津波早期警報のためのHFレーダーを用いたデータ同化: 2022 年トンガ火山津波のケーススタディ

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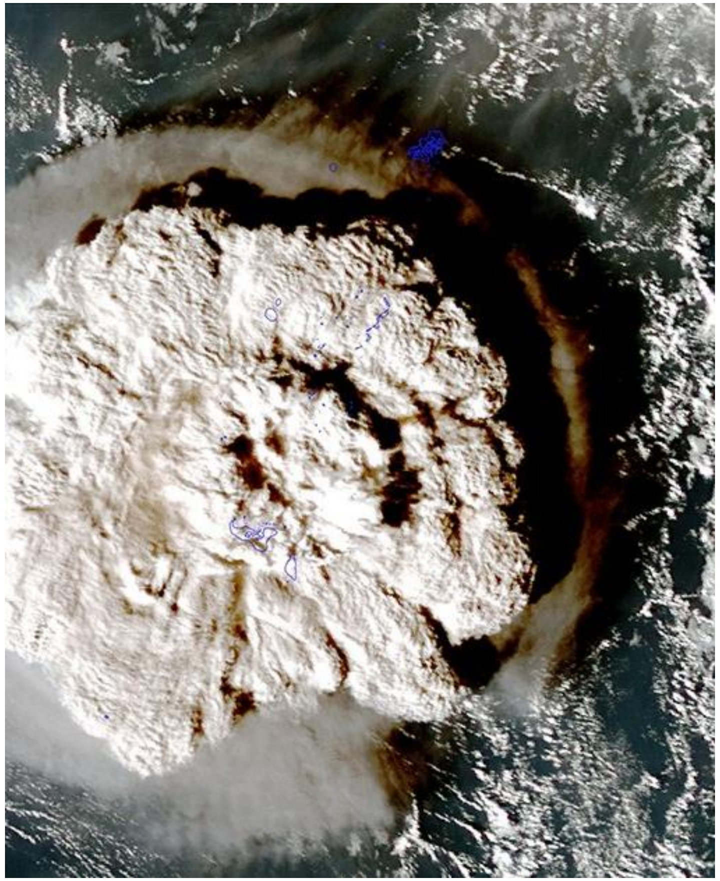
Introduction

2022 Tonga Volcanic Tsunami

- Hunga Tonga-Hunga Ha'apai volcano
- Large eruption: 04:14:45 (UTC), January 15, 2022.
- The tsunami event had a complex generating mechanism, posing a challenge for the traditional tsunami early warning method based on source inversion.

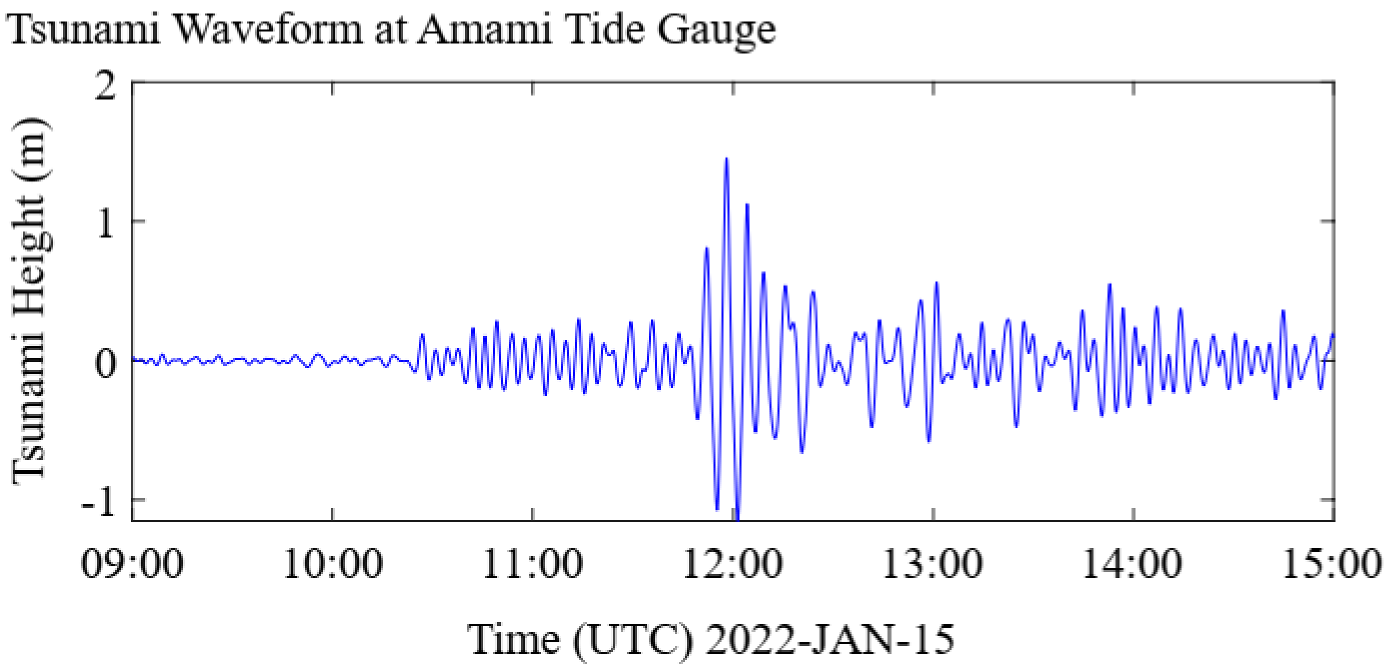


(Witze, 2022 *Nature*; SCMP, 2022)

Introduction

2022 Tonga Volcanic Tsunami

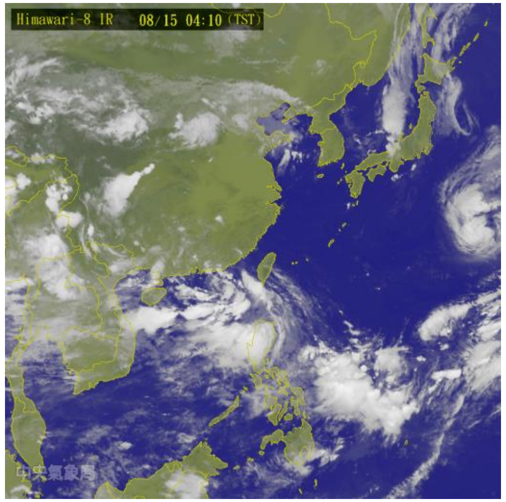
- Arrived in Japan 7 hr 15 min after the eruption, earlier than expected from an oceanic gravity wave.
- A maximum height of 1.2 m at Amami Island.

