Drift simulation of Japan Tsunami Marine Debris (JTMD) as an application of data assimilation

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Plan of the presentation

1. Introduction
2. Data Assimilation System: MOVE and K7
3. Modelling of Drifting JTMD and
   Examples of the Model Solution
4. Summary

I. INTRODUCTION

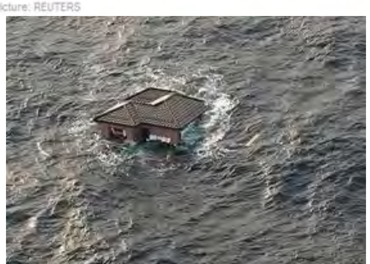
Tragic event of the March 11, 2011 tsunami in Japan has generated estimated 1.5 million tons of debris floating off the eastern Honshu (Japan Ministry of Environment, 2014).

This is an amount comparable to the annual budget of plastic marine debris of the entire North Pacific (Jambeck et al., 2015).

This Japan Tsunami Marine Debris (JTMD) was seen on photographs in the coastal areas (see the figures).

The largest "island" of debris stretches 60 nautical miles (69 miles) in length and covers an expanse of more than 2.2 million square feet, according to the US Navy's 7th Fleet, which is closely monitoring the floating rubbish

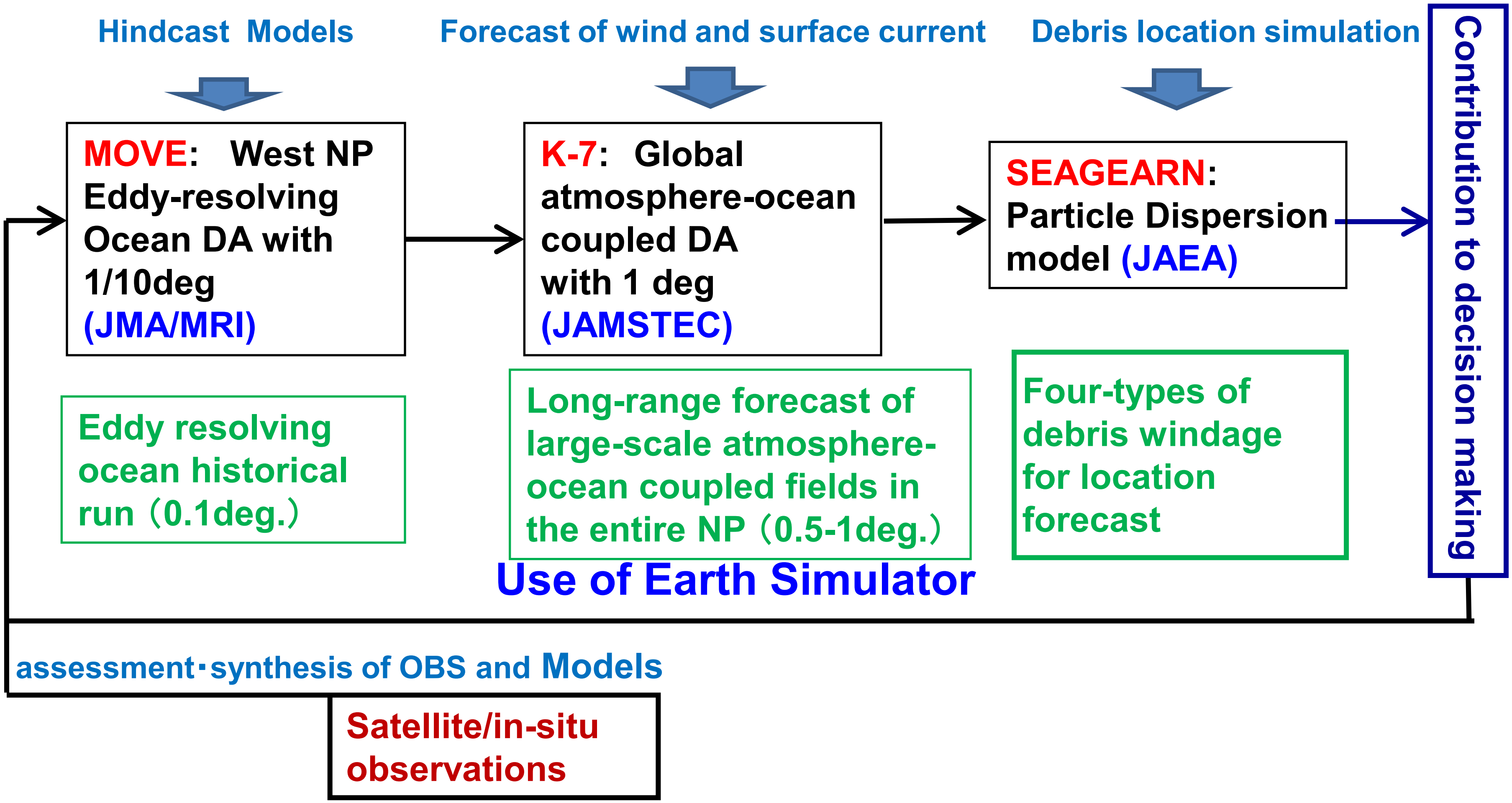
Picture: REUTERS



Several weeks later, after JTMD drifted off shore and dispersed, its monitoring became very difficult.

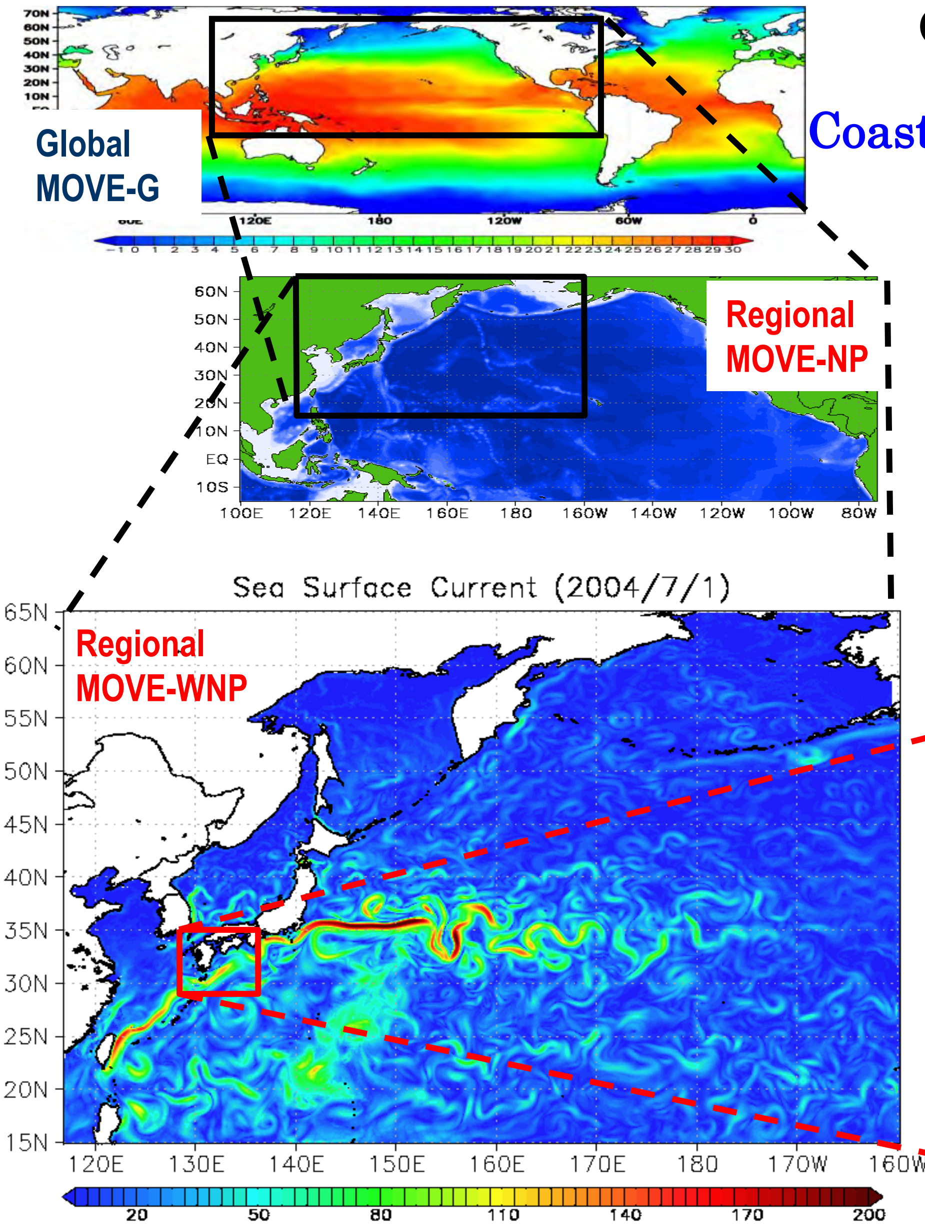
Sparse reports from the sea were not able to provide a coherent description of the pattern and drift motion of JTMD and this task was adopted by numerical models.

