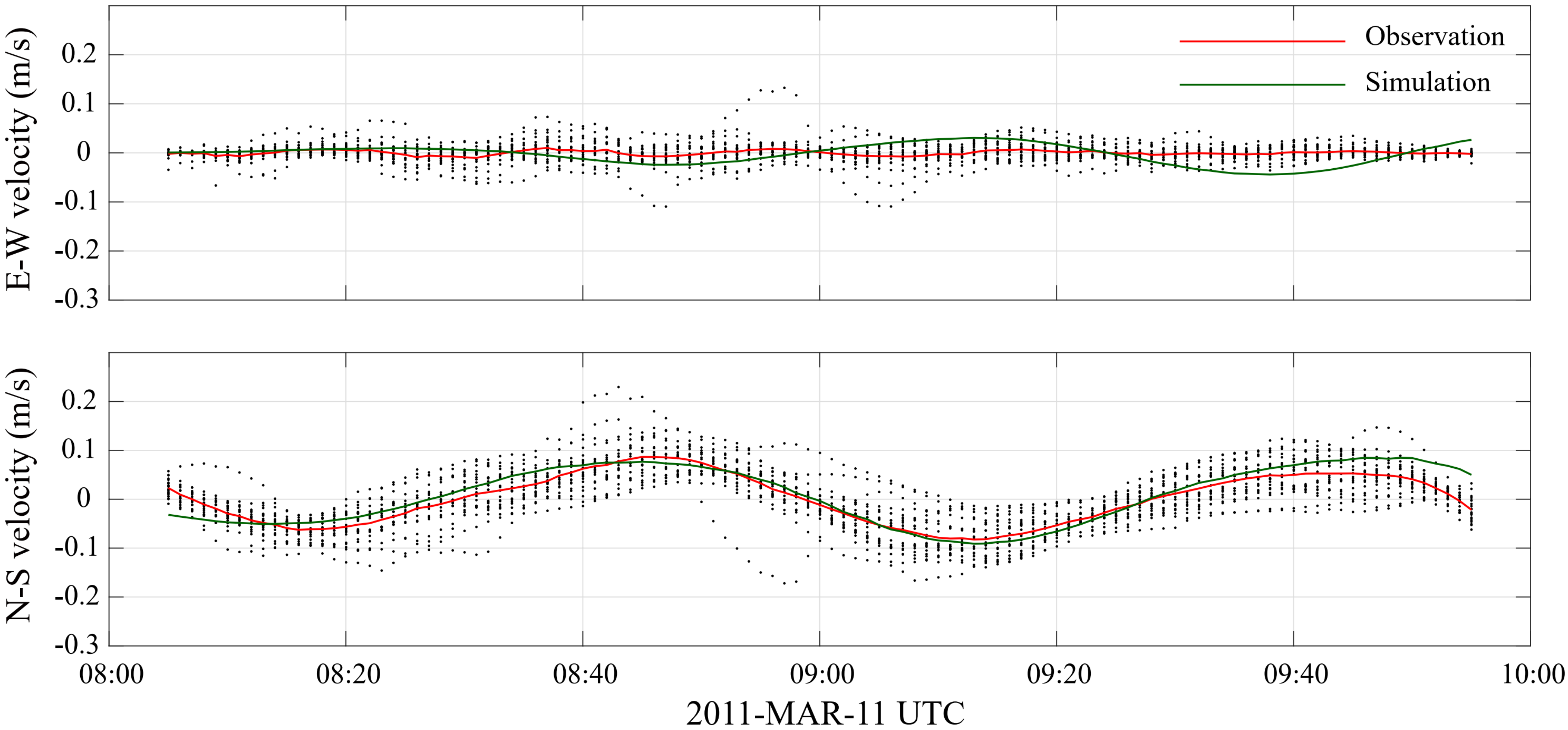


- データ解析の正確性を確認するために、**観測された流速**と**シミュレーション値**を比較した。
- シミュレーション値は断層モデルによって計算され、検潮計の波形を正確に再現できることから、流速の再現においても正確であると仮定した。

