Coastal dispersion model reliability in accidental situation (Fukushima, Japan), how to make the most of in-situ measurements?

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Fukushima accident in marine environment

Accident in the Fukushima Dai-ichi nuclear power plant represented the most important artificial radioactive release flux into the sea ever known.

Origins of the labelling:

- Atmospheric fallout onto the ocean,
- Direct release of contaminated water from the plant
- Transport of radioactive pollution by leaching through contaminated soil.

Principal radionuclides measured:

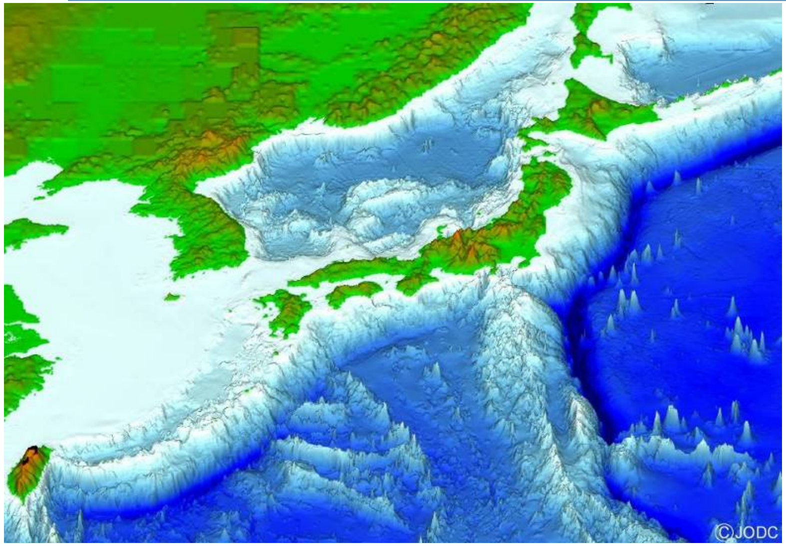
- ^{137}Cs $t_{1/2}$=30 years, ^{131}I $t_{1/2}$=8 days

In the vicinity of the plant (less than 500 m), concentrations in early April reached 68 000 Bq.L^{-1} for ^{134}Cs and ^{137}Cs, and exceeded 100 000 Bq.L^{-1} for ^{131}I

Measurement data sources: TEPCO, MEXT,

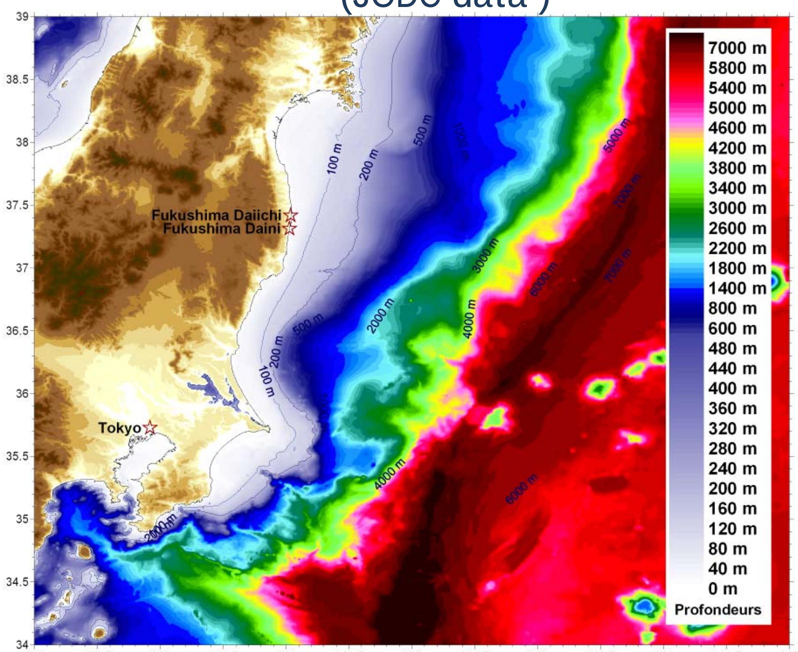
Detection limits: more than 5Bq.l^{-1} (monitoring measurements)

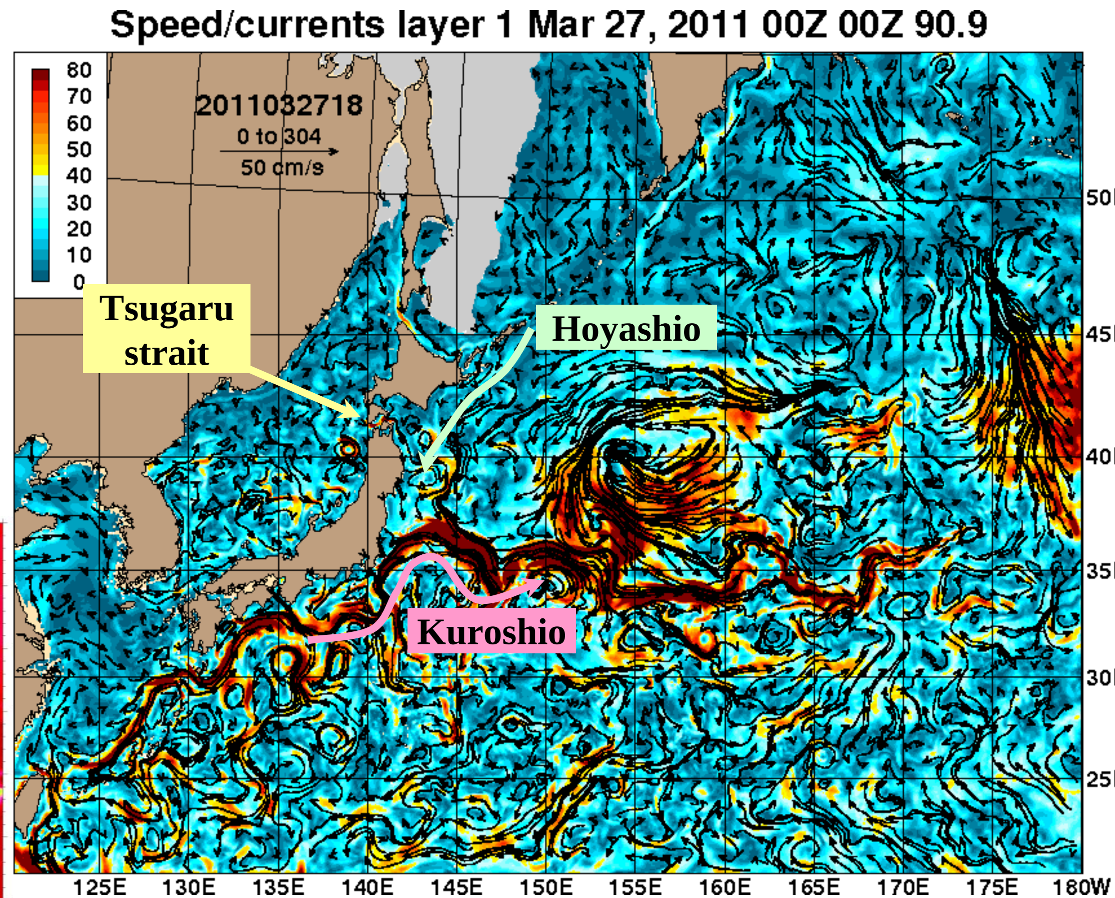
Hydrograhic domain



Bathymetry

(JODC data)