Tsunami Debris Nowcast and Forecast procedure

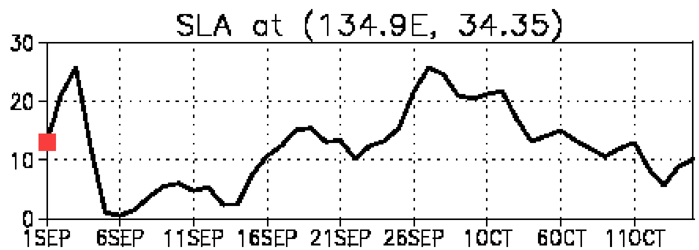


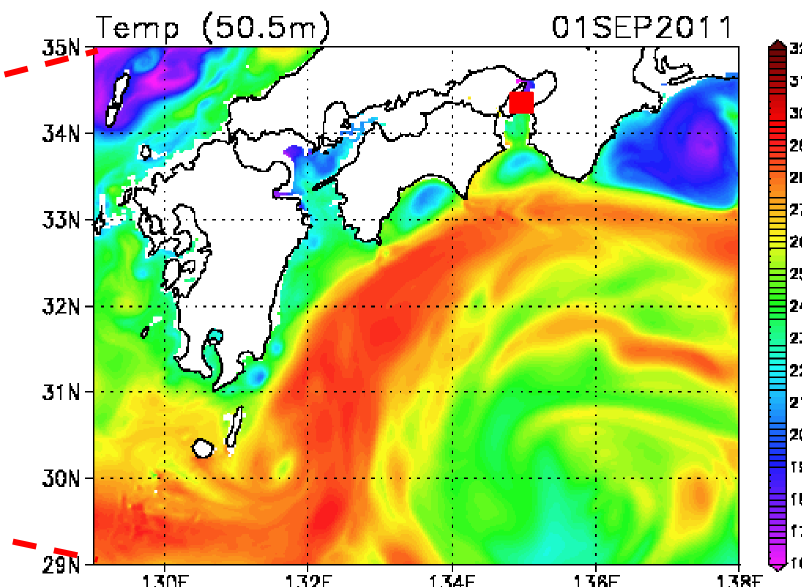
JMA/MRI systems

GlobalWarming, Seasonal-ElNino (Global, 1°)
Ocean Weather (N. Pac, 1/2°~1/10°)
Ocean Weather (W.N. Pac, 0.1°~)
Coastal mdl (Seto, Jpn, Tohoku-SICAT02:2km)



Coastal Application: Abnormal High Tide





JMA/MRI Ocean Data Assimilation System

MRI MOVE/MRI.COM (Multivariate Ocean Variational Estimation) system

OGCM: MRI.COM (MRI Community Ocean Model) (similar to MOM)

Method: Multivariate 3D-VAR, 4D-VAR

with vertical coupled T-S Empirical Orthogonal Function (EOF) modal decomposition with area partition (control variable: amp. of EOF mode)
horizontal Gaussian function (inhomogeneous decorrelation scales)
nonlinear constraints (dynamic QC, density inversion) bias correction

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T \mathbf{B}_v^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}\left[\mathbf{H}\mathbf{x}-\mathbf{y}^{\mathrm{TS}}\right]^T \mathbf{R}^{-1}\left[\mathbf{H}\mathbf{x}-\mathbf{y}^{\mathrm{TS}}\right] + \frac{1}{2\sigma_h^2}\left[\mathcal{H}(\mathbf{x})-\mathbf{y}^{\mathrm{SSH}}\right]^T\left[\mathcal{H}(\mathbf{x})-\mathbf{y}^{\mathrm{SSH}}\right]$$

Source (observation) Data:

Satellite Altimetry (TOPEX/POSEIDON, ERS-1 &-2, ENIVISAT, Jason),

SST (COBESST or GHRSST),

in situ T & S (GTSPP, ARGO, Tao/Triton, drifter),

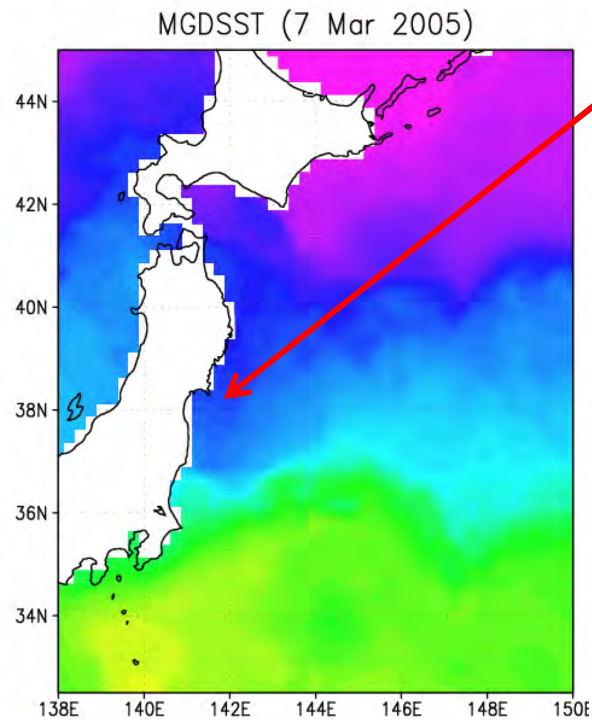
with QC in each data centers

Atmospheric forcing (Output of Numerical Weather Prediction

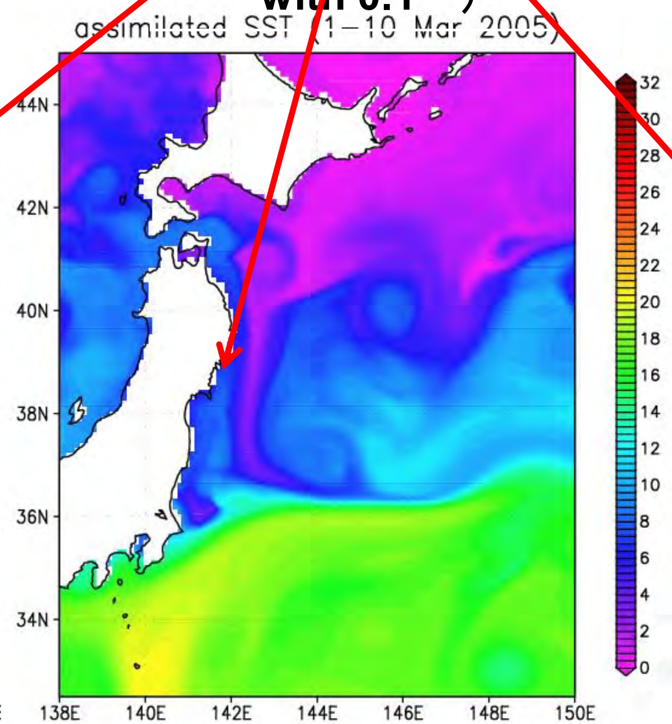
or Atmospheric Reanayses: JRA55)

Snapshot of SST（March 7, 2005） offshore of Target areas (Tohoku)