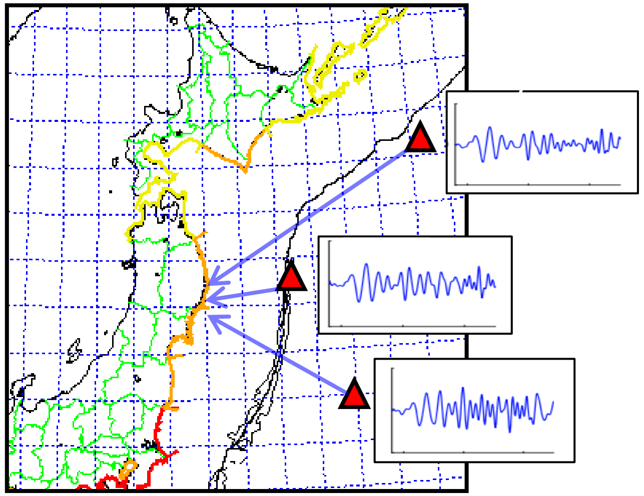
Time Series of Sea Surface Current



Time Series of Sea Surface Current



Data Assimilation for Early Warning

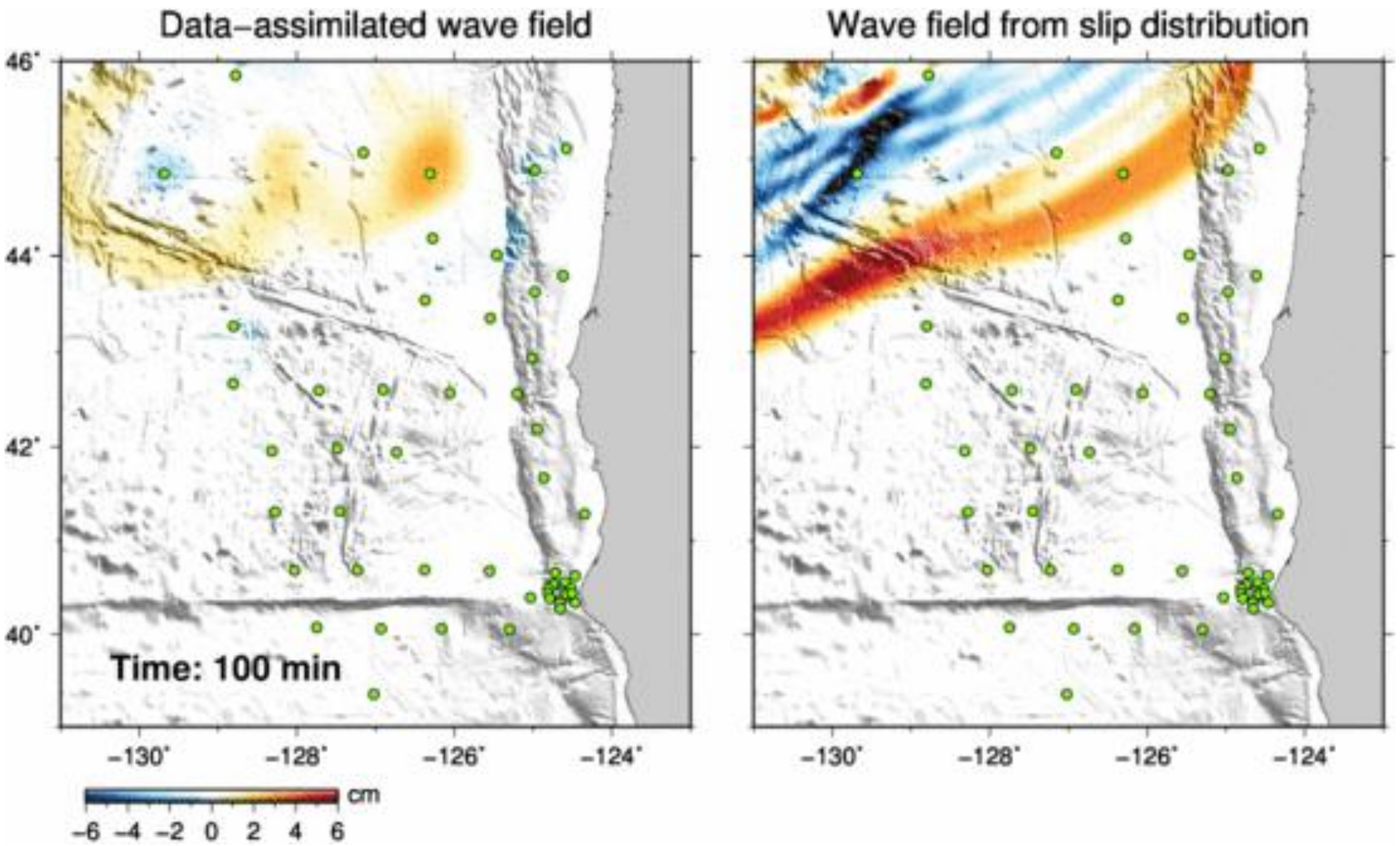


Offshore Tsunami Observation

↓

Tsunami Forecasting

Past study: 2012 Haida Gwaii tsunami (synthetic)



Do not need source information!

(Gusman et al., 2016)

Tsunami wavefield $\boldsymbol{x}_n = (h(n\Delta t, x, y), P(n\Delta t, x, y), Q(n\Delta t, x, y))^T$

Height X-Velocity Y-Velocity

I. Forecasting Step $\boldsymbol{x}_n^f(h, P, Q) = \boldsymbol{F}\boldsymbol{x}_{n-1}^a(h, P, Q)$