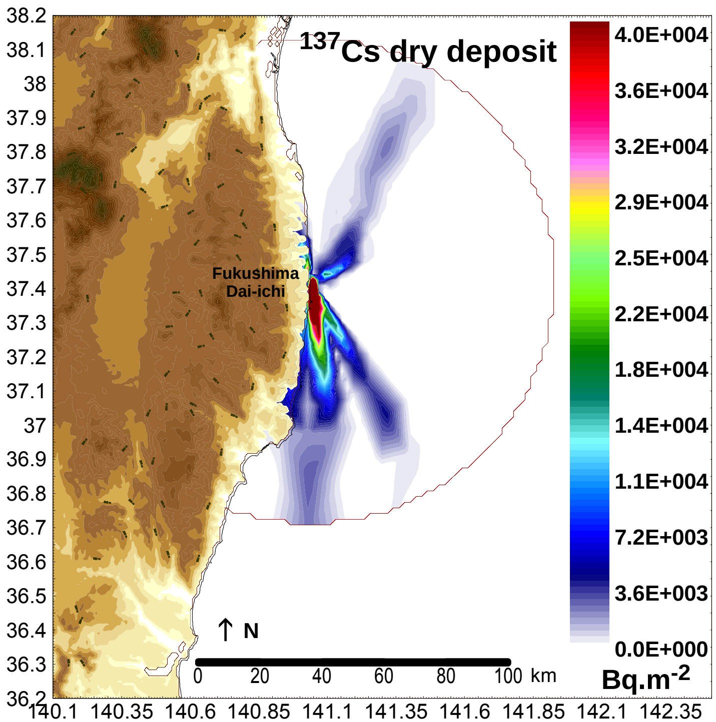
General currents

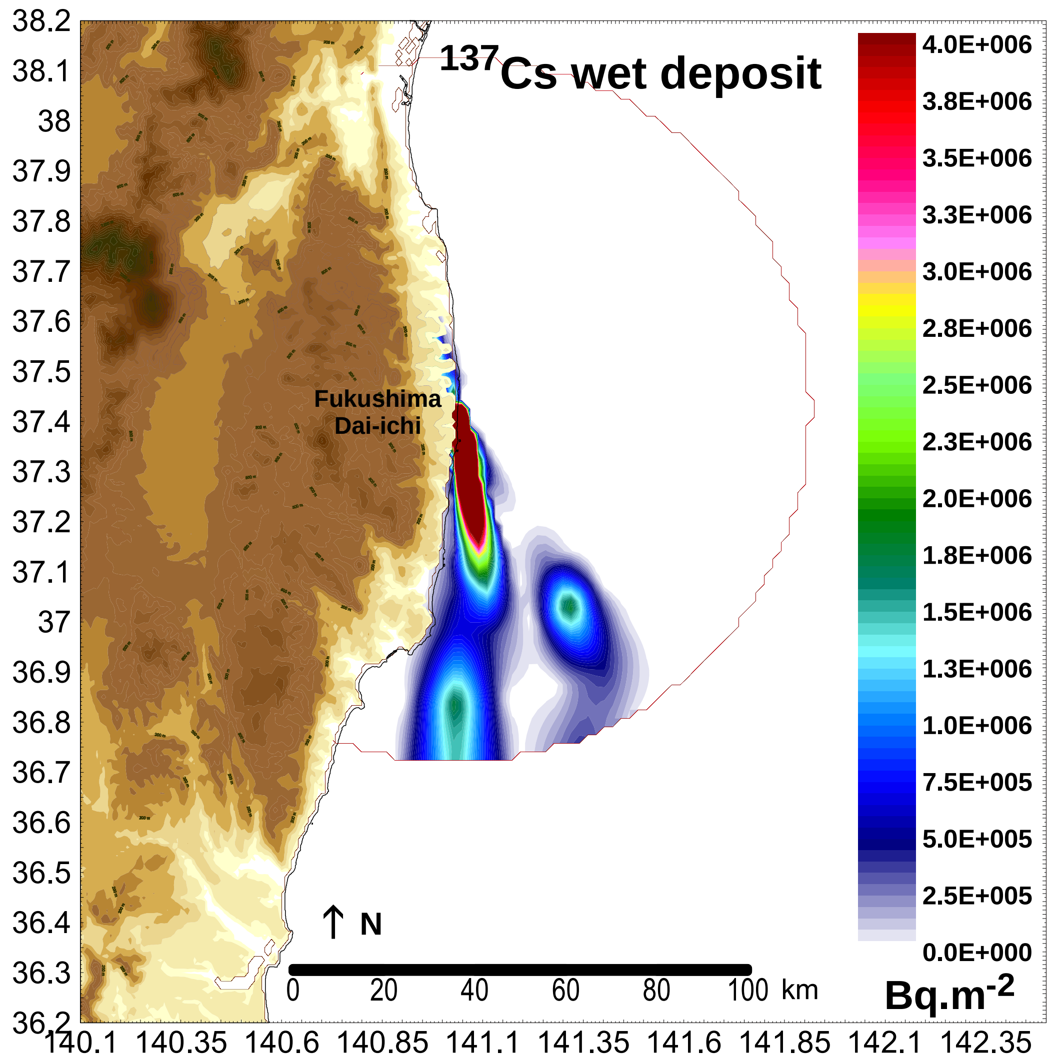
(Hycom simulation)

Atmospheric fallout

Estimation of total atmospheric release: 11.5 PBq of ^{137}Cs.

IRSN estimation of cumulated ^{137}Cs deposit at 80 km of distance from Fukushima Dai-ichi plant is 3 PBq Initial ratio ($^{131}I/^{137}Cs$) = 14)





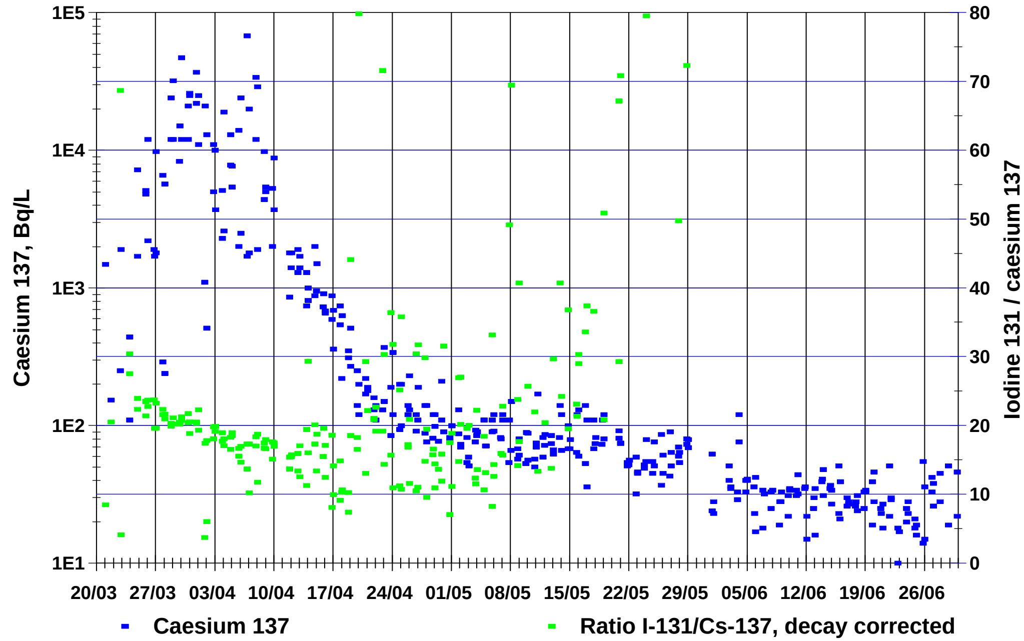
Calculated cumulate ^{137}Cs wet deposit, April 23, 2011

Seawater ^{137}Cs concentrations, $^{131}I/^{137}Cs$ ratio*

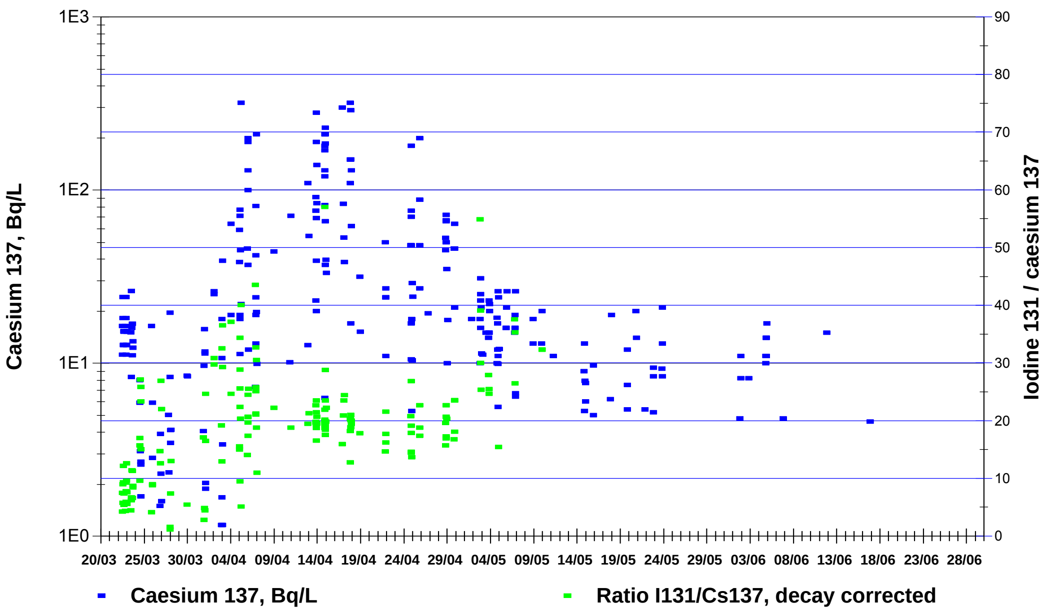
**initial ratio (IR): $^{131}I/^{137}Cs$ decay corrected to the 11 March 2011*

Seawater measurements at less than 2 km from the Fukushima Dai-ichi power plant.