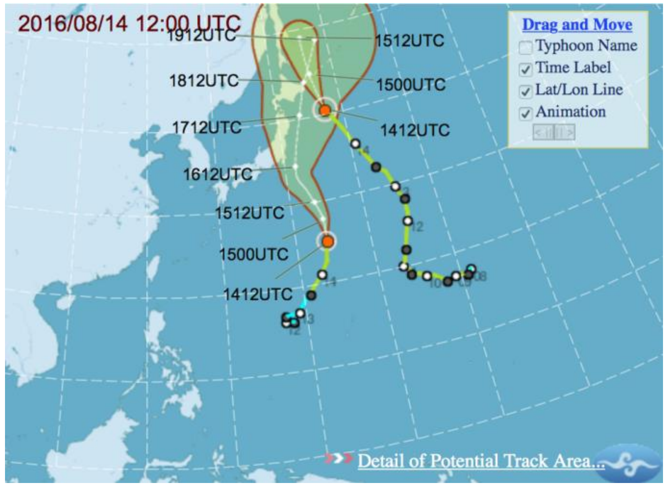


(Asahi News, 2022)

Data and Method

Tsunami Data Assimilation Approach



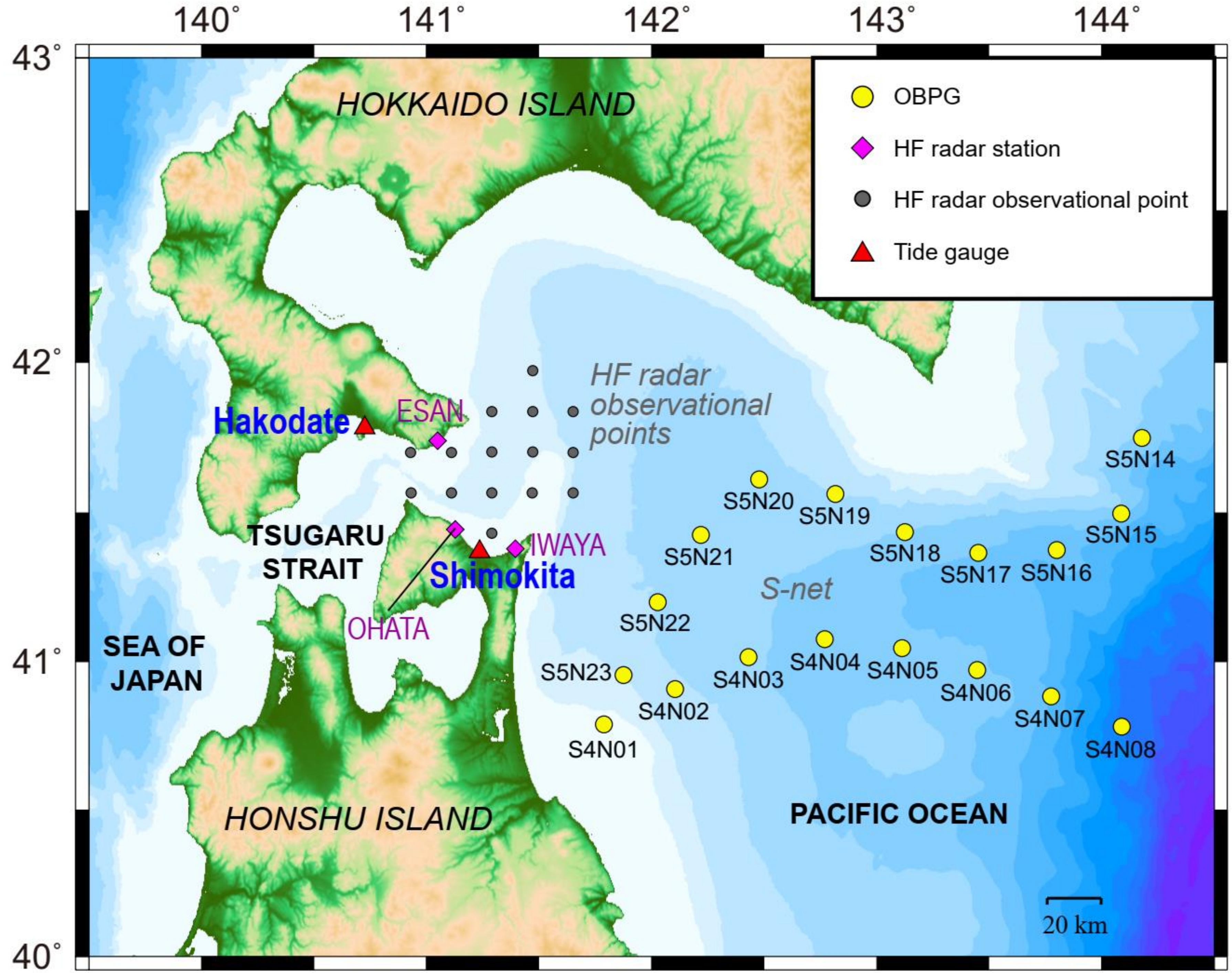


Data assimilation in Meteorology

- It does not estimate the “source” of typhoon
- Knowing the current status (wavefield), one can forecast future status by numerical modeling