II. Assimilating Step

$$\boldsymbol{x}_n^a(h, P, Q) = \boldsymbol{x}_n^f(h, P, Q) + \boldsymbol{W}(\boldsymbol{z}_n(\boldsymbol{P}, \boldsymbol{Q}) - \boldsymbol{H}\boldsymbol{x}_n^f(h, P, Q))$$

$\boldsymbol{x}_n^f$: Forward tsunami wavefield

$\boldsymbol{x}_n^a$: Assimilated tsunami wavefield

$\boldsymbol{F}$: Propagation matrix

$\boldsymbol{W}$: Weight matrix**

$\boldsymbol{H}$: Sparse linear observation matrix

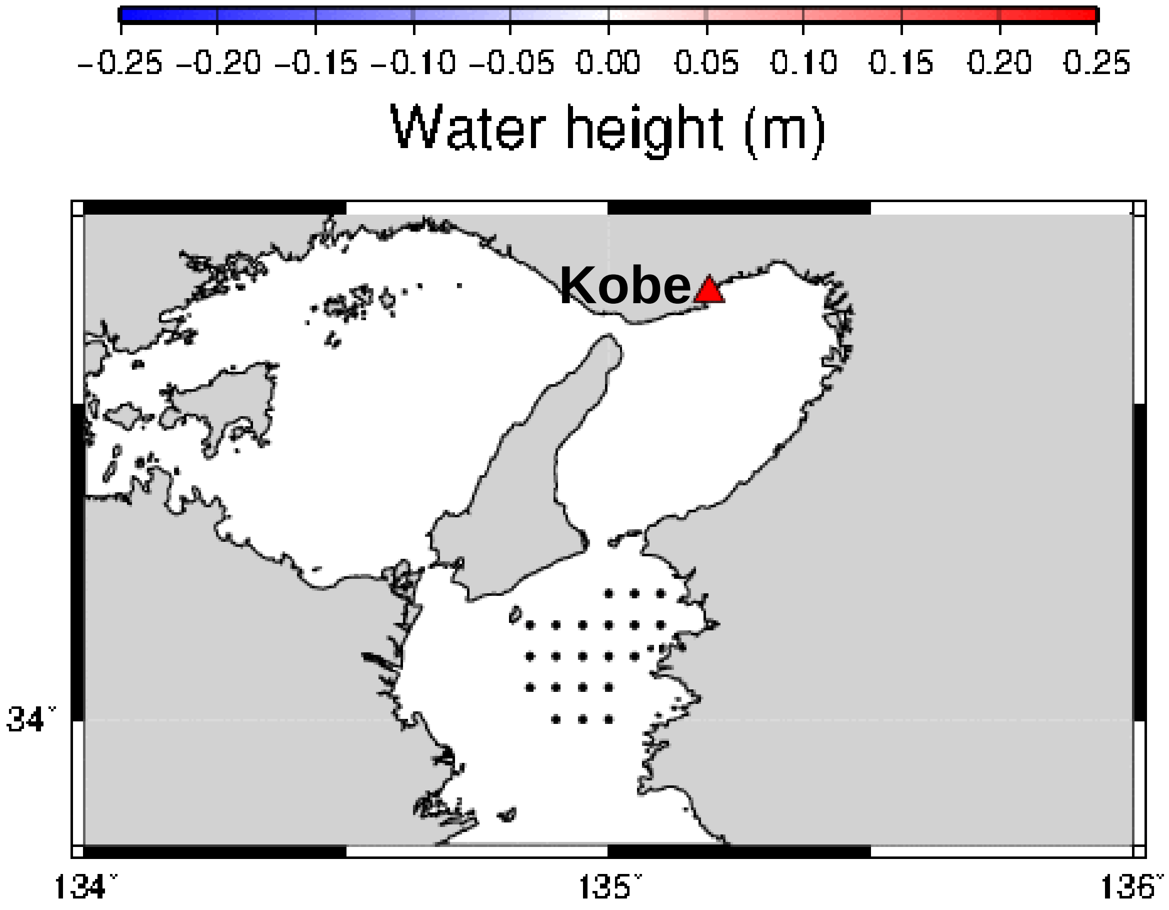
$\boldsymbol{z}_n$: Observation of HF radar (velocity)