Direct release average IR* around 20

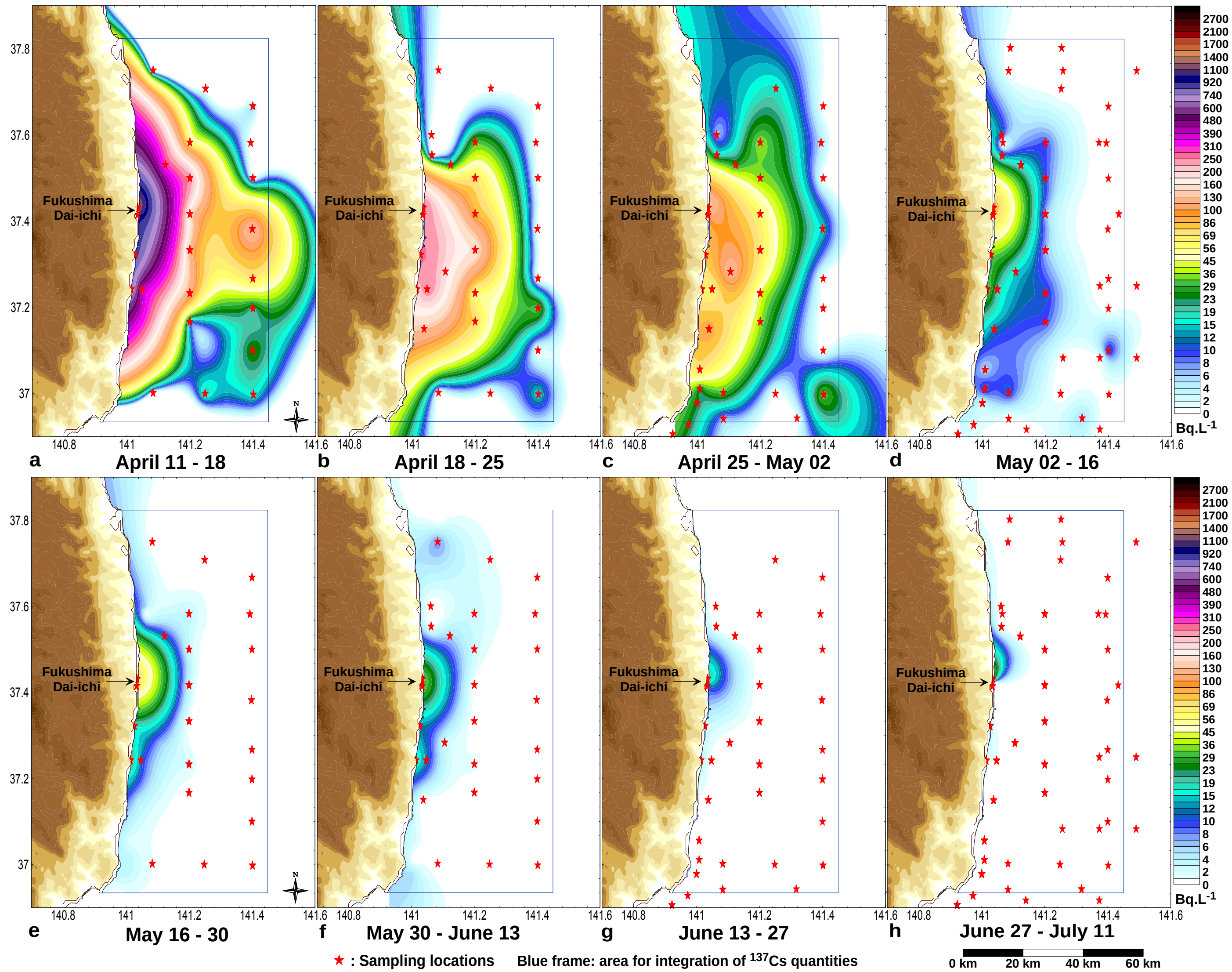


Measurements at more than 5km from the coast.
IR* 5 - 30



Estimation of the direct release source-term into seawater

^{137}Cs quantities were estimated on the basis of individual measurements in a 50 x 100 km area around the plant
(issues: depth, mixing layer, atmospheric fallout, rain water washout, …)



Interpolated ^{137}Cs concentrations from April 11 to July 11

Estimation of the source-term from direct releases into seawater

PBq: 10^{15}Bq

Measurement period			Number of measurements accounted	^{137}Cs quantity
Begin	End	Middle		
11/04/11	18/04/11	14/04/11	92	11.6 PBq
18/04/11	25/04/11	21/04/11	77	4.75 PBq
25/04/11	02/05/11	28/04/11	118	3.38 PBq
02/05/11	16/05/11	09/05/11	293	0.67 PBq
16/05/11	30/05/11	23/05/11	233	0.26 PBq
30/05/11	13/06/11	06/06/11	227	0.16 PBq
13/06/11	27/06/11	20/06/11	250	0.04 PBq
27/06/11	12/07/11	04/07/11	202	0.002 PBq

Quantities of ^{137}Cs deduced from interpolation of individual measurements in seawater.

Other estimations: 1 - 4PBq (TEPCO, Tsunume *et al.*, Kawamura *et al.*)

Average mixing layer thickness deduced from hydrographic measurement: 32m

NERH, 2011. Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety – The Accident at TEPCO's Fukushima Nuclear Power Stations. NERH Report. www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html

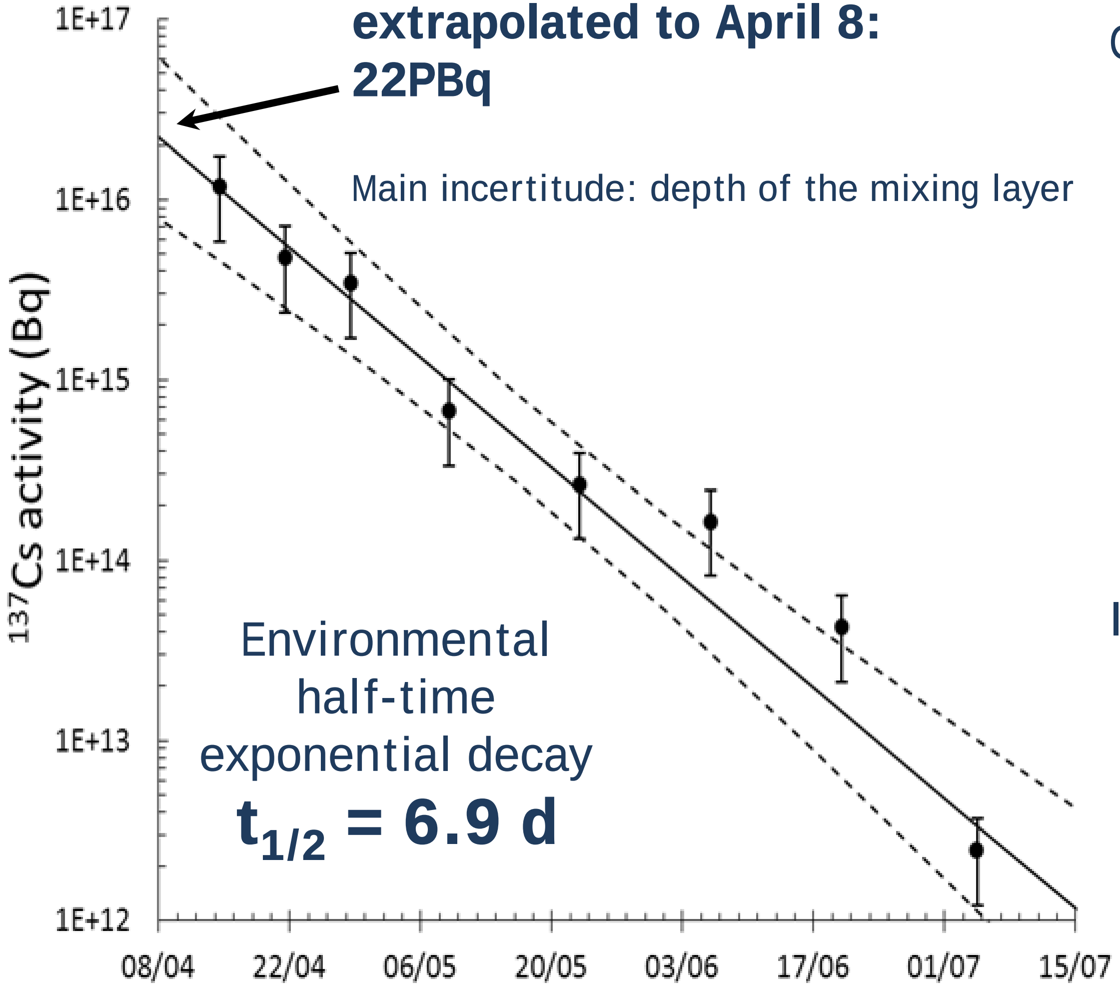
Tsumune D., Tsubono T., Aoyama M., Hirose K., 2011. Distribution of oceanic 137Cs from the Fukushima Daiichi Nuclear Power Plant simulated numerically by a regional ocean model. Journal of Environmental Radioactivity Volume, Issues 0. DOI: 16/j.jenvrad.2011.10.007

Kawamura H., Kobayashi T., Furuno A., IN T., Iishikawa Y., Nakayama T., Shima S., Awaji T., 2011. Preliminary Numerical Experiments on Oceanic Dispersion of ^{131}I and ^{137}Cs Discharged into the Ocean because of the Fukushima Daiichi Nuclear Power Plant Disaster. Journal of Nuclear Science and Technology Volume 48, Issues 11, Pages 1349-1356. DOI: 80/18811248.2011.9711826

Estimation of the rate of seawater renewal

Exponential decay back extrapolated to April 8: 22PBq

Main incertitude: depth of the mixing layer



Environmental half-time exponential decay

$t_{1/2}$ **= 6.9 d**

Evolution of ^{137}Cs quantities measured in seawater

Constant dilution by clean water through marine currents due to convergence of Kuroshio and Oyashio currents

- ➢ Seasonal changes in the ocean circulation ?
- ➢ Return of contaminated water back in the area ?

