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Technical Note

Ocean Plume Modeling for the Fukushima Dai'ichi Event: Particle tracing. [†].

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Abstract

The National Centers of Environmental Prediction (NCEP) of the National Weather Service (NWS) used particle tracing to predict the movement of radionuclides in the ocean shortly after the Japanese Nuclear disaster near Fukushima. Daily nowcast/forecast fields from 1/12° HYbrid Coordinate Ocean Model (HYCOM), implemented at NCEP as the Global Real Time Ocean Forecast System (RTOFS-Global), were used to track inert particles at the ocean surface, assuming that the surface behavior is reasonably representative for the ocean mixed layer, and that the radionuclides are mostly contained in and distributed by the upper mixed layer of the ocean. The focus was on producing actionable information for a governmental Inter-agency Working Group (IWG) in near real time using available resources.

With the particle tracing information, NCEP produced estimates of retention time of radionuclides near the coast, as well as dispersion time scale of these materials through the Pacific Ocean, particularly by persistent current systems like the Kuroshio and its extension, and the Oyashio. This helped identify both potentially safe areas in the Pacific, and areas of potential exposure on the time scales of weeks to months. Using particle tracing combined with atmospheric deposits of radionuclides, a first guess of contamination of ocean surface water was produced.

First particle tracing products were routinely delivered to the IWG within four weeks of the first significant release of radionuclide. The first quantitative offshore contamination estimates were made available to the IWG in approximately 6 weeks.

Acknowledgments. The authors thank the members of the IWG for their fruitful discussions and collaborations. In particular, the collaboration with the US Navy (through Frank Bub) in physical ocean modeling, with the NOAA Air Resources Laboratory (ARL, through Steve Fine and Roland Draxler) with respect obtaining HYSPLIT model output, and with the Environmental Protection Agency (EPA) in establishing contamination guidelines (Appendix A) where essential for this project. The interactions with the Japanese Ministry of Education, Culture, Sports Science and Technology (MEXT), and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) was also greatly appreciated. The present study was made possibly by redirecting base funding from NOAA. Most of this report had been written by February 2012,. Publication was delayed due to lack of funding for the project.

This report is available as a pdf file from

http://polar.ncep.noaa.gov

Contents

1 Introduction

At 5:46:23 UTC on March 11, 2011, a magnitude 9.0 earthquake struck near the east coast of Honshu, Japan and generated a devastating tsunami. The earthquake and tsunami caused significant damage to Fukushima Dai'ichi nuclear power plant (FDNPP), located on the east coast of Honshu, approximately 200 km north of Tokyo. Since that time, the National Oceanic and Atmospheric Administration (NOAA), an agency within the Department of Commerce, has been providing support to the lead agency for this event, the Department of Energy. Shortly after the event, NOAA began to anticipate the need to predict the movement of radionuclides within the ocean after they are deposited into the ocean by wet and dry deposition downwind of the FDNPP. Later in the event, it became clear that contamination from coastal runoff from the FDNPP should also be considered. This document describes the corresponding modeling effort at NCEP. Note that this modeling effort was first and foremost focused on rapidly providing actionable information to decision makers, and should therefore not be confused with a scientific oriented modeling study. Reporting to the US Government occurred through an Interagency Working Group (IWG).

At the onset of this tragic event, the Marine Modeling and Analysis Branch (MMAB) of the Environmental Modeling Center (EMC) of the National Centers for Environmental prediction (NCEP) of NOAA, together with NCEP Central Operations (NCO) was running a global version of the HYbrid Coordinate Ocean Model (HYCOM) with a horizontal resolution of 1/12° and 32 hybrid vertical levels in pre-operational mode[1]. The model runs daily, receiving initial conditions from the U.S Navy (Naval Oceanographic Office, Stennis, MS). The model uses initial conditions from two days before the model run, adjusting the model to analyzed NCEP atmospheric forcing (GDAS), and during the event produced a six day[2] forecast forced with forecasted NCEP atmospheric forcing. Since NCEP identifies products rather than the models used to generate the products, this model is generally identified as the Real Time Ocean Forecast System - Global (RTOFS-Global). This model has been run at NCEP since December 2010, and full archive of data is available starting March 8, 2011. The model became fully operational on October 25, 2011.