Assimilation starts at 08:05 UTC (JST 17:05)

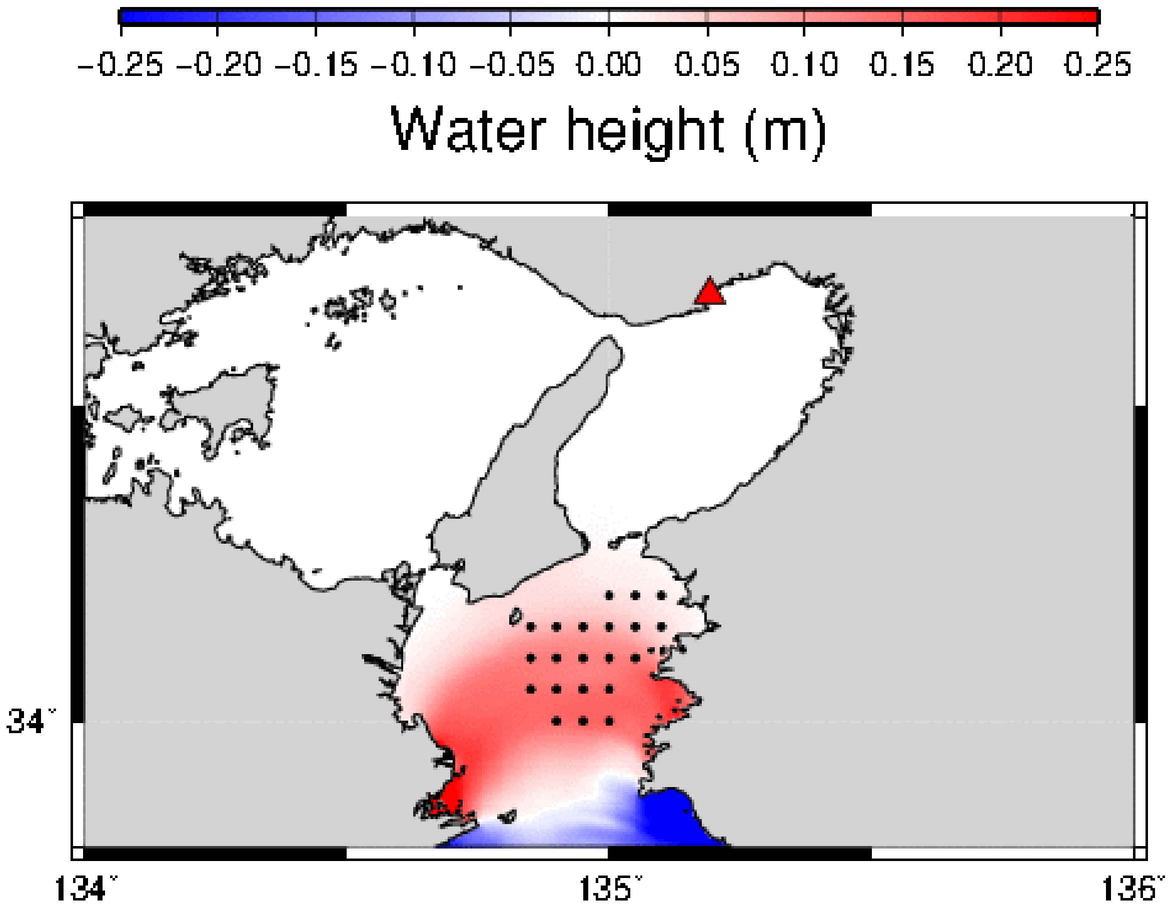
** New algorithm of calculating W was proposed by Dr. Sahana