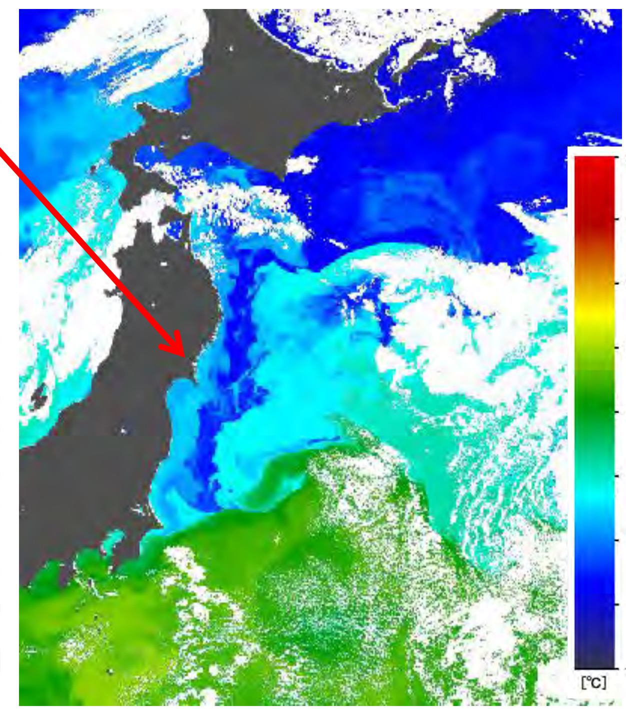
MGDSST
（statistical 1/4°）



MOVE / MRI.COM
（data assimilation with 0.1°）



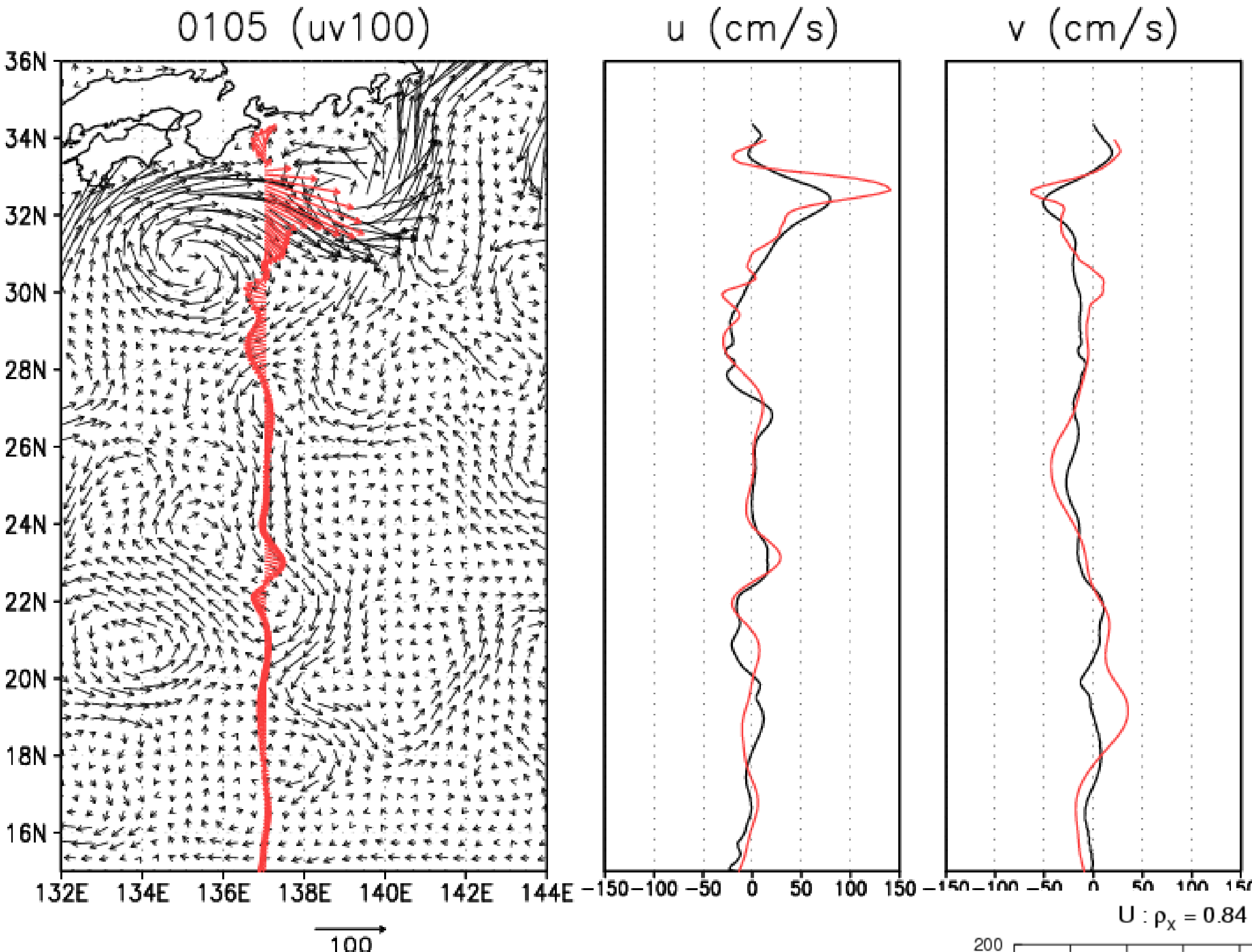
Terra/Aqua MODIS
（satellite OBS）



Validation

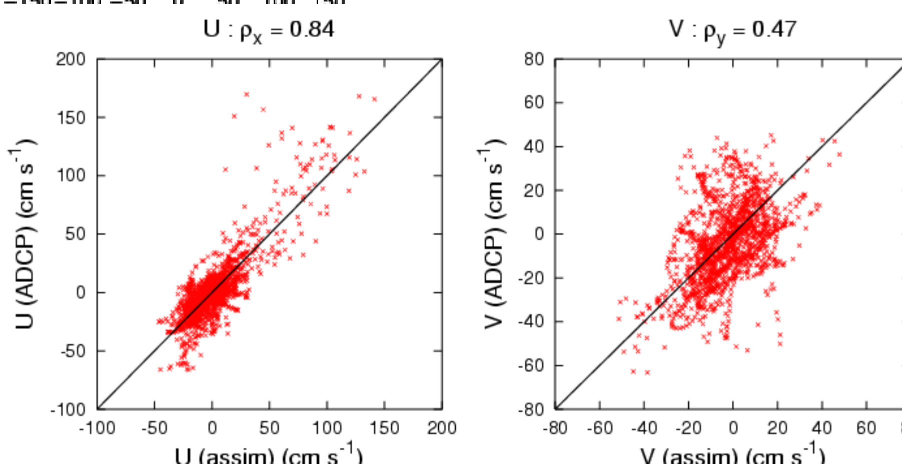
Horizontal Velocity

2005/1



Black: Assim (MOVE)

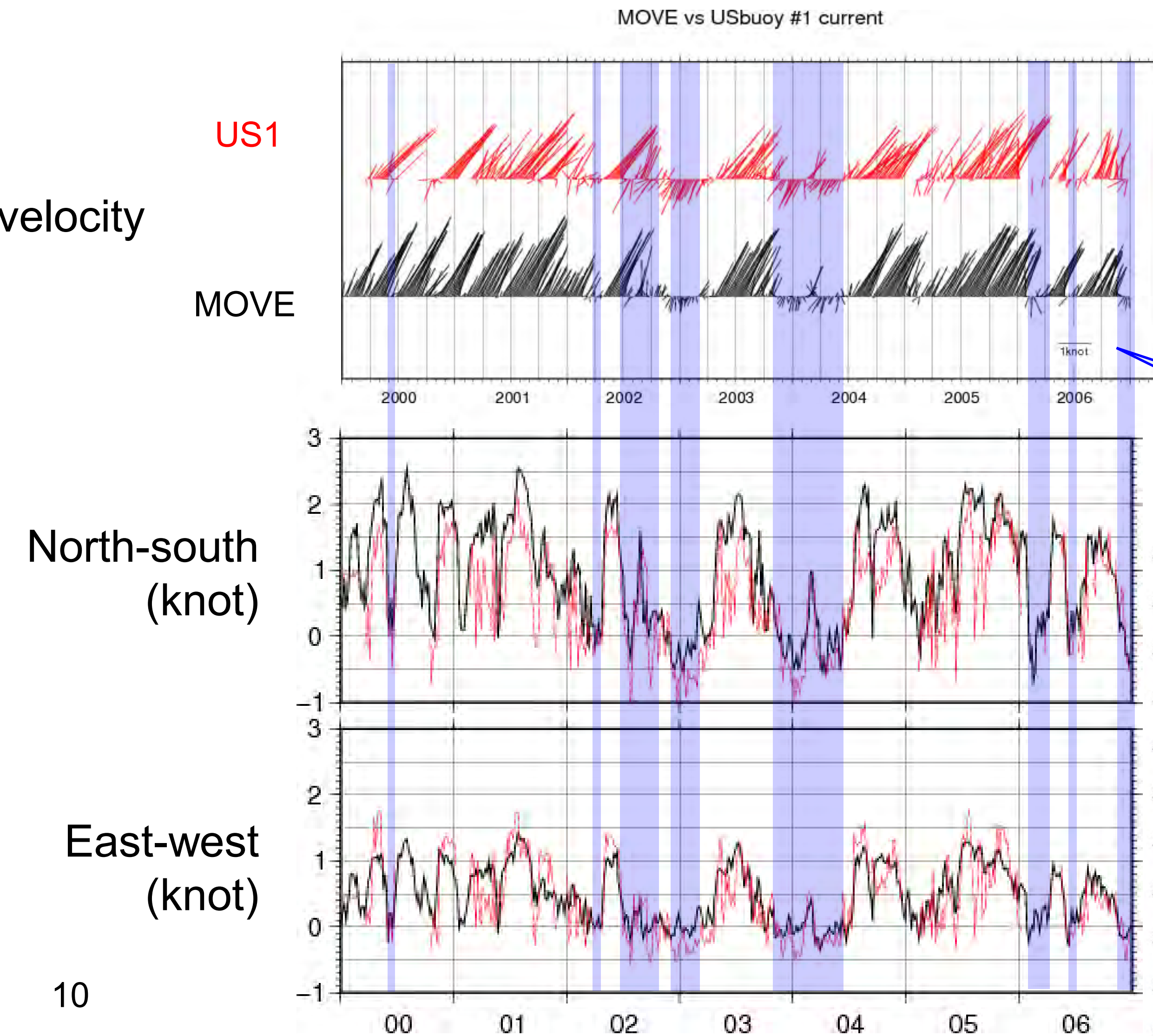
Red: Independent Obs. (ADCP)