If no more releases occur and dilution remains constant, back to prior situation could be expected in Nov 2011

Flux estimation of ^{137}Cs from direct releases

Assumptions:

- Measurements close to the plant are representative of the released flux.
- Amount of 22 PBq corresponds to the quantity of ^{137}Cs released from March 26 to April 8 (average concentration:15 716 Bq.L^{-1}, number of values = 28, duration = 13.2 days).
- Fluxes of ^{137}Cs could be deduced from concentrations by applying the factor:

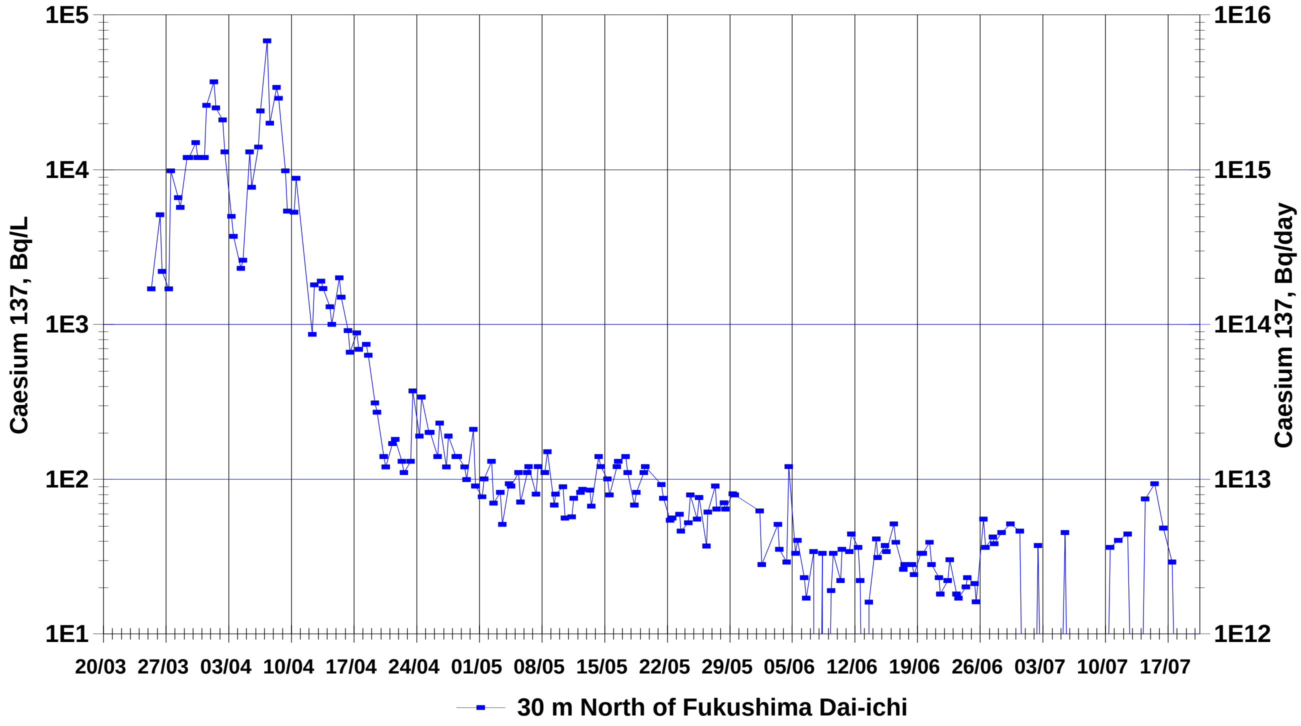
$$1.06E^{+11}\ \mathrm{Bq}_{\ released} / \mathrm{Bq.L}^{-1}_{\ measured}$$

Right Y axis in figure shows this conversion.

➢ **This source-term could be used in numerical dispersion models**

Evolution of concentrations and corresponding fluxes of ^{137}Cs in seawater

Total direct release until July 18 -> 27 PBq (12 PBq -> 41 PBq)



More details in: Bailly du Bois P., Laguionie P., Boust D., Korsakissok I., Didier D., Fiévet B. 2011. Estimation of marine source-term following Fukushima Dai-ichi accident. Journal of environmental Radioactivity. DOI:10.1016/j.jenvrad.2011.11.015

Hydrodynamic models in marine accidents

- Coastal models are key components of operational forecast systems which could be deployed during crisis such as point-source pollution incidents.
- Model reliability can be assessed with field-based data.
- In this context, artificial radionuclides are exceptional validation tools because they can be measured at all scales and source-terms are generally well known.
- The MARS (Model for Applications at Regional Scale) model was used After Fukushima Dai-ichi accident to reproduce and forecast the behaviour of contaminated waters for direct releases and deposit in Pacific ocean.
- Dissolved ^{137}Cs measurements allowed assessing model reliability in this low energetic tidal environment (currents of 1 $m.s^{-1}$), but strong general circulation (Kurushio and Oiashio currents).

Crisis modelling for Fukushima marine Accident

Constraints :

- **High resolution to follow the radionuclide releases**

- **Taking into account the regional an local circulation**
  - Kuroshio current (strong density unstable current)
  - The flux trough the Tsugaru Strait
  - The wind forcing (possibility of typhoons)
  - The tides (relatively low)

- **Use the data available in the framework of a crisis**

- **The oceanic forecast and hindcast of global model of MERCATOR-Ocean**
  - resolution about 8-10 km (1/12°)
  - one field per day (T, S, U, V, ssh)

- **The atmospheric forecast and hindcast of global model NCEP**
  - resolution about 50 km(1/2°)

- **Tidal Harmonic component (16) atlas FES2004 (1/8°)**

The FUKU0 configuration of MARS3D code

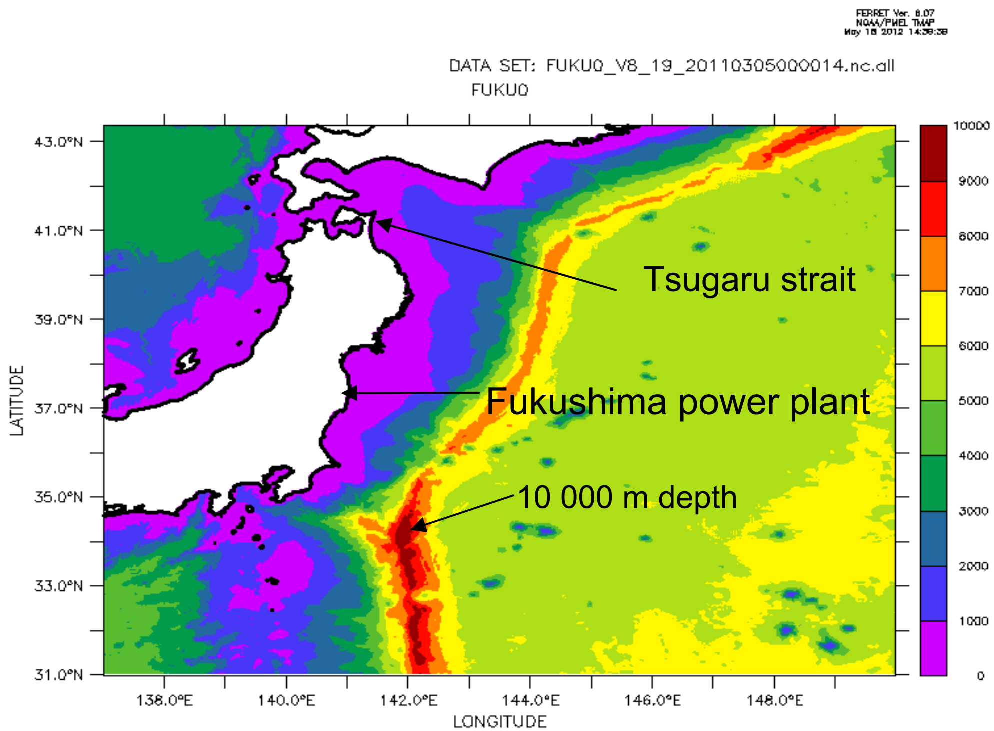
Extension : 31°N - 43.2°N , 137°E - 152°E (1000km*1200km)
Resolution : about 1 nautical mile (1/60°)
: 40 sigma levels refined near the surface