To predict the movement of radionuclides in the ocean in near real time using RTOFS-Global, NCEP considered several options. The most direct way to predict the concentration of radionuclides throughout the ocean would be to use the models capability for full tracer computations (comparable to HYSPLIT in the atmosphere). This capability, however, had not yet been tested at NCEP,

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[1] In pre-operational mode the model was running in the resource slot intended for this model in operations. For in-house use, the pre-operational model therefore had a product delivery reliability comparable to that of fully operational models.

[2] In the summer of 2013 the forecast range of the model was increased to eight days.

and would require modifications to the pre-operational model. Furthermore, this approach would require re-running the full ocean model for each scenario considered, and hence be computationally expensive. Finally, it would require data on deposits and behavior of radionuclides, which even now, two and a half years after the event, are not yet agreed upon. All these considerations made dispersion modeling in the ocean not suitable for producing rapid response actionable information on radioactive contamination of sea water. However, this approach is more feasible to provide long term operational modeling, once proper sources of relevant contaminants have been produced (see Garaffo et al., 2013).

Alternatively, particle tracing can be performed using output of the ocean model. NCEP had a tested capability to trace particles from model output (i.e., without the need to re-run the expensive hydrodynamic model), and started experimenting with this approach shortly after the news of damage to the FDNPP was made public. NOAA started using the 1/12° HYCOM (RTOFS-Global) model output to track inert particles at the ocean surface, assuming that the surface behavior is reasonably representative for the ocean mixed layer, and that the radionuclides are mostly contained in, and distributed by the upper mixed layer of the ocean. This approach is described in the present report, and has been performed for six months.

With the particle tracing information, NCEP has produced estimates of retention time of radionuclides near the coast, as well as dispersion time scale of these materials through the Pacific Ocean, particularly by persistent current systems like the Kuroshio and its extension, and the Oyashio. This identified both potentially safe areas in the Pacific, and areas of potential exposure on the time scales of weeks to months. To provide additional information on the contamination levels from the particle tracing the following necessary additional information was identified:

- Deposit rates of radionuclides from the atmosphere (e.g., in Bq/m^2/day), as georeferenced numerical information.
- Estimates of point sources at the coast, and development of methods to convert this into a proxy load per model particle.
- Estimates of vertical dispersion of pollutants in the ocean. As a first guess, it can be assumed that the particles are homogeneously dispersed throughout the mixed layer of the ocean. This mixed layer is estimated from RTOFS-Global using the KPP vertical mixing scheme (Large et al., 1994).
- Horizontal diffusion rates in the ocean associate with low particle density far away from source. Dispersion modeling may be helpful and a reasonable assumption can be made to estimate the associated uncertainty with such an assumption.

- Radioactive decay information of material involved and the composition of that material. Decay information on Iodine and Cesium is available. However, it is not clear if these materials should be considered as dissolved or particulate.

- Observed radionuclides in the ocean. The modeling activities described here include significant uncertainty, making it of paramount importance that in-situ observations of radionuclides are available to develop as well as validate the model with respect to predicted levels of radioactivity.

- Additional observations of the physical state of the ocean (temperature, salinity and current velocity, including profile data). These data are particularly critical near the coastal sources of the pollution, as they describe the initial containment or dispersion of pollution from the coast. Generally, better description of ocean currents will result in more realistic dispersion patterns. Because the Navy preforms the data integration in the modeling for this effort, additional ocean state observations should be coordinated with the Navy (Naval Oceanographic Office (NAVO), Naval Research Laboratory (NRL)).