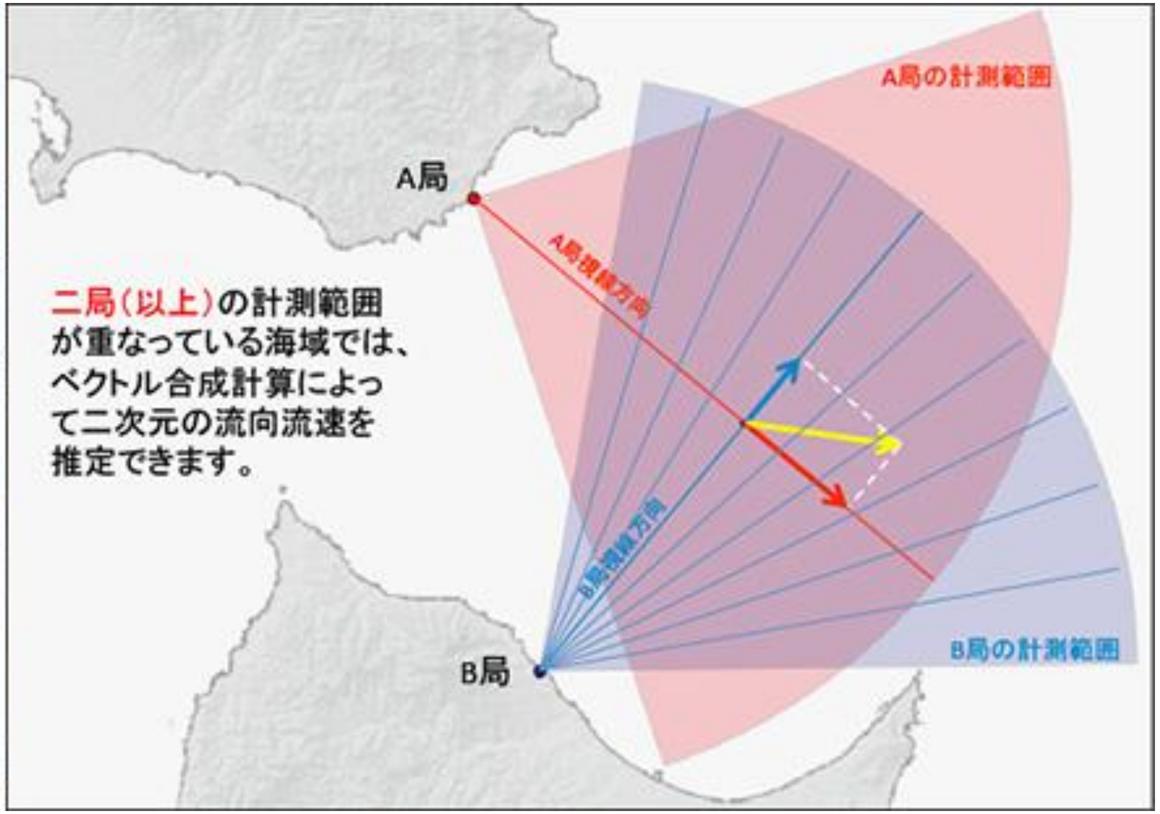
We can also successively estimate the current tsunami status by **data assimilation** technique with **offshore tsunami observation**.

- Offshore bottom pressure gauge (OBPG)
- High-frequency (HF) radar



140°
141°
142°
143°
144°
43°
42°
41°
40°
HOKKAIDO ISLAND
OBPG
HF radar station
HF radar observational point
Tide gauge
HF radar observational points
Hakodate
ESAN
TSUGARU STRAIT
IWAYA
Shimokita
OHATA
S-net
SEA OF JAPAN
HONSHU ISLAND
PACIFIC OCEAN
S5N14
S5N20
S5N19
S5N15
S5N21
S5N18
S5N17
S5N16
S5N22
S5N23
S4N03
S4N04
S4N05
S4N06
S4N02
S4N07
S4N01
S4N08
20 km

HF Radar in the Eastern Tsugaru Strait

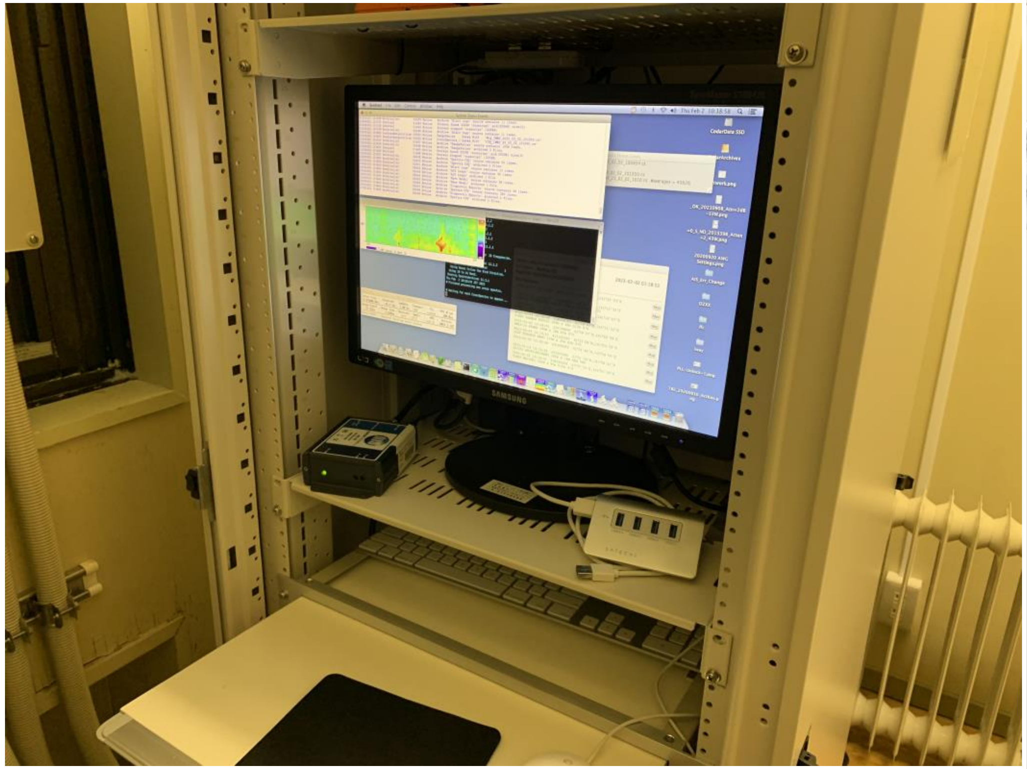


津軽海峡東部に設置された観測システムは、使用周波数13.9MHz帯の米国CODAR社製のSeaSonde海洋短波レーダーです。距離分解能は約3km、観測範囲は各海洋短波レーダー局より3kmから60kmで、観測範囲が2局以上重なっている海域での流況が得られます。