OBC and IC : temperature, salinity, currents, sea level from Mercator-Ocean, combined with the tidal harmonics
Run : on 256 MPI ranks

Animation of the sea surface temperature:

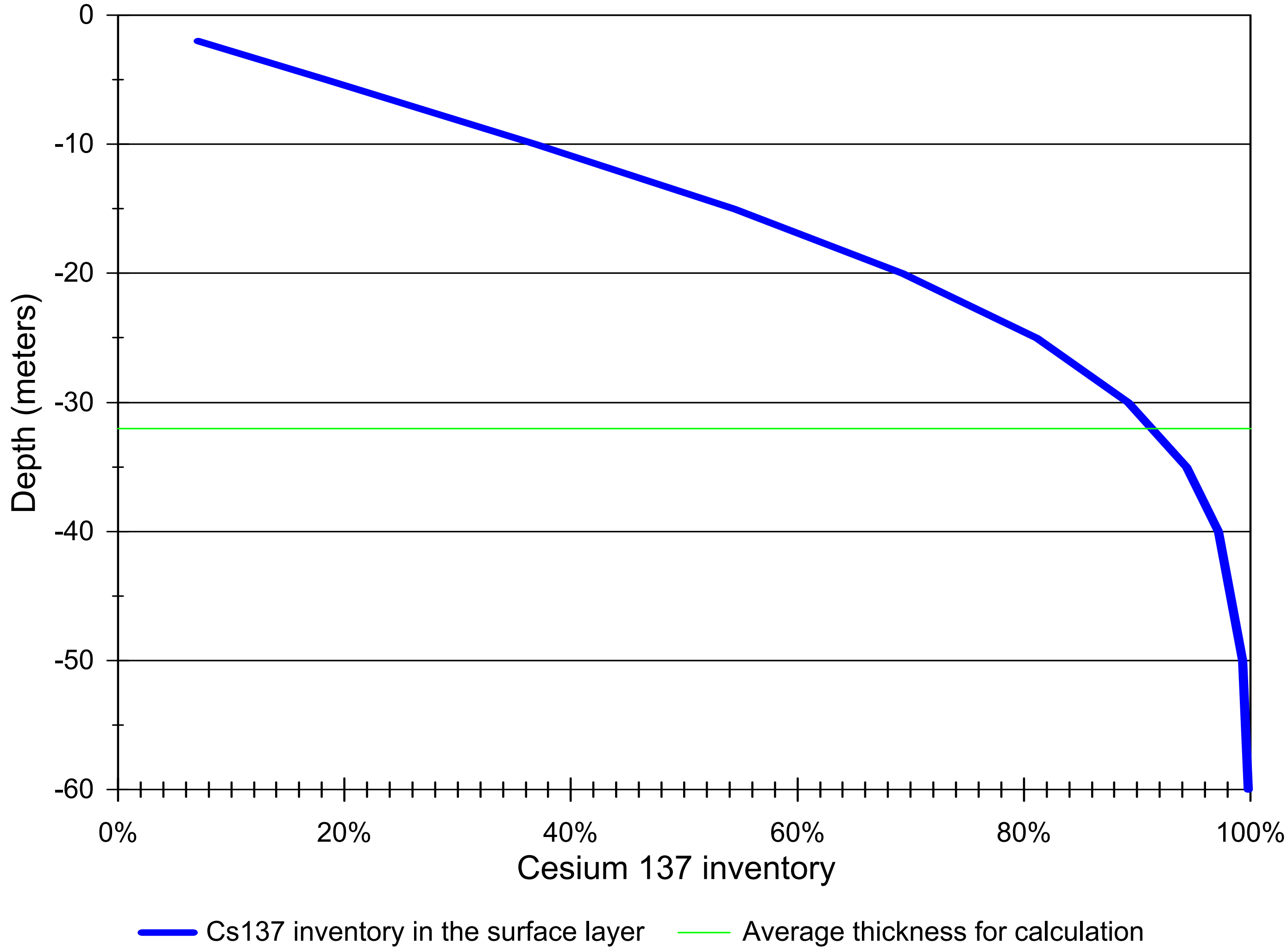
ftp://ftp.ifremer.fr/ifremer/dyneco/pgarreau/FUKU/film_temp.gif

Animation of current (zoom):
ftp://ftp.ifremer.fr/ifremer/dyneco/pgarreau/FUKU/film_tsugaru.gif



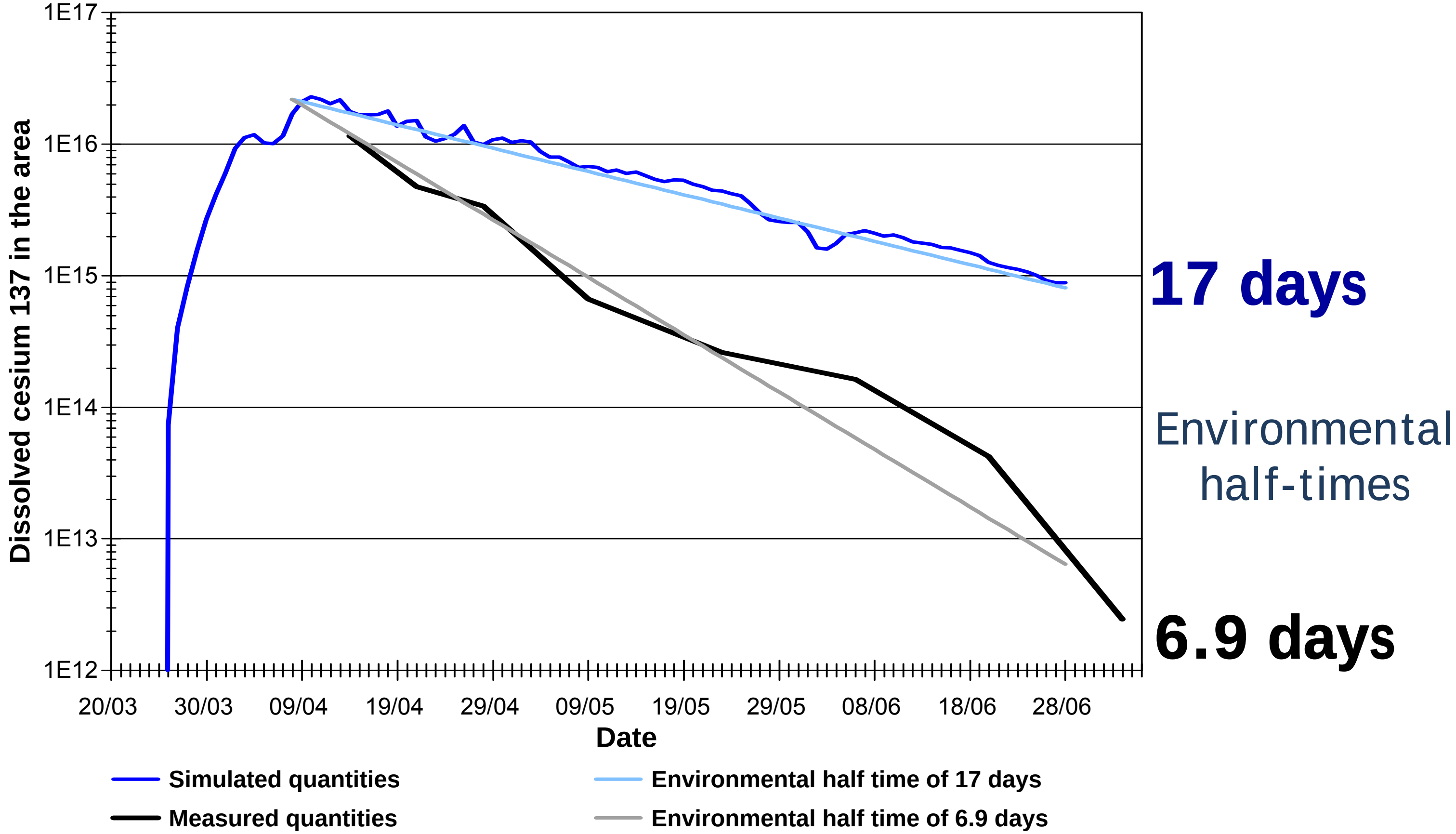
bathymetry relative to the mean level (m)

Model calculation of the mixing layer



Quantities of ^{137}Cs simulated in the inventory area confirms the 32m estimation of the mixing layer for the computation of inventories.