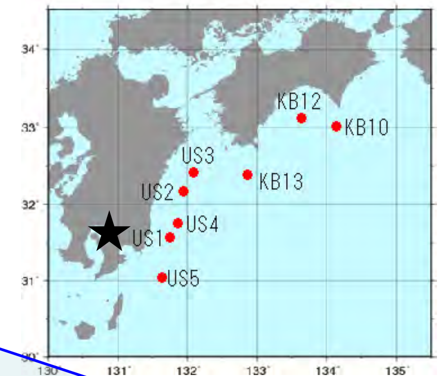


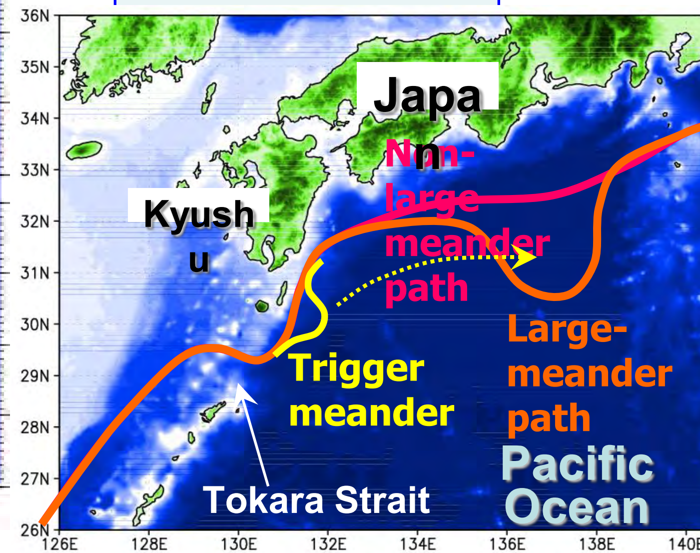
Correlation Coefficient

V variability is smaller->difficult

Comparison with Umisachi buoy #1(2000-2006)







Dynamic framework of Particle tracking

$$x_{t+\Delta t} = x_t \;+\; u_m \Delta t \;+\; \delta x$$

(time evolution) (advection) (random diffusion)

u_m **JAEA (SEAGELN)** → Particle Movement by = Ocean current + Wind – force velocity

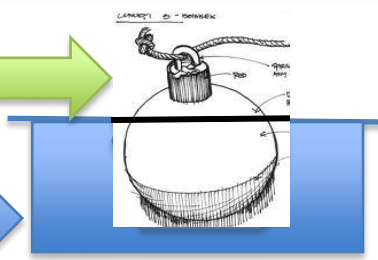
K7 Coupled Data Assimilation system

MRI_(MOVE high-resolution 3DVAR) and JMA wind (JCDAS)