津軽海峡東部 海洋レーダーデータサイト

MIO Ocean Radar data Site for the Eastern Tsugaru Strait（MORSETS）

HF Radar in the Eastern Tsugaru Strait



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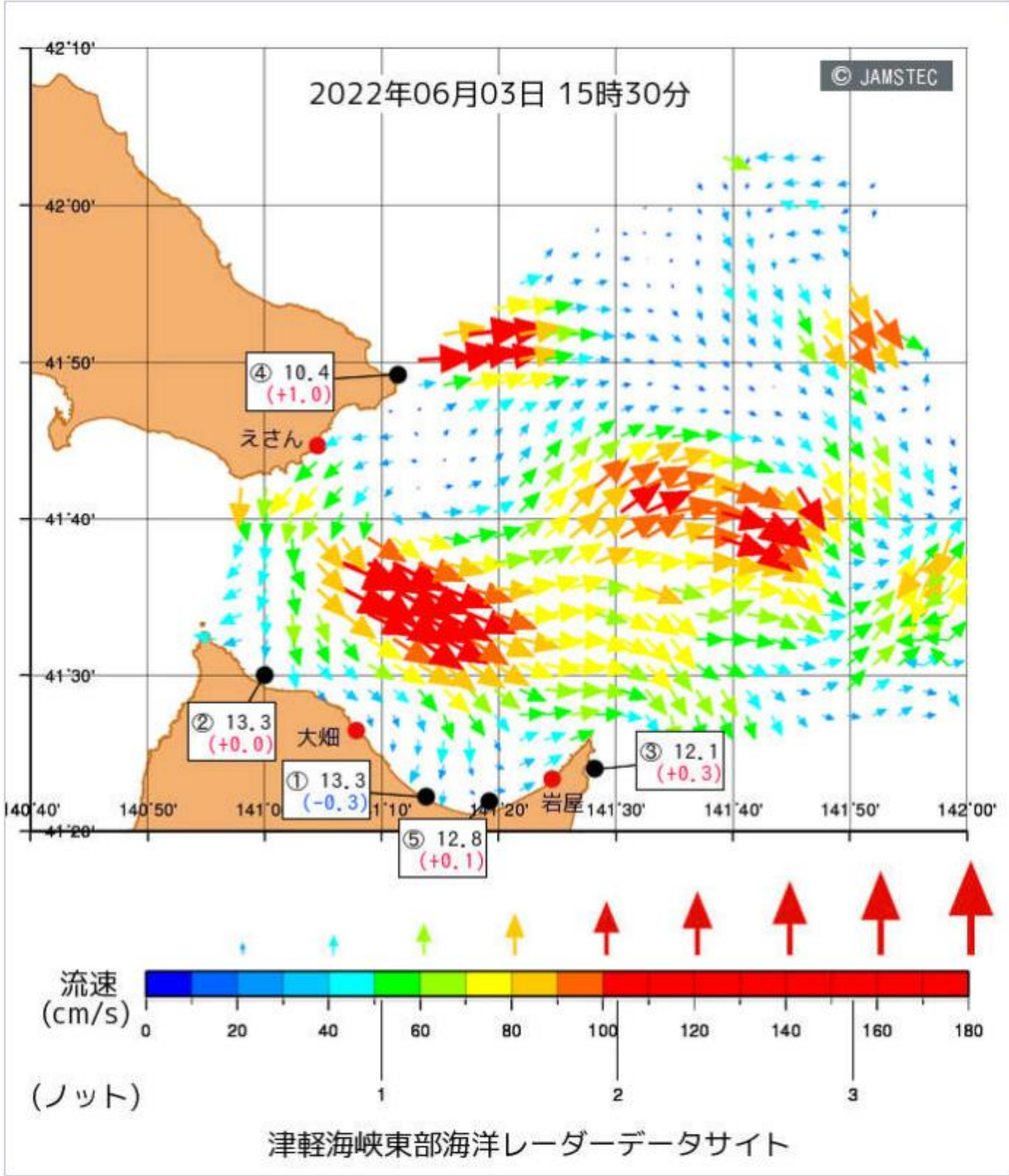


流況を見る

※過去2日間の流況が見られます。

画像 連続再生

<<前へ 次へ>>

時刻設定：
2022/06/03
15:30

最新データ取得時刻：
2022/06/03 15:30

地図背景の切替

● 緯度経度表示
○ 等深線表示
海面水温表示
○ 衛星水温※1
○ 推定水温※2
○ 合成表示

ブイ水温値を…

● 表示する
○ 表示しない

流速図について

矢印の向きは流向、矢印の色と大きさは流速を示しています。矢印が大きいほど速い流れを意味しています。

矢印の色で示す流速値は図の下のカラーバーをご覧ください。

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

$$\boldsymbol{x}_n^a(h, P, Q) = \boldsymbol{x}_n^f(h, P, Q) + \boldsymbol{W}_1\left(\boldsymbol{y}_n(\boldsymbol{h}) - \boldsymbol{H}_1\boldsymbol{x}_n^f(h, P, Q)\right) + \boldsymbol{W}_2\left(\boldsymbol{z}_n(\boldsymbol{P}, \boldsymbol{Q}) - \boldsymbol{H}_2\boldsymbol{x}_n^f(h, P, Q)\right)$$

Offshore bottom pressure gauge (OBPG)