Environmental half time

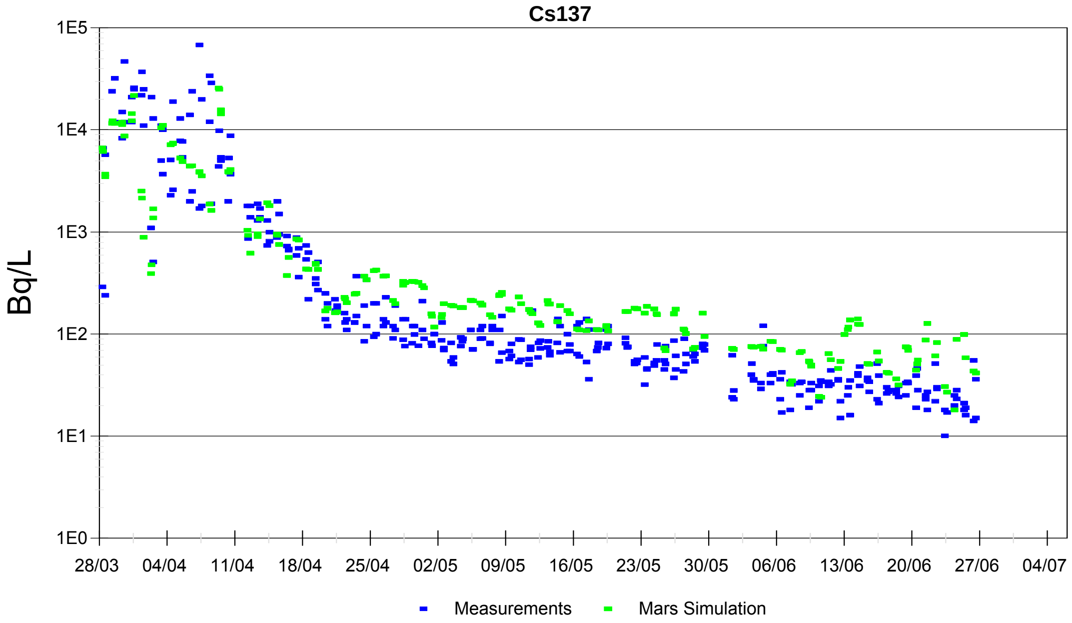


Model renewing time is lower than deduced from in-situ measurements

Differences between model and measurements concentrations will increase with time.
It could explain why other model/measurement comparisons gives lower estimations of direct releases (Tsunume *et al.*, Kawamura *et al.*).
But estimation from Buesseler *et al.* based on other measurements confirms our order of magnitude for direct releases.

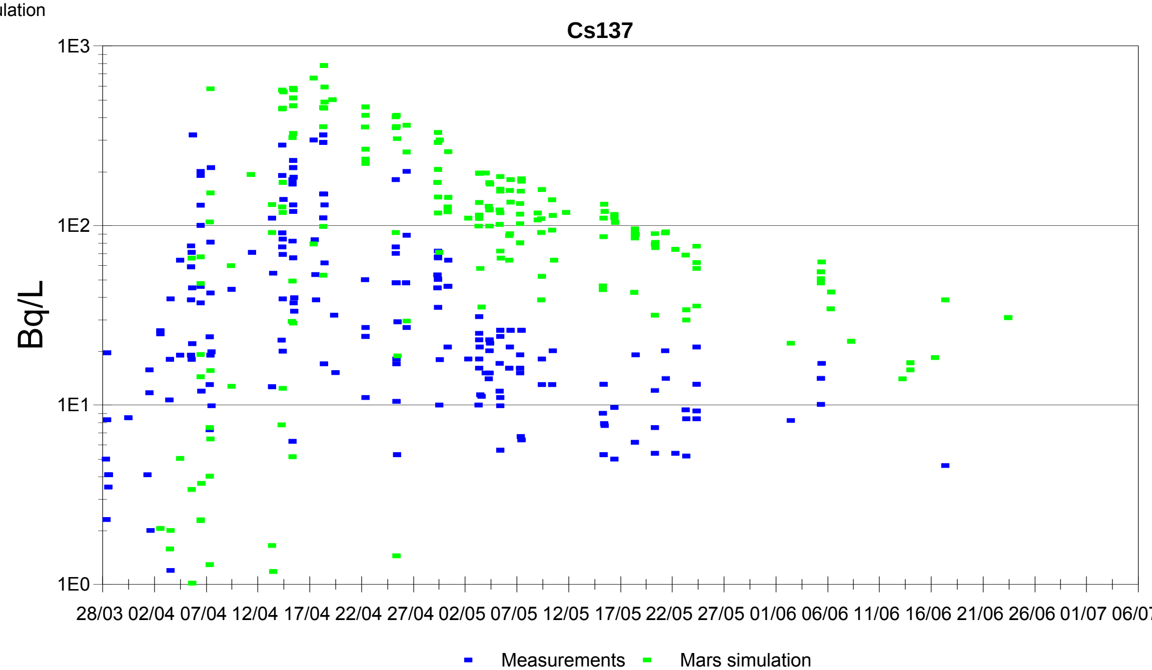
Buesseler, K. O., Jayne S. R., Fisher N. S., Rypina I. I., Baumann H., Baumann Z. et al. 2012. Fukushima-derived radionuclides in the ocean and biota off Japan. PNAS 2012 109 (16) 5984-5988, doi:10.1073/pnas.1120794109.