Wind-driven effect for particle movement

wind

Ocean current



Square measure of cross-section above sea surface: A

Square measure of cross-section beneath sea surface: B

Wind force velocity = $k\sqrt{\frac{A}{B}} \times W_{10}$

windage ↗ **sea surface wind velocity**

Forecast runs for 4 windage cases

k=0.025

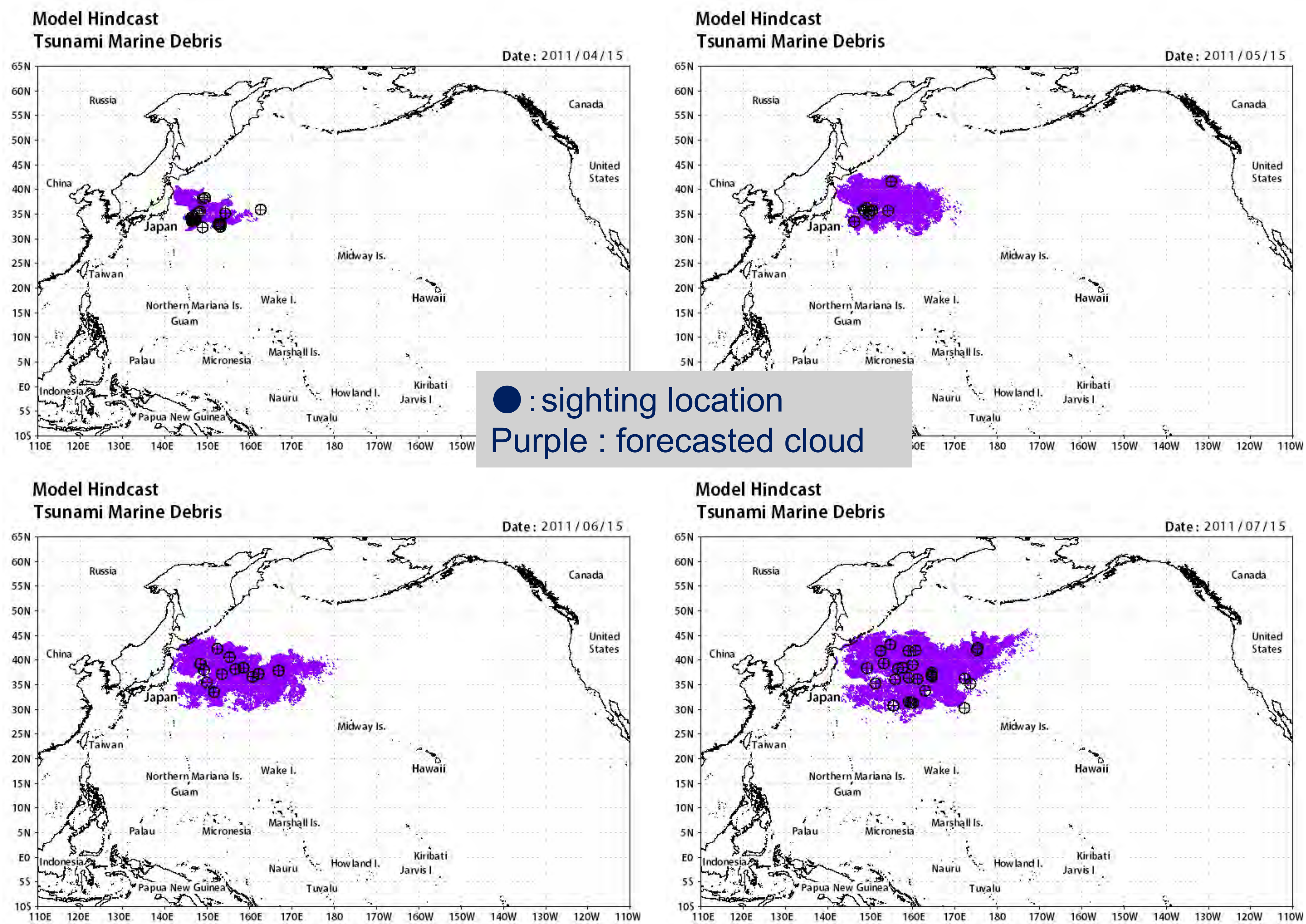
A:B=windage%

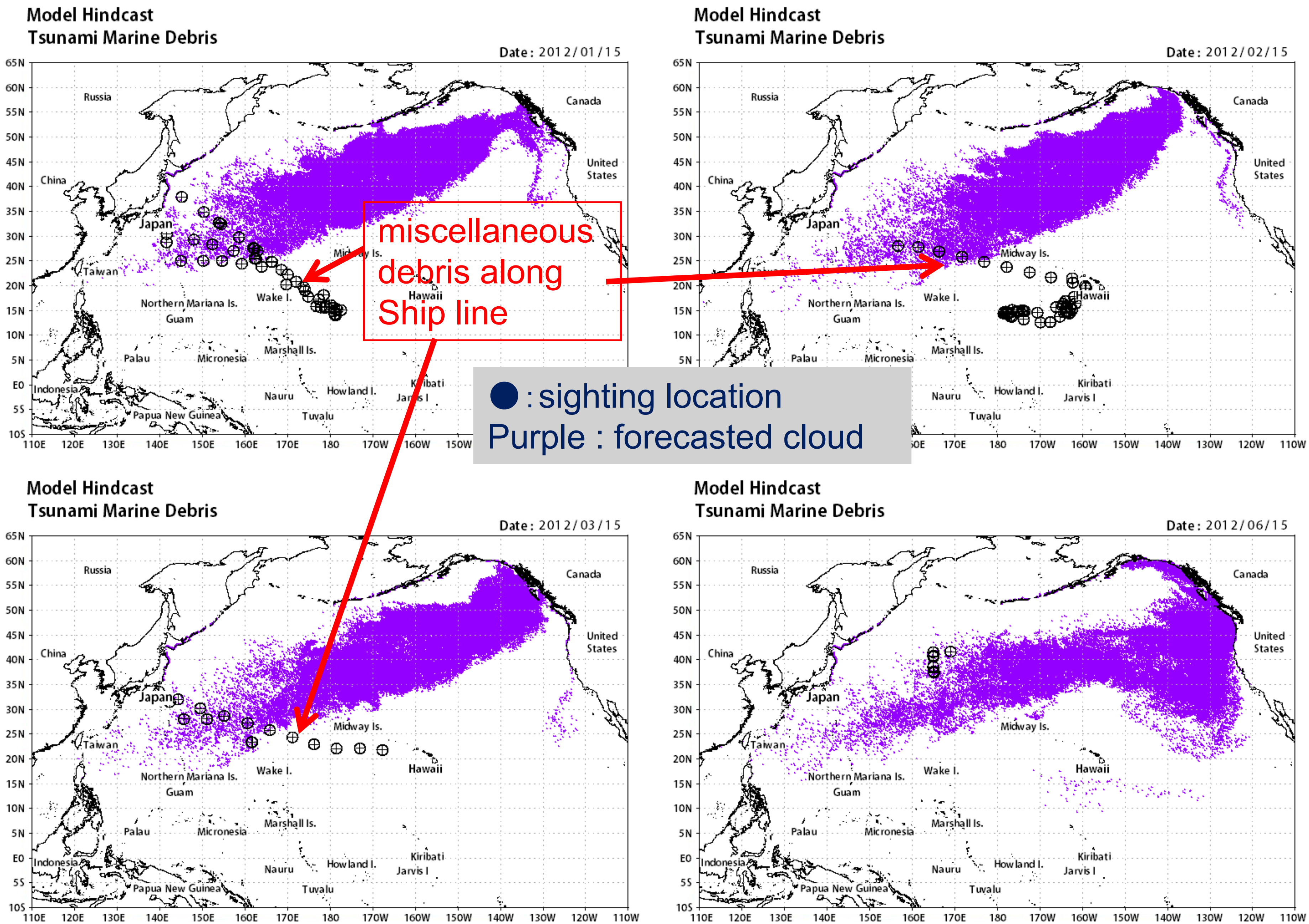
0:1=0% Low windage

1:1=2.5%

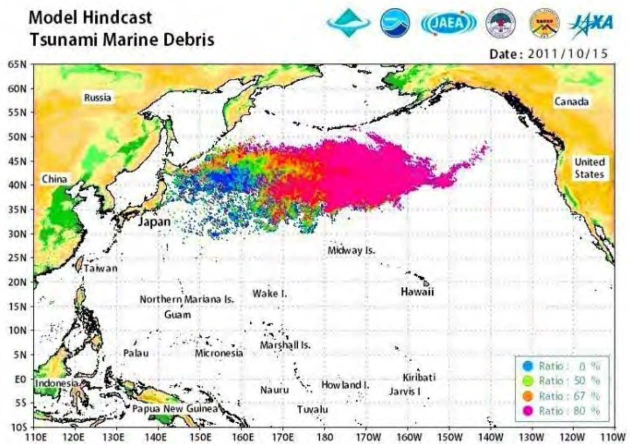
2:1=3.5%

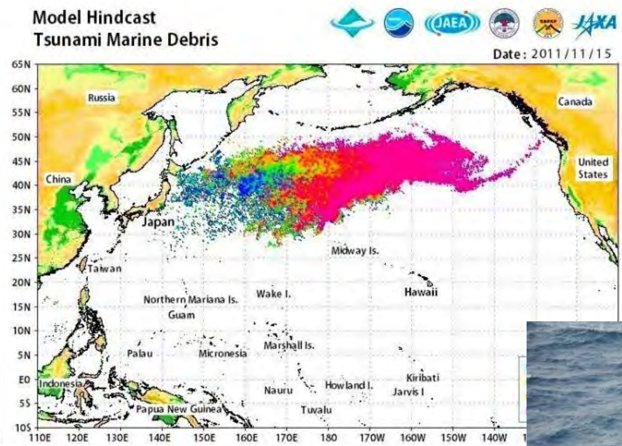
4:1=5.0% High windage

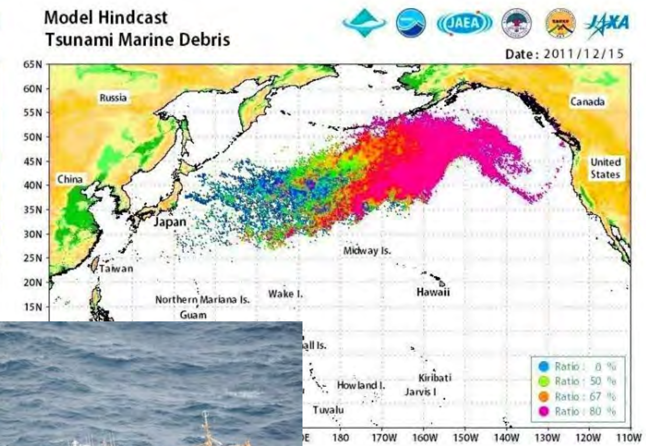

Model Hindcast
Tsunami Marine Debris
Date : 2011/04/15
Model Hindcast
Tsunami Marine Debris
Date : 2011/05/15
Model Hindcast
Tsunami Marine Debris
Date : 2011/06/15
Model Hindcast
Tsunami Marine Debris
Date : 2011/07/15
● : sighting location
Purple : forecasted cloud
Russia
Canada
United States
China
Japan
Taiwan
Midway Is.
Hawaii
Wake I.
Northern Mariana Is.
Guam
Marshall Is.
Palau
Micronesia
Kiribati
Jarvis I
Howland I.
Nauru
Indonesia
Papua New Guinea
Tuvalu
65N
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
E0
5S
10S
110E
120E
130E
140E
150E
160E
170E
180
170W
160W
150W
140W
130W
120W
110W


Model Hindcast
Tsunami Marine Debris
Date : 2012/01/15
Model Hindcast
Tsunami Marine Debris
Date : 2012/02/15
miscellaneous
debris along
Ship line
● : sighting location
Purple : forecasted cloud
Model Hindcast
Tsunami Marine Debris
Date : 2012/03/15
Model Hindcast
Tsunami Marine Debris
Date : 2012/06/15
Russia
Canada
United States
China
Japan
Taiwan
Midway Is.
Hawaii
Wake I.
Northern Mariana Is.
Guam
Marshall Is.
Palau
Micronesia
Indonesia
Nauru
Howland I.
Kiribati
Jarvis I
Papua New Guinea
Tuvalu

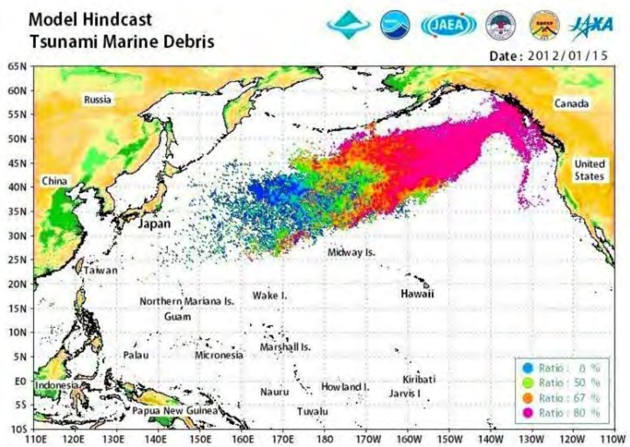
forecast（Oct. 2011 ～ March 2012）: time-series of all forecast cases: overlapped