HF radar

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

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

$\boldsymbol{F}$: Propagation matrix

$\boldsymbol{W}$: Weight matrix

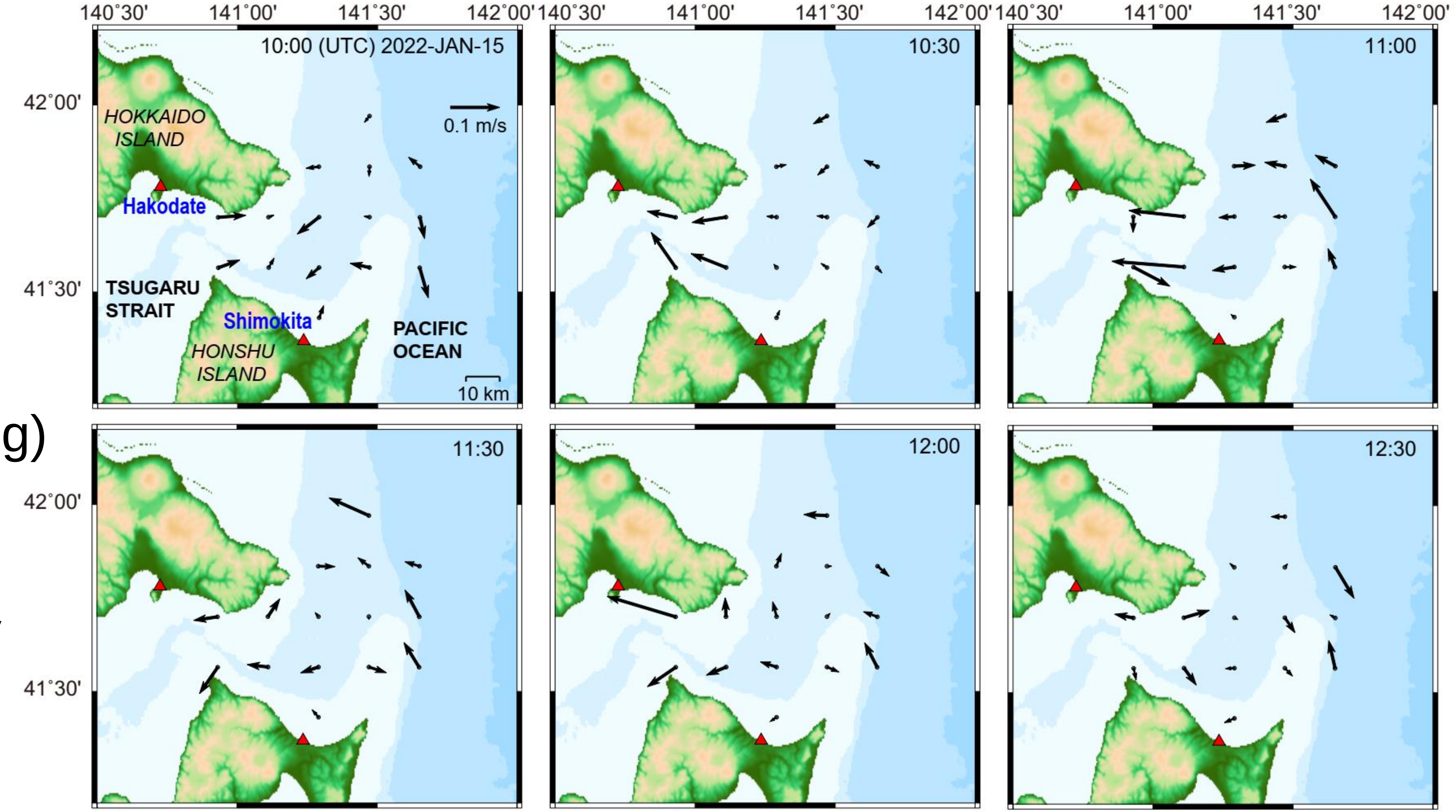
$\boldsymbol{H}$: Sparse linear observation matrix

$\boldsymbol{y}_n$: Observation of OBPG (height)