Matching calculations / measurements



Less than 1 km off the facility

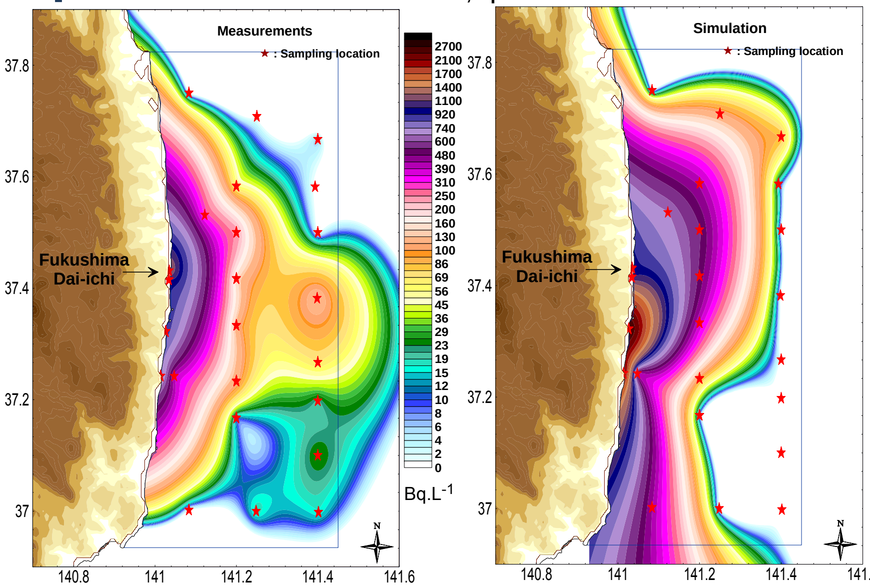
More than 5 km off the facility



Matching calculations / measurements

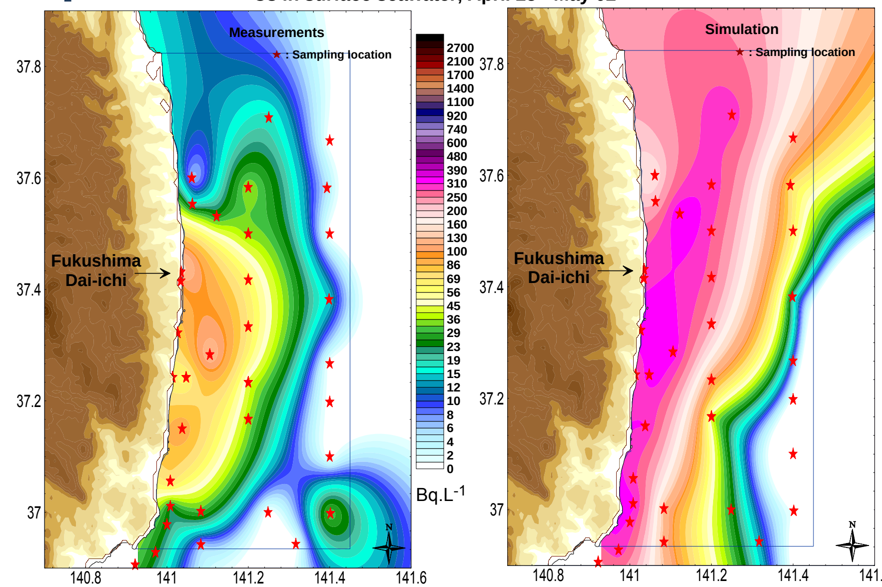
April, 14

^{137}Cs in surface seawater, April 11 - 18



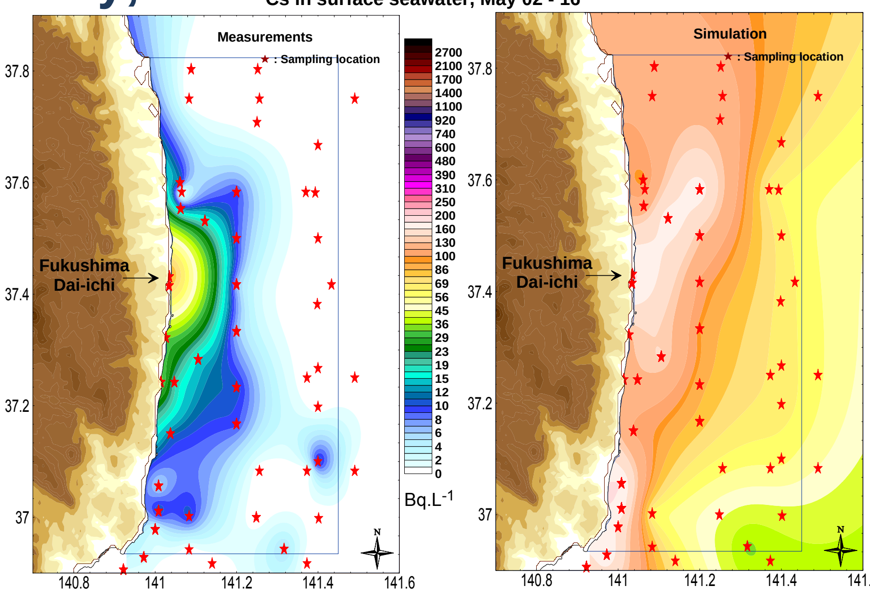
April, 28

^{137}Cs in surface seawater, April 25 - May 02



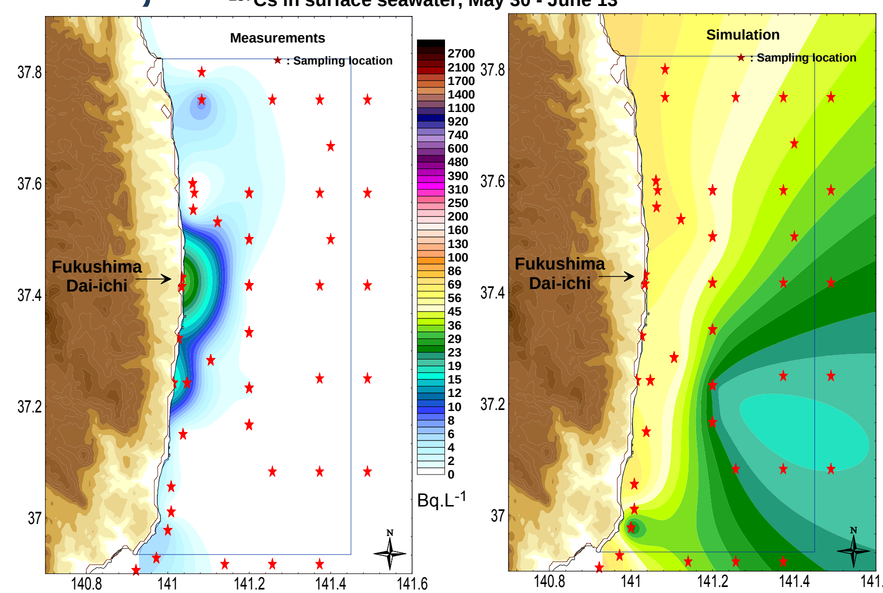
May, 9

^{137}Cs in surface seawater, May 02 - 16



June, 6

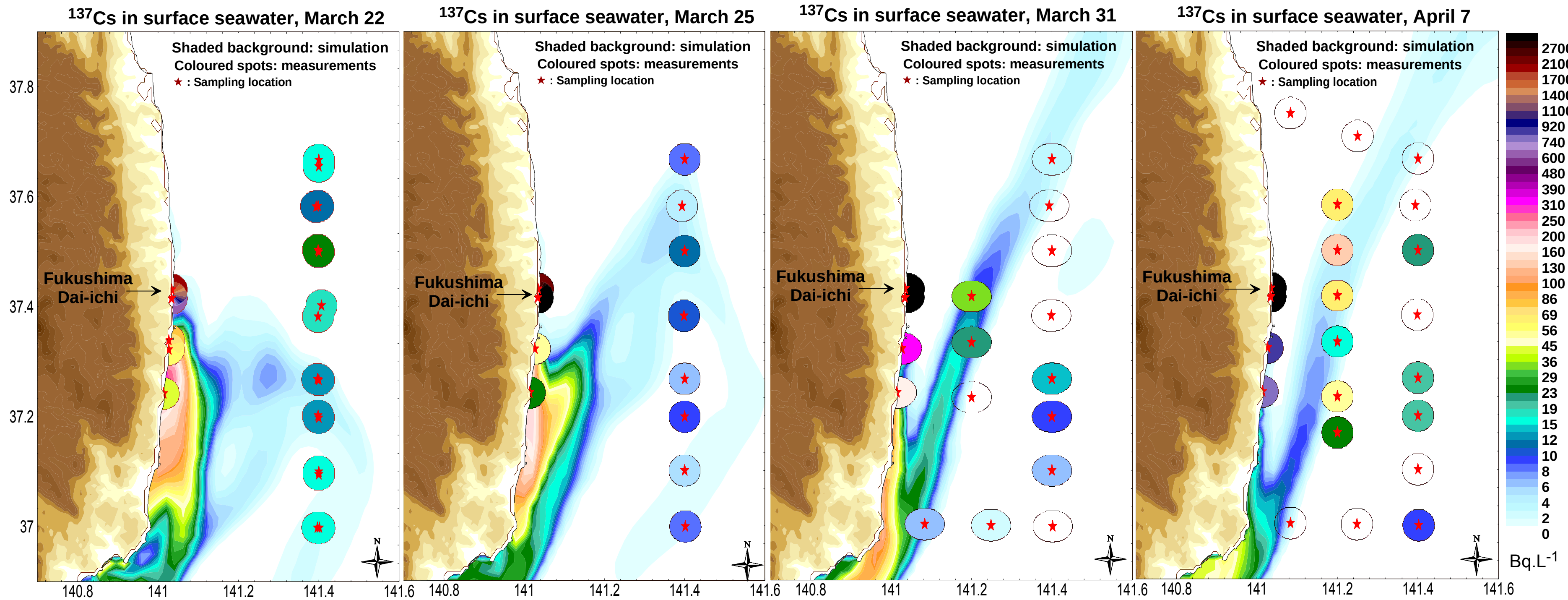
^{137}Cs in surface seawater, May 30 - June 13



Atmospheric wet deposit

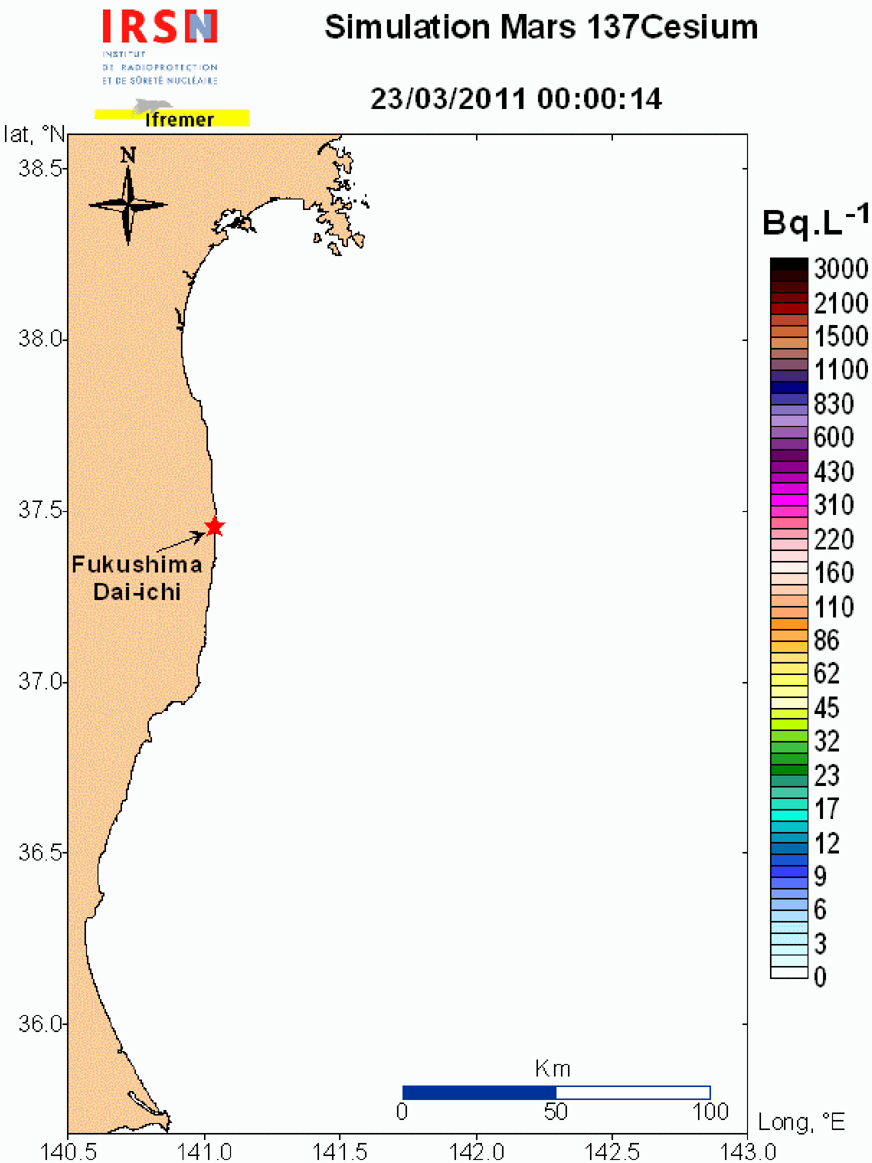
End of the atmospheric deposit: 16 March