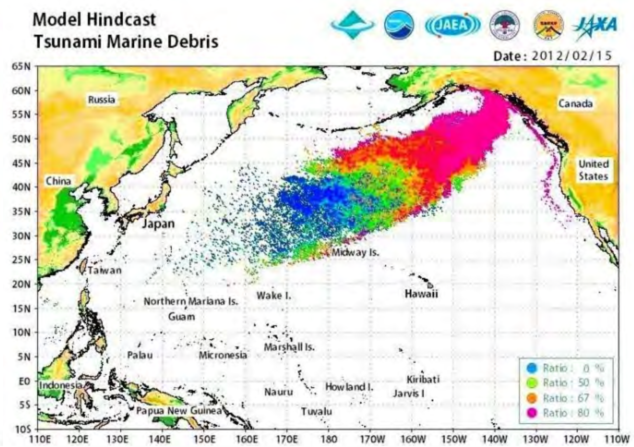


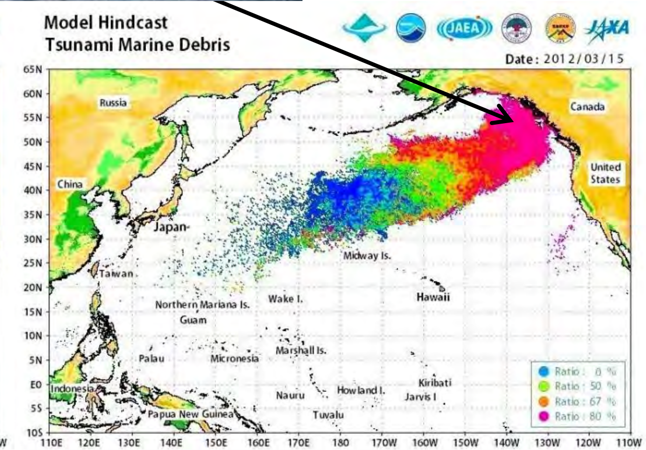




robust agreement

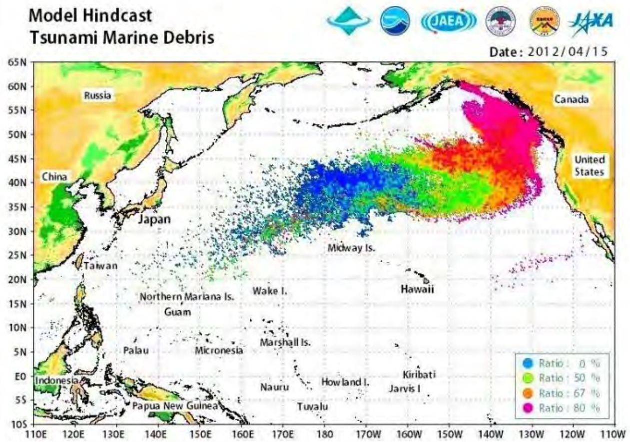


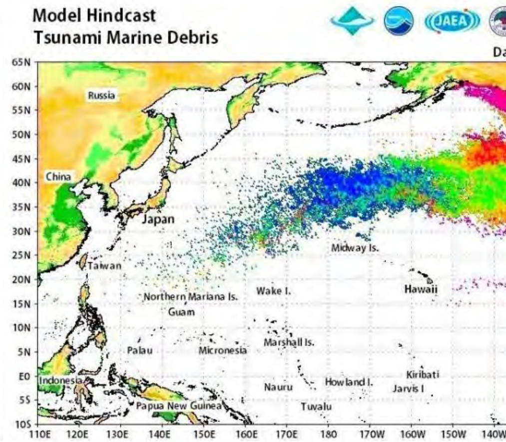


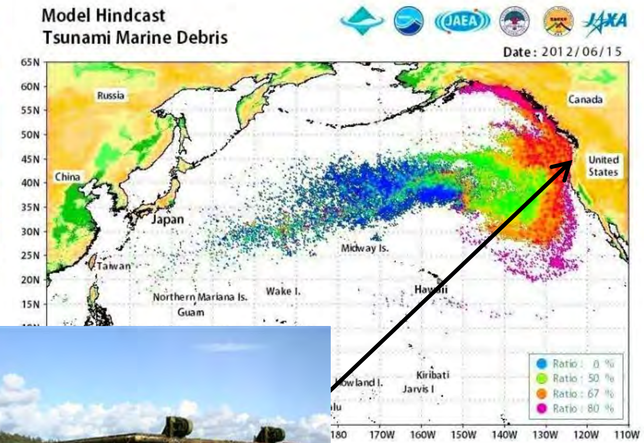


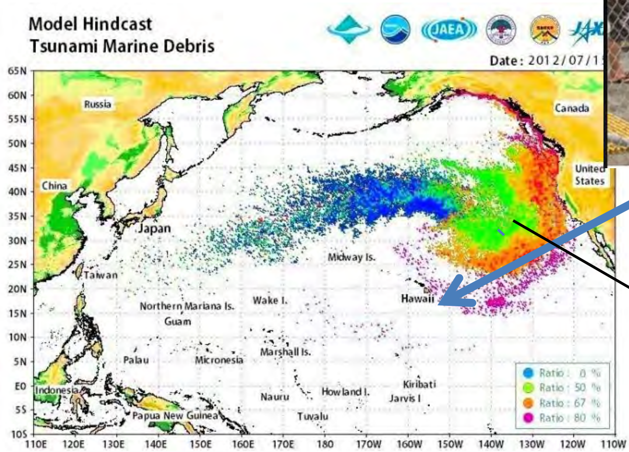
Ratio		beneath : above （the sea surface）		windage
Ratio : 0%	->	1 : 0	->	0.0 %
Ratio : 50%	->	1 : 1	->	2.5
Ratio : 67%	->	1 : 2	->	3.5
Ratio : 80%	->	1 : 4	->	5.0

forecast (Apr. 2012 ～ July 2012): time-series of all forecast cases: overlapped









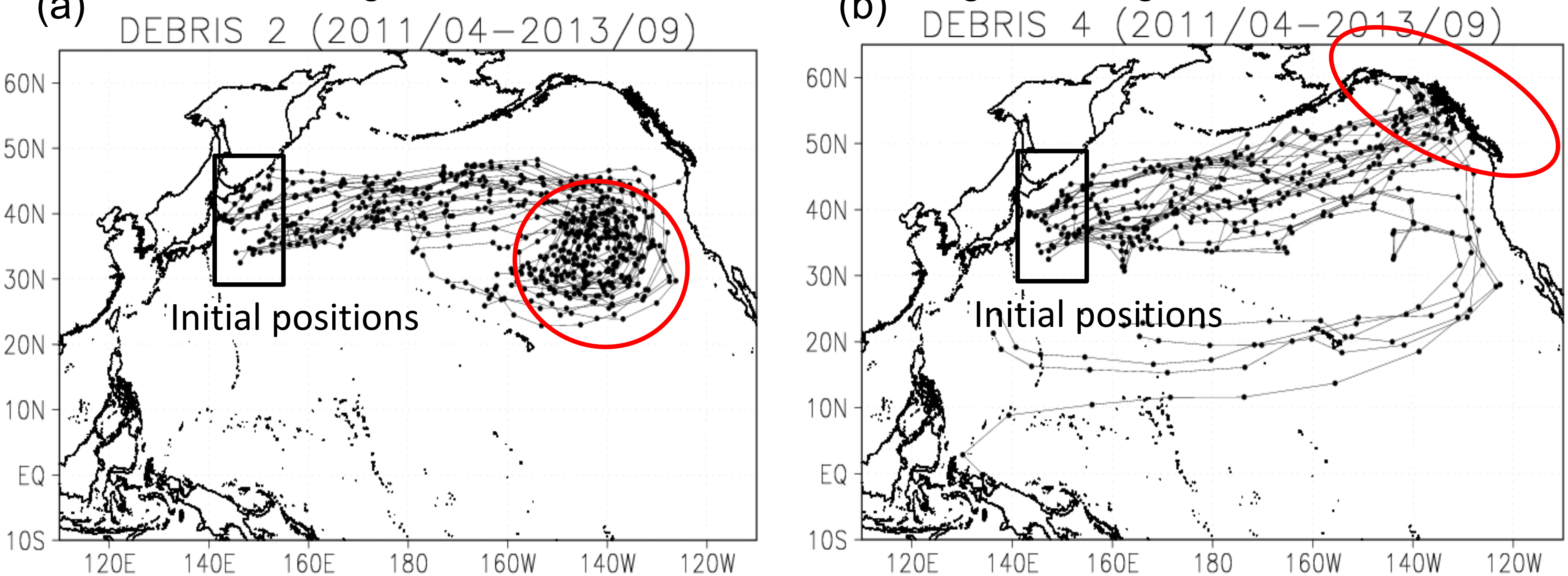
Convergence area
"Garbage Patch"

Ratio		beneath : above (the sea surface)		windage
Ratio : 0%	->	1 : 0	->	0.0 %
Ratio : 50%	->	1 : 1	->	2.5
Ratio : 67%	->	1 : 2	->	3.5
Ratio : 80%	->	1 : 4	->	5.0

Typical debris trajectories with windages (a) 2.5% and (b) 5.0% from April 2011 to September, 2013.