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

HF Radar

1. Basic quality control
2. Spatial average (smoothing)
3. Remove low-frequency signals



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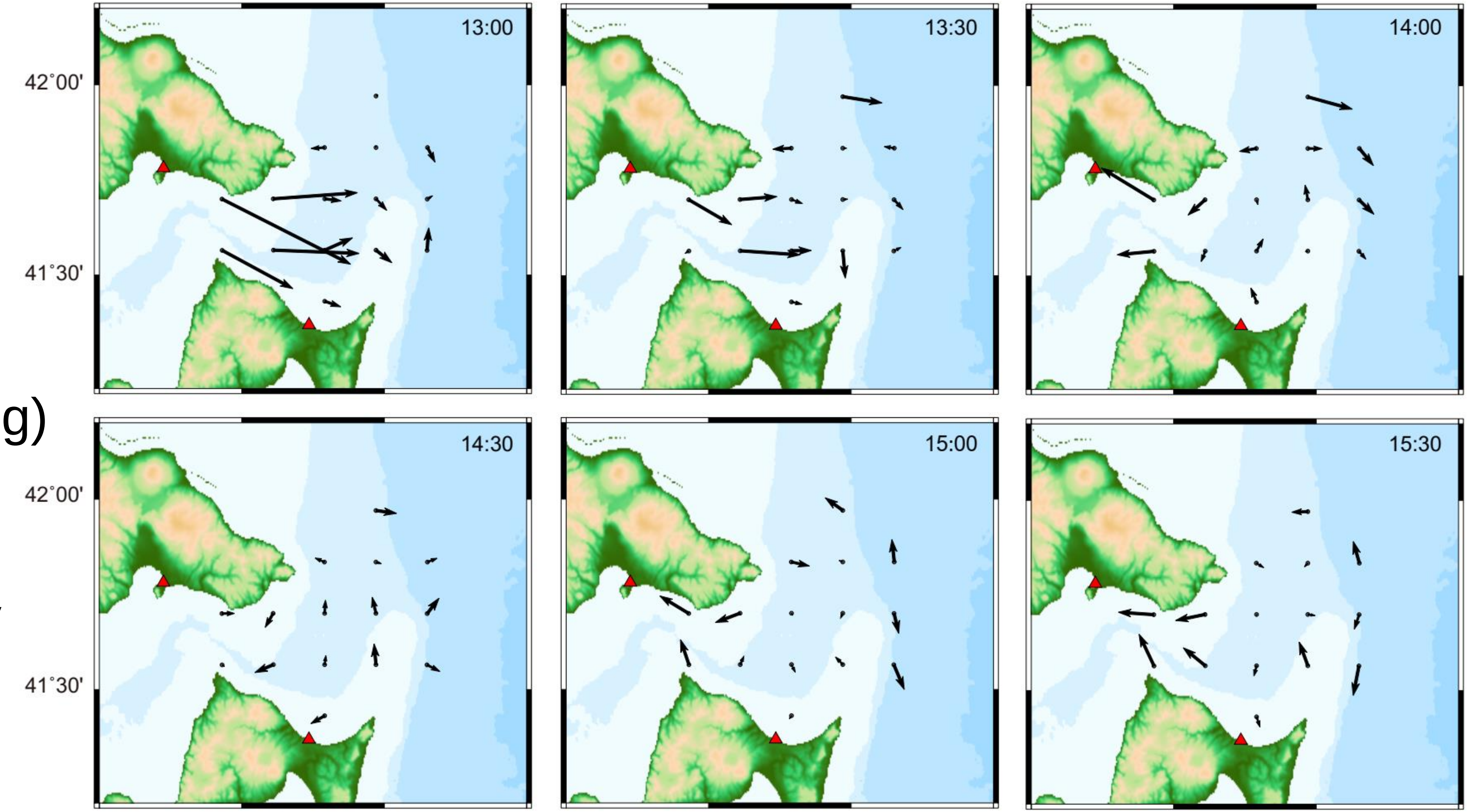
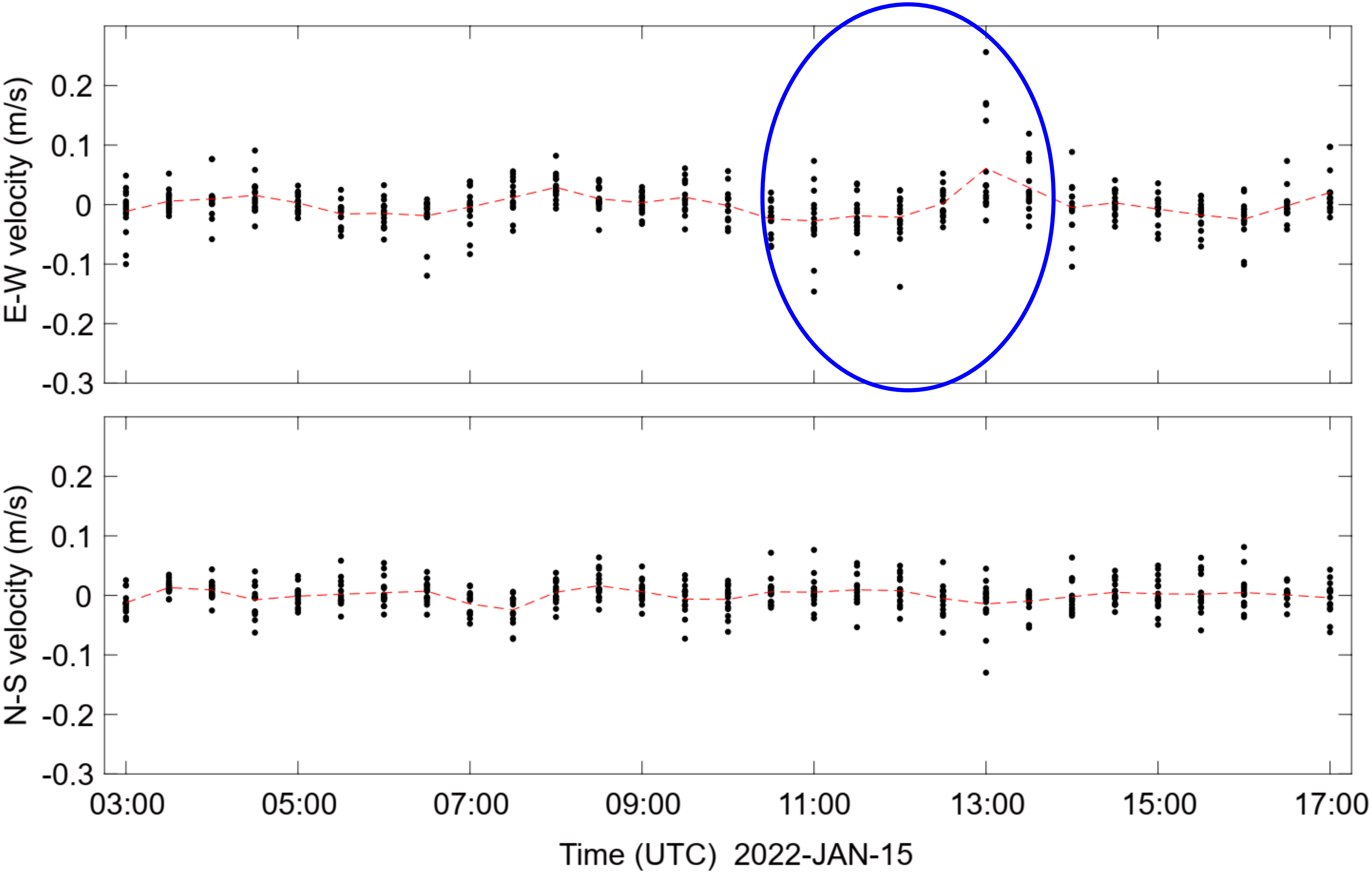
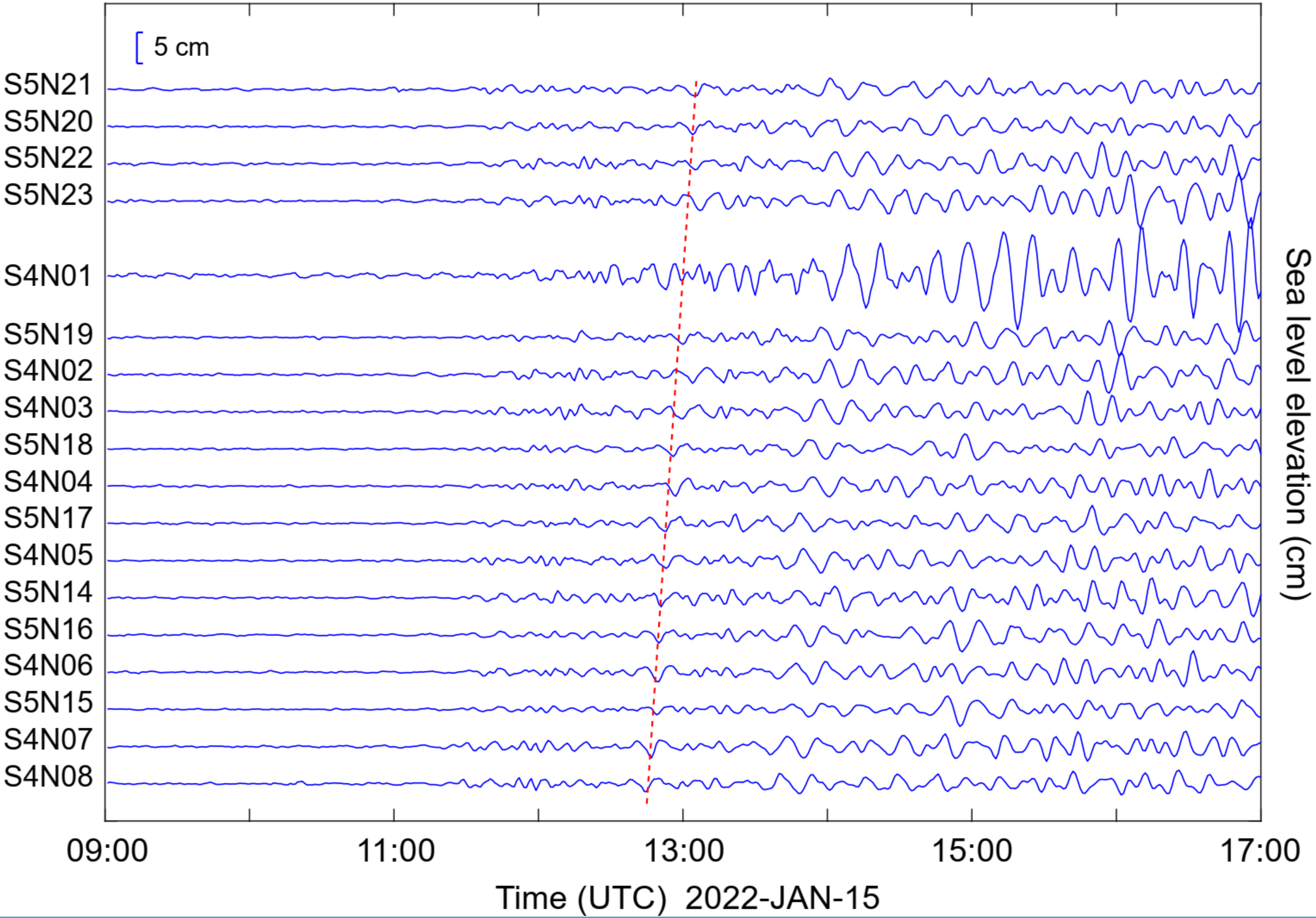