3. 結果

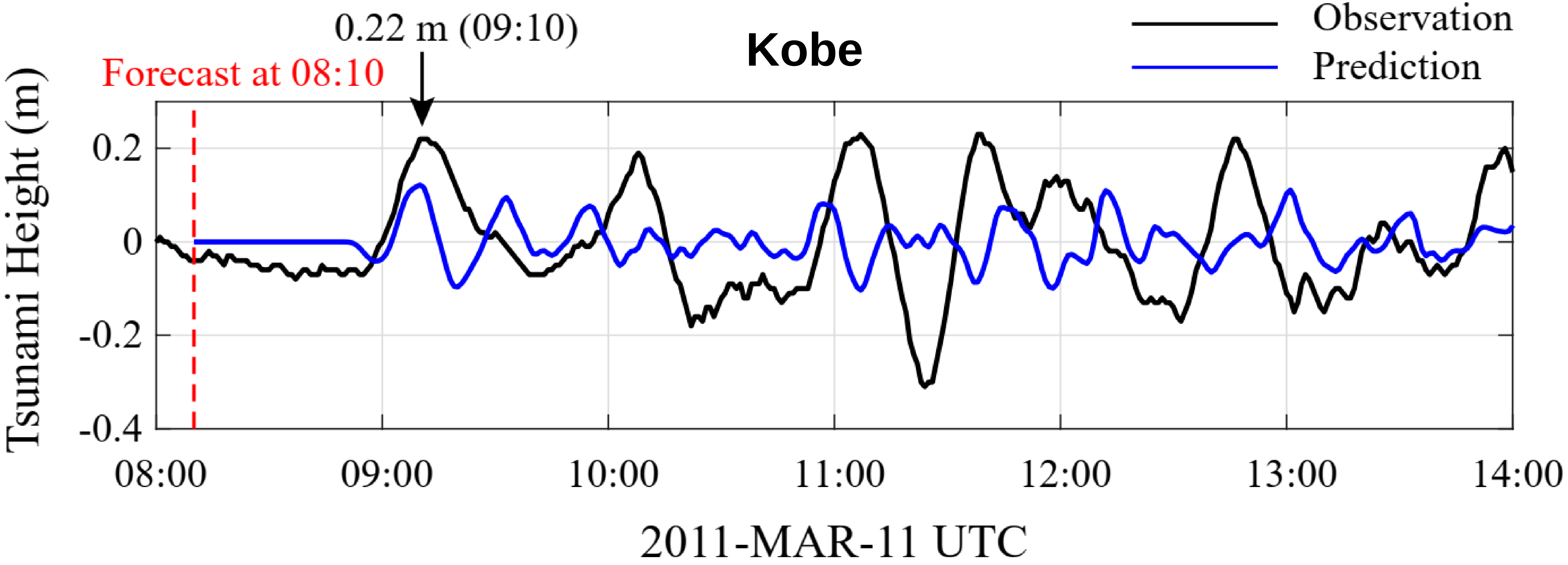
Time: 2011 March 11, 08:05 – 09:00 UTC (17:05 – 18:00 JST)