(a) Lower windage

(b) Higer windage



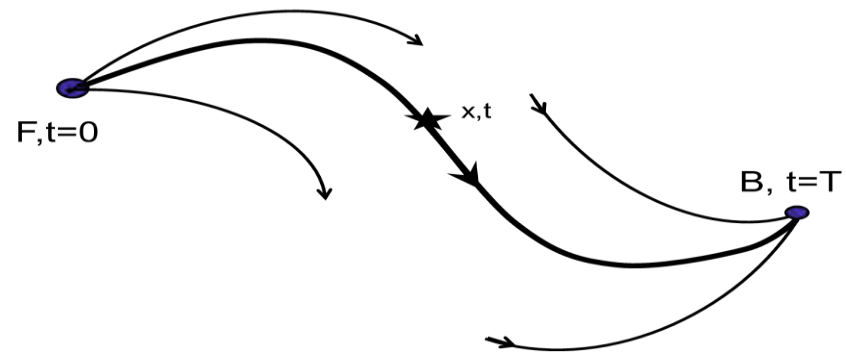
Deterministic Trajectory

Probabilistic Trajectory

The trajectories as well as distributions of debris have uncertainties, which can be expressed in a probabilistic way. For selected start and destination (or target) points, the uncertainties can be estimated from a combination of trajectories from the starting point forward in time and trajectories from the destination point backward in time in a manner of Fujii et al. (2013).

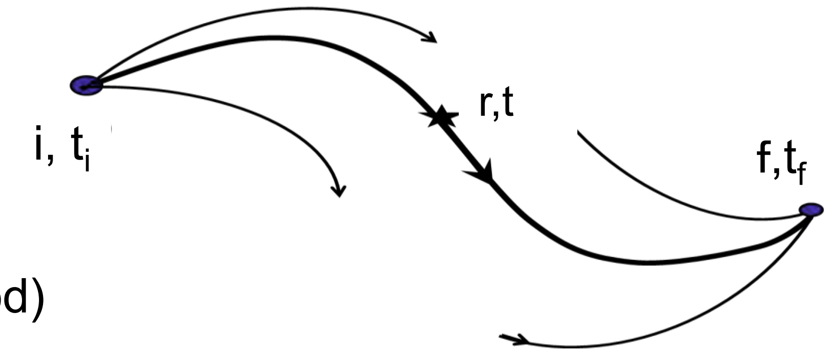
Chapman-Kolmogorov eqn.

$$p(B|F) = \int p(B|x, F)p(x|F)dx$$



Theoretical justification of the method was given in the forward (prediction) and backward (adjoint) models systems which are common in the data assimilation community. Holzer and Primeau (2008) and Fujii et al. (2013) used them to calculate the "path density" in different applications (e.g., water mass movements). In these studies the basic method is according to a balance that the time derivative of forward variable multiplied by its adjoint variable equals with the divergence of terms derived from advection and diffusion. Then the combined (multiplied) variable is conserved, and its distribution gives the probability density. Maximenko et al. (2015b) based their estimates on the interpretation of tracer concentration as a probability density of a single particle motions.

Probabilistic Trajectory: Theoretical Beckground



Method 1 (forward pdf by ensamble method)

Method 2 (Joint pdf) (Holzer & Primeau, 2008; Fujii et al., 2013)
(forward)x(backward full adjoint)

$$\rho\left(\mathbf{r}, \tau, \Omega_i, \Omega_f; t\right) = \frac{\rho(\mathbf{r}, t)}{M} \int_{t-\tau}^{t} dt_i \, \widetilde{\mathcal{G}}\left(\mathbf{r}, t | \Omega_f, t_i + \tau\right) \mathcal{G}(\mathbf{r}, t | \Omega_i, t_i)$$

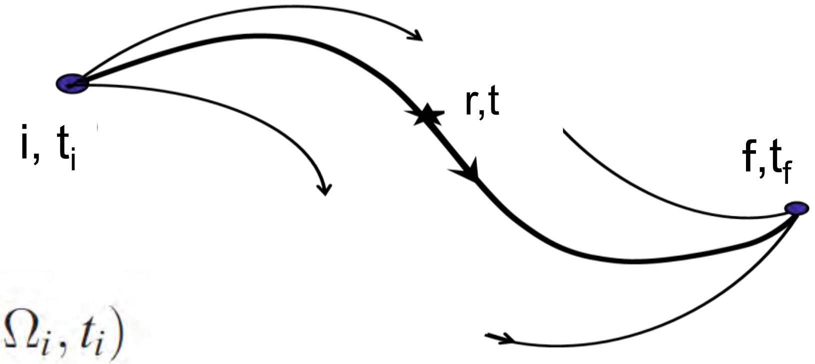
Method 2' (forward version: simplified Jpdf) (Holzer, 2009a,b)

$$\rho\left(\mathbf{r}, \Omega_f, t_f | \Omega_i, t_i\right) = \frac{1}{\mathcal{N} M} \mathcal{J}_f \int_{t_i}^{t_f} dt \, G(\mathbf{r}_f, t_f | \mathbf{r}, t) \rho(\mathbf{r}, t) \mathcal{G}(\mathbf{r}, t | \Omega_i, t_i)$$

$$\mathbf{J}(\mathbf{r}, t | \Omega_i, t_i) \equiv [\rho \mathbf{u} - \rho \mathbf{K} \nabla] \mathcal{G}(\mathbf{r}, t | \Omega_i, t_i)$$

Probabilistic Trajectory: Theoretical Beckground

Method 2'' (simplified joint pdf) (Maximenko and Hafner, 2015)
time-reverse, u->-u, K->K^T



$$\frac{\partial}{\partial t}[\rho \mathcal{G}(\mathbf{r}, t|\Omega_i, t_i)] + \nabla \cdot \mathbf{J}(\mathbf{r}, t|\Omega_i, t_i) = 0$$

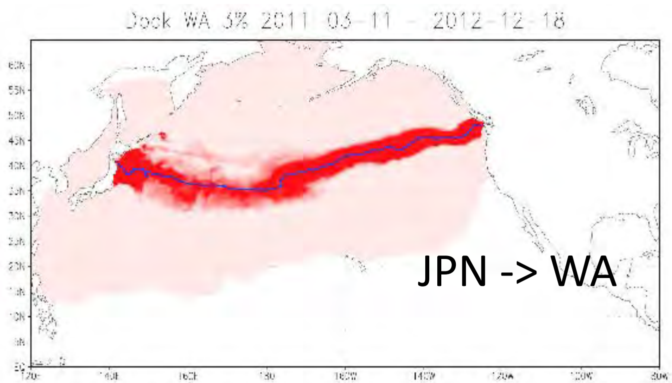
$$\mathbf{J}(\mathbf{r}, t|\Omega_i, t_i) \equiv [\rho \mathbf{u} - \rho \mathbf{K} \nabla]\mathcal{G}(\mathbf{r}, t|\Omega_i, t_i)$$

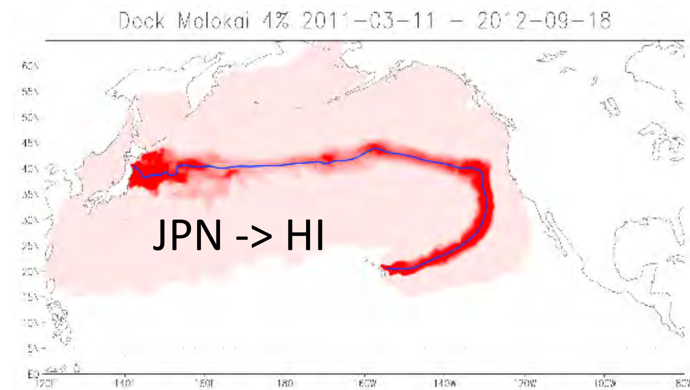
$$\mathcal{G}(\mathbf{r}, t|\Omega_i, t_i) = \begin{cases} \delta(t - t_i) & \text{if } \mathbf{r} \in \Omega_i \\ 0 & \text{otherwise,} \end{cases}$$