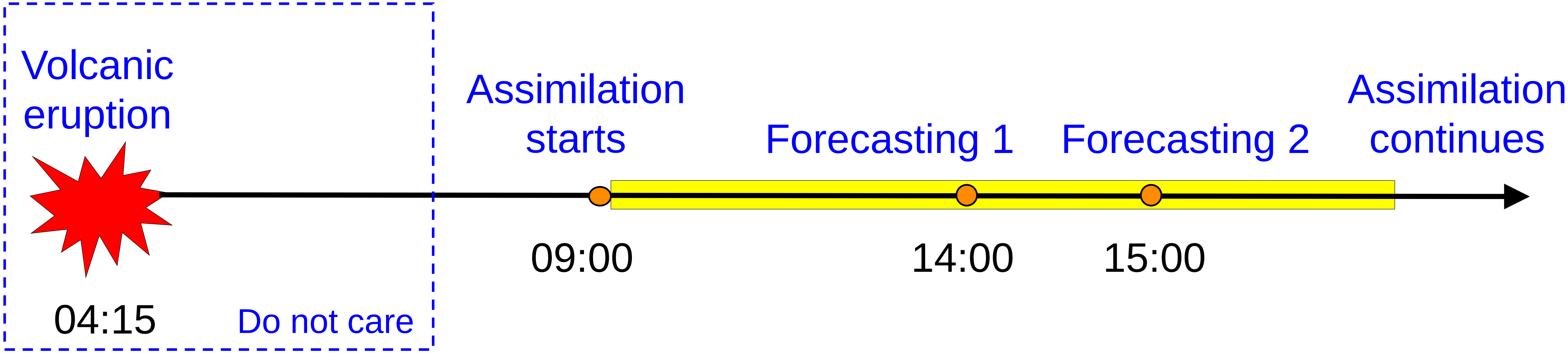
E-W velocity (m/s)
0.2
0.1
0
-0.1
-0.2
-0.3
N-S velocity (m/s)
0.2
0.1
0
-0.1
-0.2
-0.3
03:00
05:00
07:00
09:00
11:00
13:00
15:00
17:00
Time (UTC) 2022-JAN-15