Forecasted tsunami wavefield using data assimilation of HF radar



Simulated tsunami wavefield computed from source model of Satake et al. (2013)



Observed maximum height: 0.23 m

Predicted maximum height: 0.12 m

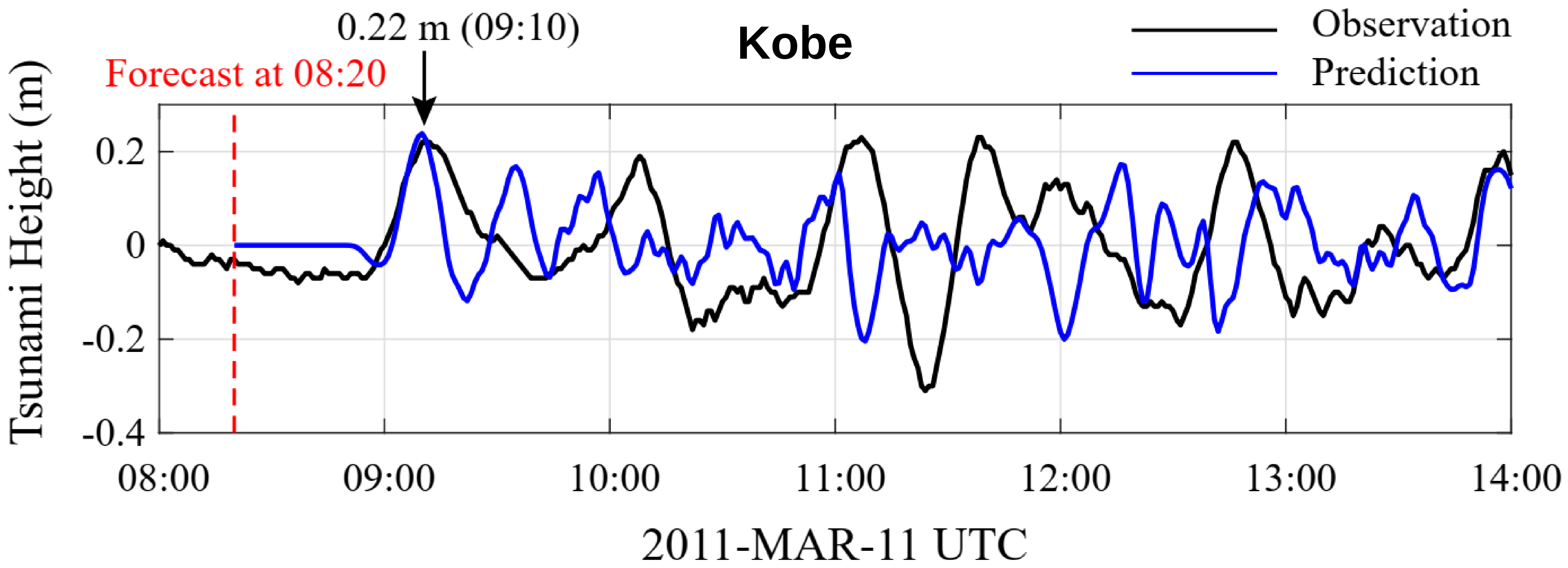
Accuracy (%): 52.2%

Normalized Prediction Error (Navarrete et al., 2019)

$$\min\left\{\sqrt{\frac{\frac{1}{T}\sum_{t=1}^{T}(y_{pre}(t+L)-y_{obs}(t))^2}{\frac{1}{T}\sum_{t=1}^{T}(y_{pre}(t+L))^2+\frac{1}{T}\sum_{t=1}^{T}(y_{obs}(t))^2}};1\right\}=0.991$$