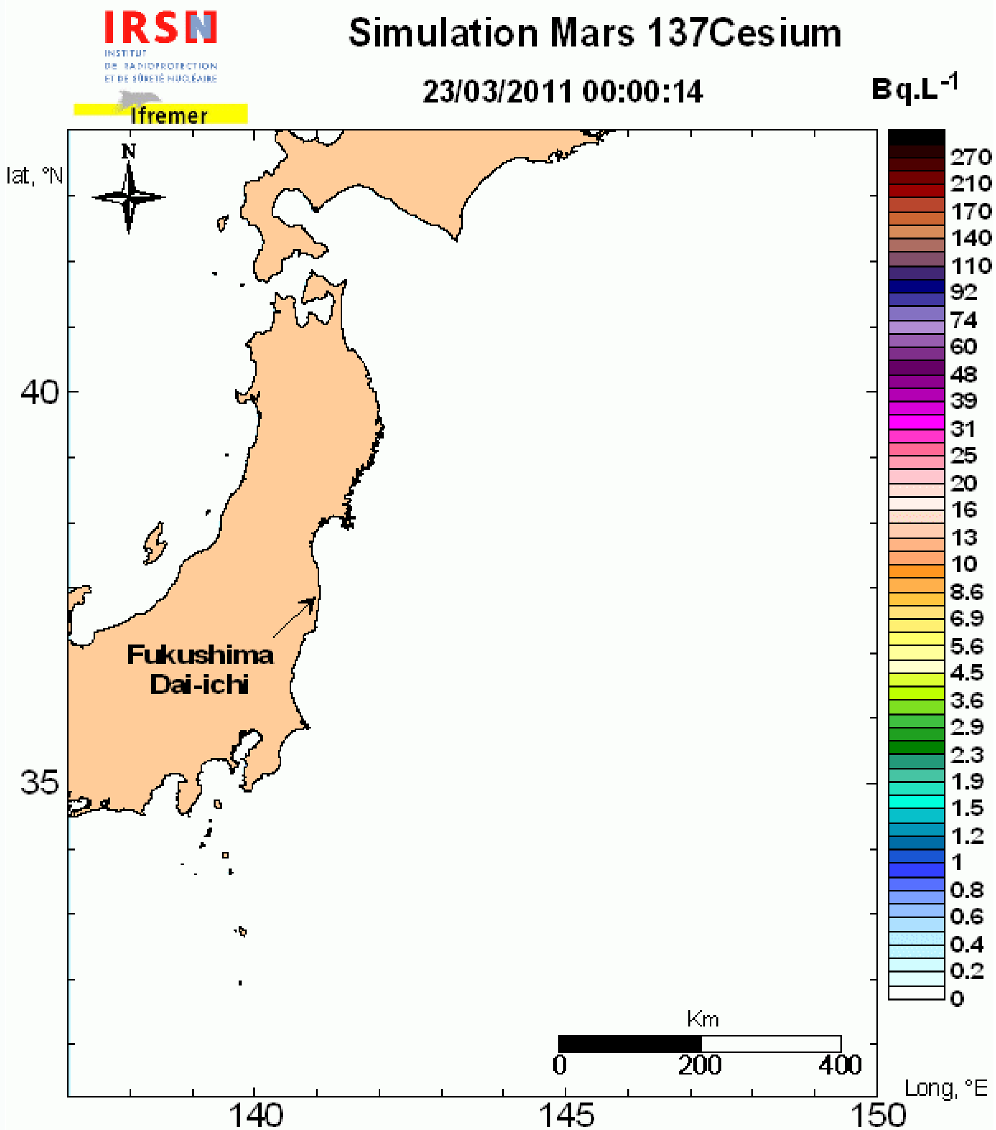
After 28 March: influence of the direct release



A large incertitude remain concerning parameters of wet deposit onto the sea.
Results confirms the orders of magnitude used in simulation of deposit (vd=5.10^{-5} m/s, lambda=5.10^{-5} hr.mm^{-1}.s^{-1})

Model animation





Color-scale changed by a factor 10

Discussion

- Association between simulations and measurements and early measurements are essential to estimate source terms.
- Why simulated renewing time is too long: wind shear stress or open condition limits?
    - Studies in the English Channel and North Sea show that the wind drag coefficient is a key parameter, depending of the meteorological data applied. This question will be examined in more details.
- Before March 11 2011, direct releases to the sea was not accounted for possible nuclear power plant accidents. Generally marine systems are not the first emergency in such situations, but answers must be prepared and other situations could end up to dispersion of radionuclides (ship wreck).
- Stochastic turbulence in the Fukushima area, measurements available and poor knowledge of the source term made difficult to investigate exact location of the plume following releases.

Conclusions: radionuclides

- **Contamination of the marine environment following the accident in the Fukushima Dai-ichi nuclear power plant represents the most important artificial radioactive direct liquid release into the sea ever known (arround 27 PBq for ^{137}Cs only).**
- **Available measurements made possible to estimate the environmental half-time of the release area, and the radionuclide fluxes from direct releases.**
- **Due to the exceptional dilution conditions, concentrations in seawater decrease strongly at the end of 2011.**
- **It will be different for benthic species living close to the plant or concerned by transfer through suspended matter coming from deposited sediments, rivers or desorption in seawater of radionuclides fixed onto sediments.**
- **Caesium 137 and 134 from Fukushima will remain detectable for several years in the North Pacific. $^{137}Cs/^{134}Cs$ ratio could be used as a tracer for studies on water masses pathways and transit times.**

Conclusions: hydrodynamic models

- Hydrodynamic models are essential tools to approach consequences of accidents in marine environment. It is our duty to apply them, even very far from Europe.
- Simulations during accidents are useful to : organize in-situ intervention and sampling, manage living resources and human uses of marine system, information of stakeholders and populations.
- Models made possible dynamic calculation of transfers to living species by using biological half-lives of radionuclides (if available).
- Measurements of dissolved radionuclides made possible to approach Mid- and long-term precision of hydrodynamic models.
- Measured and simulated process are comparable, some key parameters as renewing time could be improved.
- Even if few early data are available, useful orders of magnitude for atmospheric deposit parameters are provided by simulations.

Special thanks to:

MEXT and TEPCO for the Internet publication of the concentration data collected in the environment.

Celine Duffa, Mireille Arnaud, Olivier Connan, Vanessa Parache, Tina Odaka and "Centre Technique de Crise" staff of the French Institute of Radioprotection and Nuclear Safety for searching compiling and checking thousands of measurements.

We want to express all our sympathy to Japanese people.

Inventory of main ^{137}Cs releases in the oceans

Source		PBq (1E+15Bq)
Fallout from nuclear weapon tests		704*
Nuclear fuel reprocessing 1951 - 2010	BNFL Sellafield	41.21
	Areva-NC La Hague	1.04
Tchernobyl accident		16*
Solid waste dumping		41.4 (total beta + gamma)
Fukushima accident	Direct liquid release	27
	Atmospheric fallout	3 (80 km radius circle)

* Aarkrog, 2003. Input of anthropogenic radionuclides into the World Ocean. Deep Sea Research Part II: Topical Studies in Oceanography Volume 50, Issues 17-21, Pages 2597-2606