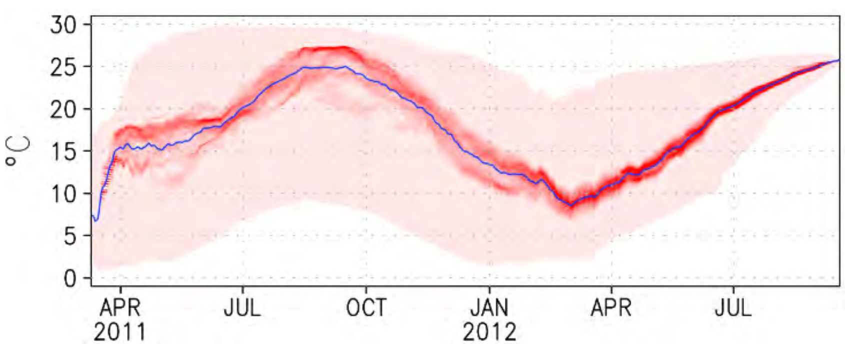
$$\rho\left(\mathbf{r}, \tau, \Omega_i, \Omega_f; t\right) = \frac{\rho(\mathbf{r}, t)}{M} \int_{t-\tau}^{t} dt_i \, \widetilde{\mathcal{G}}(\mathbf{r}, t|\Omega_f, t_i + \tau) \, \mathcal{G}(\mathbf{r}, t|\Omega_i, t_i)$$

$$\widetilde{\mathbf{J}}(\mathbf{r}, \ t|\Omega_f, \ t_f) \equiv [-\rho \mathbf{u} \ - \ \rho \mathbf{K}^T \nabla]\widetilde{\mathcal{G}}(\mathbf{r}, \ t|\Omega_f, \ t_f)$$

Probabilistic Trajectory







Probability density function of near-seasurface temperature, measured by the Argo network, along the probable path of Molokai dock

As shown in the figure (Maximenko et al., 2015b, and also Maximenko and Hafner, 2010), such approach gives not only the uncertainty of the trajectoriy of debris but also probabilistic information of the sea environment (e.g., temperature) along the trajectory and time. This information is critical for detecting probable path of invasive species colonizing debris items.

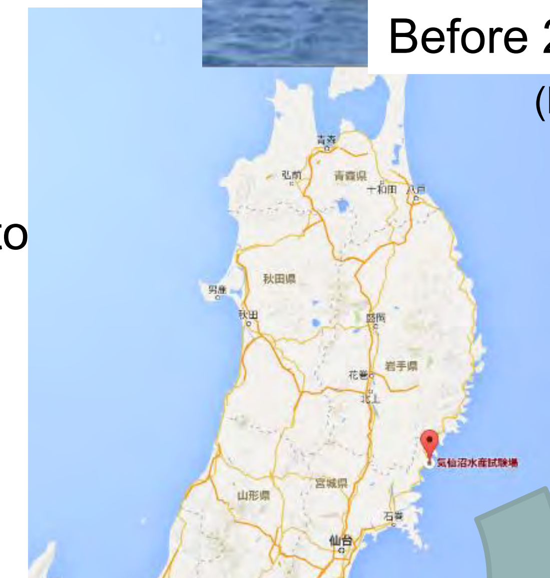
Next Presentation!

Example (Request)

Research Vessel (Kaisyou, 1.1ton) of Kesennuma Local Fisheries Laboratory (Miyagi prefectural Government) was found at about 6km offshore area from Miyako-city, Okinawa prefecture in May 12, 2016.

The prefectural government group would like to know the route.

Before 2011



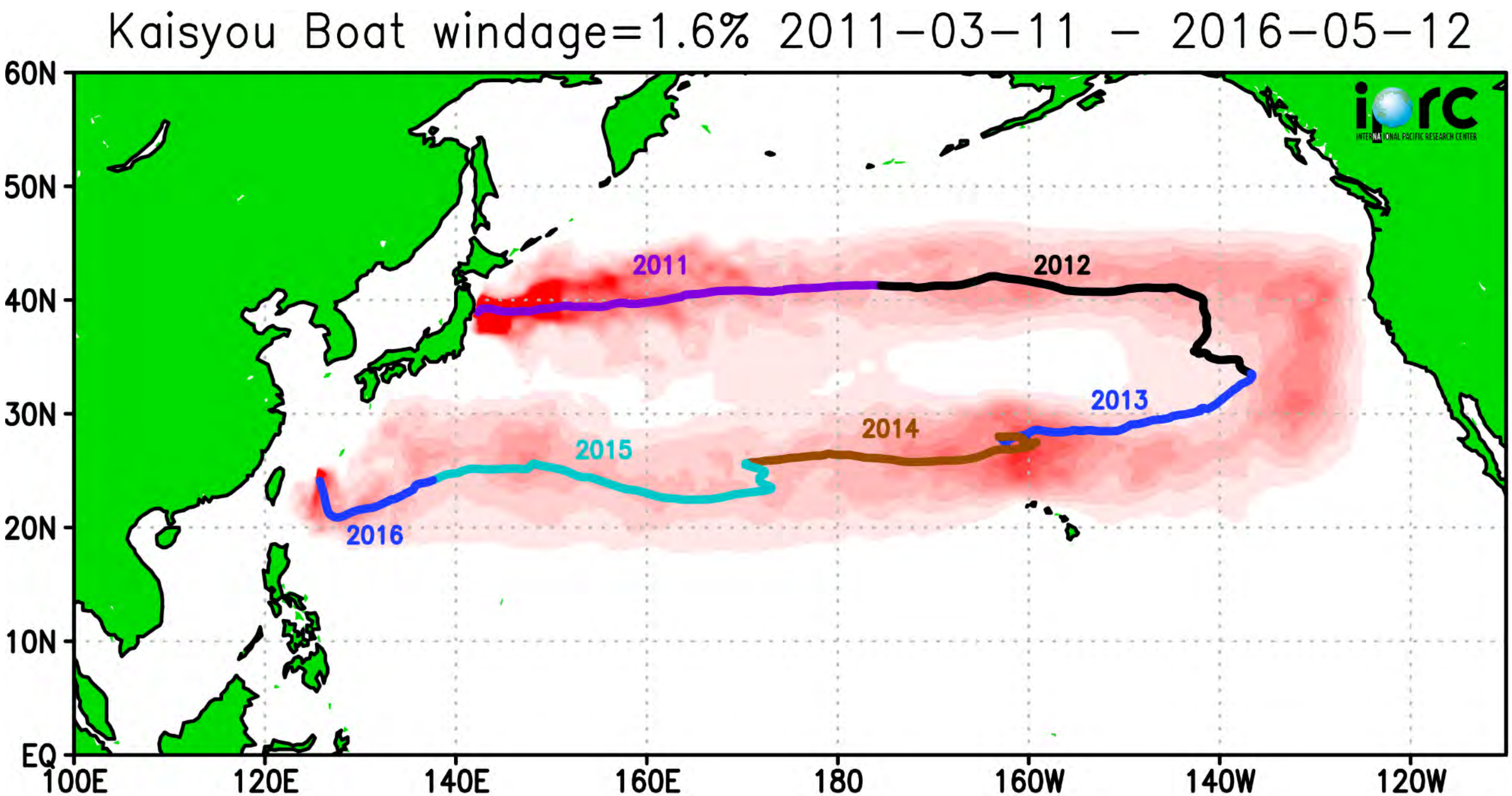
(Lat=38.8, Lon=141.6

(Lat=24.7, Lon=125.3)

After found in 2016/5/12

?

Example (Answer)
Probabilistic route



Summary (some figures are not shown)

1. High computing simulation and data assimilation are useful for the calculation of marine debris distribution. The model solution depends on the windage.
2. On-shore observation and model solution estimated seasonal change: e.g., summer 2012, winter-spring 2013, spring-summer 2014, due to seasonal wind and ocean current fields.
3. Model solution estimates that less than 10% of the tracer washes ashore annually and suggests that more than 50% of JTMD with boat type windage was still floating in the end of 2016. This means that boats from the 2011 tsunami, built to withstand rough ocean conditions, will likely continue coming to the US/Canada coastline in several future years. At the same time, JTMD wandering in the gyre gradually mixes with marine debris from other sources and loses its identity.
4. Future progress in marine debris modeling requires radically improved at-sea and on-shore observing systems as well as better model descriptions of coastal process and processes on the sea surface (such as Stokes drift by wind waves) and their effects on floating objects.

Thank you for your attention