最大振幅：津波早期警報にとって大事

後続波：津波警報解除にとって大事



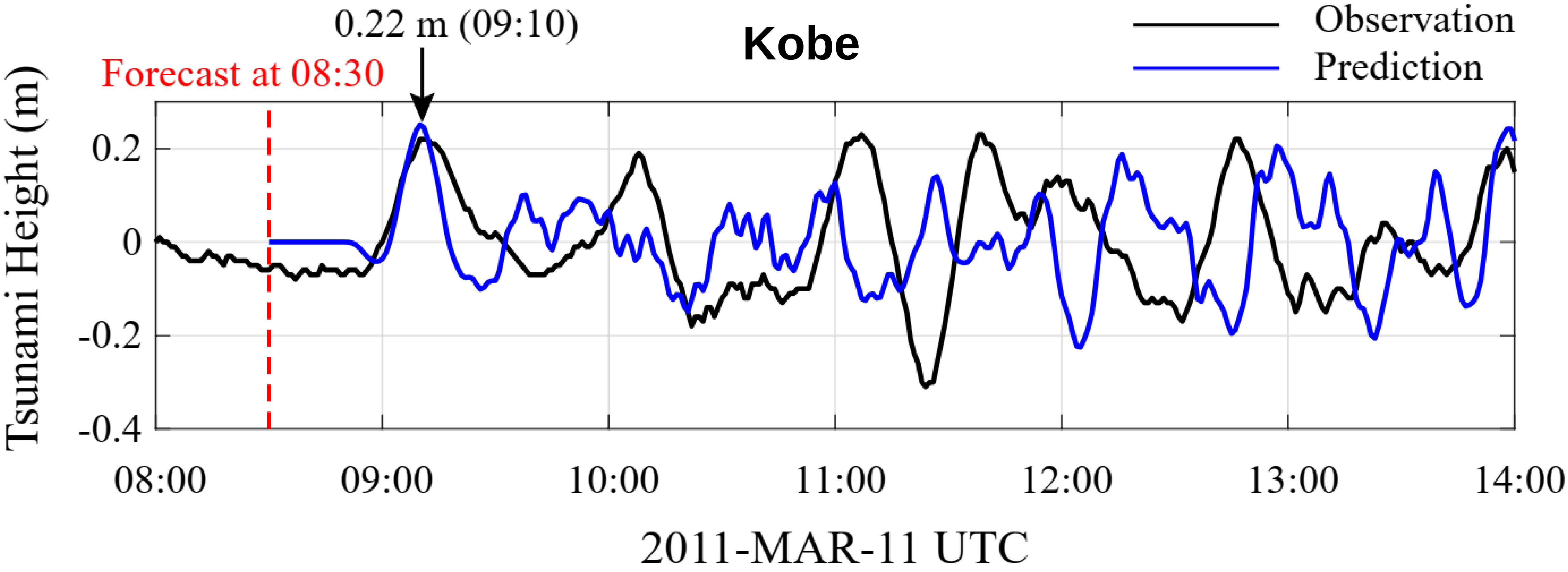
Observed maximum height: 0.23 m

Predicted maximum height: 0.24 m

Accuracy (%): 95.8%

Normalized Prediction Error

$$\min\left\{\sqrt{\frac{\frac{1}{T}\sum_{t=1}^{T}(y_{pre}(t+L)-y_{obs}(t))^2}{\frac{1}{T}\sum_{t=1}^{T}(y_{pre}(t+L))^2+\frac{1}{T}\sum_{t=1}^{T}(y_{obs}(t))^2}};1\right\} = 0.976$$



Observed maximum height: 0.23 m

Predicted maximum height: 0.25 m

Accuracy (%): 92.0%

Normalized Prediction Error

$$\min\left\{\sqrt{\frac{\frac{1}{T}\sum_{t=1}^{T}(y_{pre}(t+L)-y_{obs}(t))^2}{\frac{1}{T}\sum_{t=1}^{T}(y_{pre}(t+L))^2+\frac{1}{T}\sum_{t=1}^{T}(y_{obs}(t))^2}};1\right\} = 0.929$$

4. まとめ

- HF radar observed the tsunami of the 2011 Tohoku earthquake, with a value of ~ 0.1 m/s at most observational points after 08:00 (UTC).
- Data assimilation of surface current velocity successfully predicted the tsunami waveforms of Kobe tide gauge at 08:20, approximately 50 min prior to tsunami arrival.
- The normalized prediction error decreased over assimilation time.

Thank you for your attention!

Article Navigation

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Yuchen Wang; Kentaro Imai; Hiroki Horikawa

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