S-net OBPG

1. Basic quality control
2. Convert pressure to water height
3. Linear interpolation
4. Band-pass filtering (200–1200 s)



Assimilation Setting

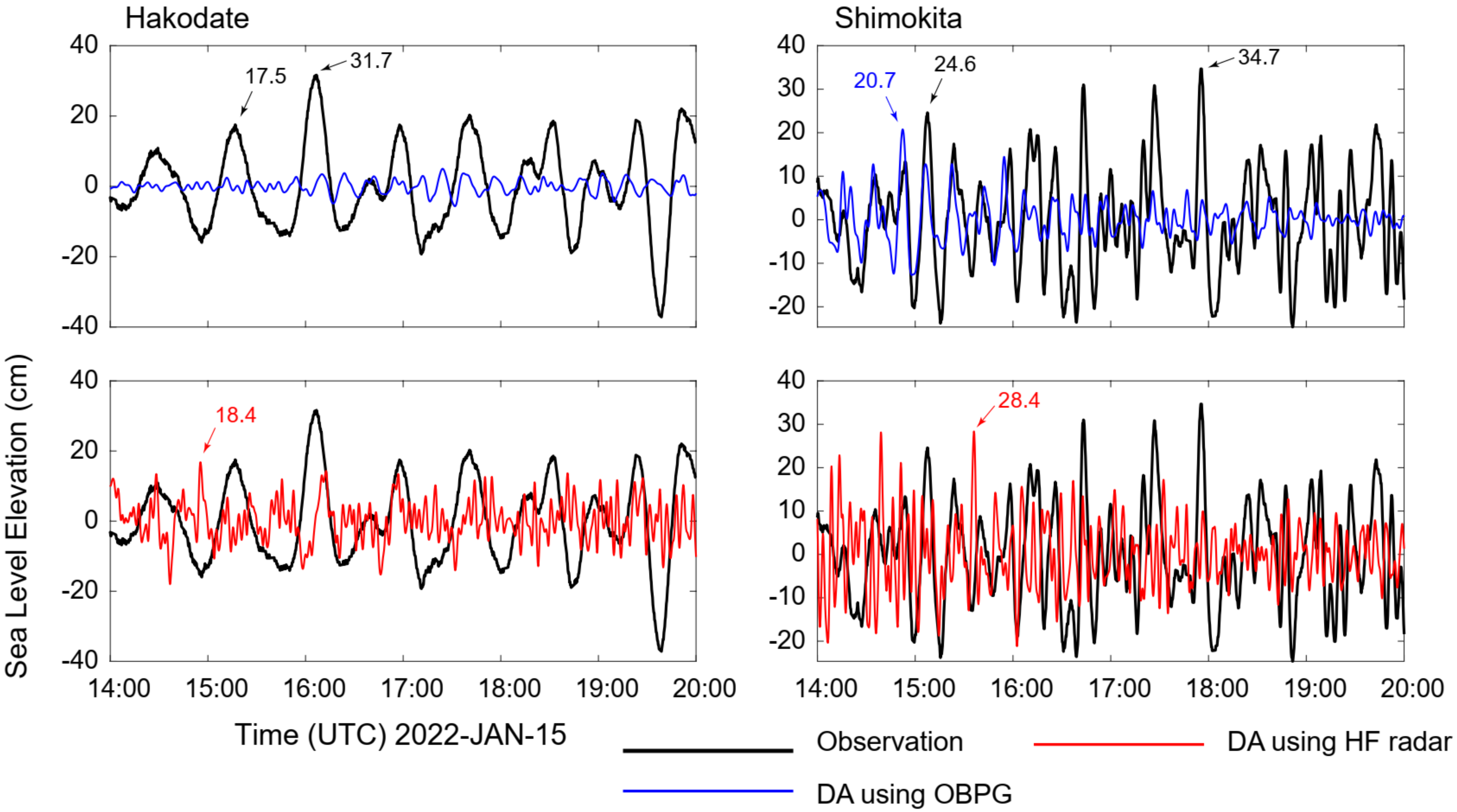


Computational parameters

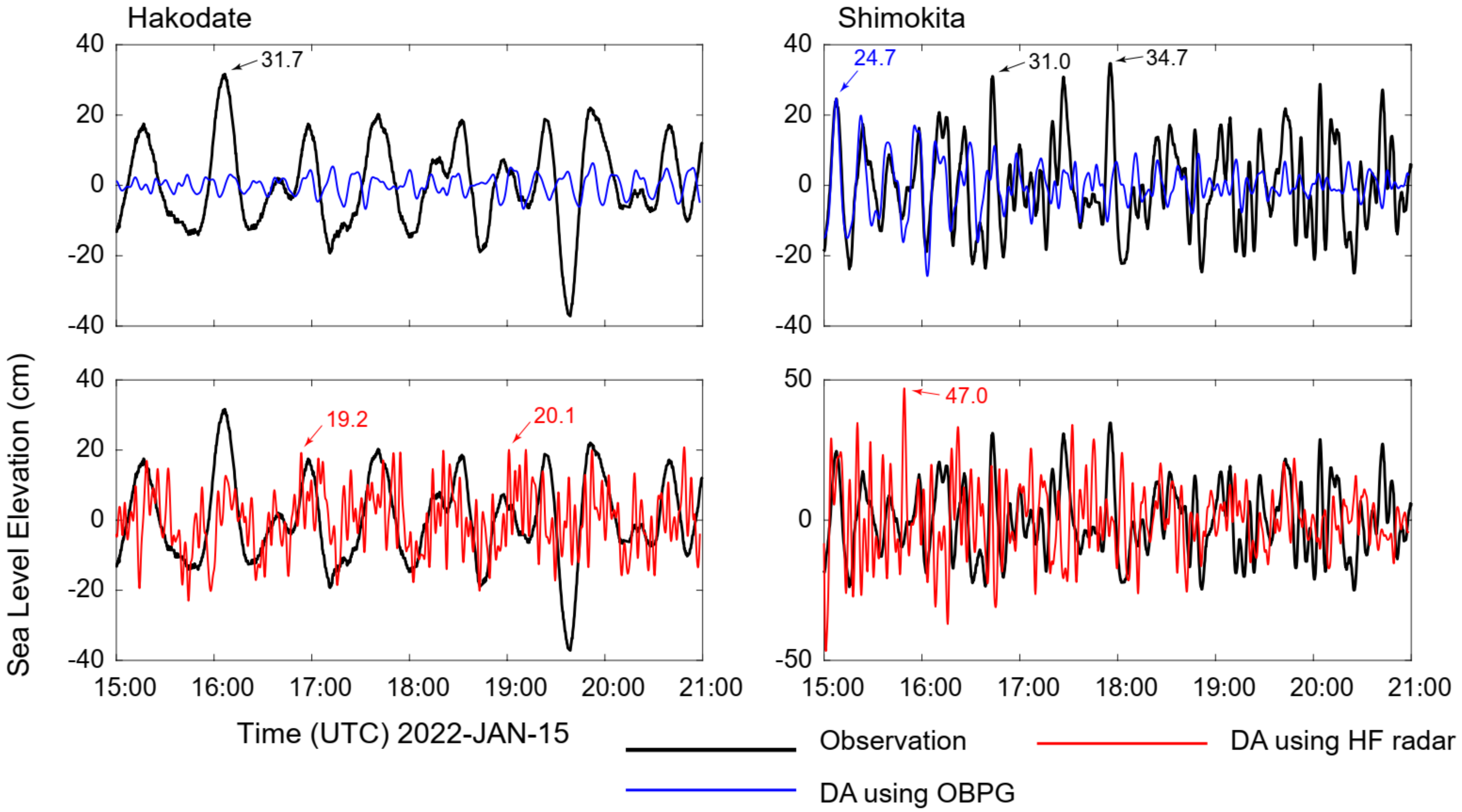
- Time step: 1 s
- Grid size: 0.25 arc min (~ 450 m)
- Grid range: 140.0–144.5° E and 40.5–42.5° N
- Assimilation step of S-net OBPG: 1 s
- Assimilation step of HF radar: 30 min

Results

14:00 UTC



15:00 UTC


Hakodate
Shimokita
31.7
24.7
31.0
34.7
19.2
20.1
47.0
Sea Level Elevation (cm)
Time (UTC) 2022-JAN-15
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Observation
DA using HF radar
DA using OBPG

Accuracy Analysis

$$K = \frac{1}{N}\sum_{i=1}^{N}\min\{\frac{A_i^f(t:t+T)}{A_i^o(t:t+T)}, \frac{A_i^o(t:t+T)}{A_i^f(t:t+T)}\} \times 100\%$$

A^f: Forecasted maximum amplitude
A^o: Observed maximum amplitude
N: Number of coastal tide gauges ($N = 2$)
T: A defined time interval after the forecast time

Forecast Time 14:00		
Data	HF radar	OBPG
$T = 2$ **hr**	91%	50%
$T = 6$ **hr**	67%	38%
Forecast Time 15:00		
Data	HF radar	OBPG
$T = 2$ **hr**	63%	47%
$T = 6$ **hr**	70%	46%

Summary

- Data assimilation successfully forecasted the 2022 Tonga volcanic tsunami.
- This was the first time an HF ocean radar system was used for data assimilation.
- The accuracy indexes of HF radar were generally higher than those of OBPG.
- Specifically, at 14:00, the accuracy index of HF data was 91% for the following 2 hours and 67% for the following 6 hours. At 15:00, it was 63% for the following 2 hours and 70% for the following 6 hours.

JGR Solid Earth

Research Article

Data Assimilation Using High-Frequency Radar for Tsunami Early Warning: A Case Study of the 2022 Tonga Volcanic Tsunami

Yuchen Wang, Kentaro Imai, Iyan E. Mulia, Keisuke Ariyoshi, Narumi Takahashi, Kenichi Sasaki, Hitoshi Kaneko, Hiroto Abe, Yoshiaki Sato

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