- Because the actionable information is intended for decision makers (and ultimately the general public), the presentation of results becomes important. Rather that providing data contamination data in 'scientific' format (direct contamination values), it is more appropriate to frame this in terms of risks for decision makers. In order to translate model results to risks, acceptable contamination levels need to be adopted. At the beginning of this efforts, such information was not available for sea water.

1.1 Limitations

There are several important limitations of the particle tracing approach that need to be understood by any user of its products.

First, the resolution of the NCEP ocean model is insufficient to address the detailed dispersion of radioactive material in coastal areas near the power plant. This limitation can be mitigated by using high-resolution ocean models as run by our partners, particularly the U.S. Navy Operational Global Ocean Model (NCOM) using a horizontal gridspacing of 1 km (see below). The data of the latter model have been distributed by NOAA's Ocean Prediction Center (OPC). The Navy routinely runs the NCOM for the West Pacific including Japan, using a horizontal gridspacing of 3.5 km. These data have also been archived at NCEP. The archive of ocean model data from the Navy at NCEP contains data starting at March 6.

Second, this modeling approach deals with dispersion on weather time scales, and is suitable (and feasible) to be run for time scales of up to a few months. For Iodine, this is not an issue, because its half live is 8 days. For Cesium or other pollutants associated with catastrophic failure at the reactor, climate scale dispersion modeling may be required to address long-term impacts. For this reason, the particle tracing model was discontinued after six months (170 days).

Third, any effort to modeling ocean contamination is seriously hampered by the fact that there is insufficient observation data, both with respect to model development and model validation. This is true for physical ocean modeling, as is obvious from the fact that the leading ocean modeling efforts in the world did not agree upon the existence and strength of a large eddy offshore of Sendai, even though all these models have access to virtually all routinely available ocean data. It is even more true for radioactive contamination. At the onset of the disaster, there were effectively no recent observations on radioactive contamination of the North Pacific ocean available. As will be illustrated below, even now there is only very limited validation data available for ocean plume models.

Fourth, NOAA is only modeling the physical dispersion radioactive material and does not have the knowledge or capability to address human or biological impacts.

Fifth, advancing particles (or tracers) in the presence of data assimilation ideally require an inverse model or an ensemble approach. For example, maintaining coherent structures inside of an eddy would require a more sophisticated data assimilation module for particles (or tracers) which is not yet available for HYCOM.

1.2 Active Collaborations

Whereas NOAA (NCEP) was appointed as the lead agency for ocean plume modeling, the full effort represents a collaboration between many agencies. Below, a few of the main collaborations are identified.

The HYCOM model is a community model, developed with major contributions of the Navy, academia and NOAA. The RTOFS-Global implementation is an operational partnership between NCEP and the Naval Research Laboratory (NRL) and NAVO. NCEP adopted the model configuration developed at NRL and being operationalized at NAVO, and NAVO provides daily initialization data for the NCEP model. This partnership allowed NCEP to accelerate the model implementation by up to a decade. Furthermore, navy ocean modelers have been available for discussion of the physical ocean state throughout this project.

NCEP is starting to become a distribution point for Navy (NAVO) ocean models data. The Ocean Prediction Center (OPC) is distributing global 1/8° resolution NCOM data for selected areas. NAVO has a 3.5 km NCOM model running routinely for the Japanese waters. NAVO has set up a high resolution (1 km horizontal grid spacing) nested NCOM model for the area around FDNPP (model runs have recently been discontinued). These data are transitioned in real time to NCEP through operational communication channels, and NCEP acts as the archive and distribution point of these model data.

NCEP has the capability to provide any other partners with boundary and initialization data for local models from the HYCOM and NCOM models described above.

NCEP had been considering standing up particle tracing capabilities based on the 1km NCOM model, particularly to address behavior of continuous or catastrophic releases of radioactive material at the coast. NCEP has been coordinating with both the Navy and National Ocean Services (NOS) to leverage coastal modeling capabilities (removing the need for NCEP to run such models). The following potential collaborations have been identified:

The Navy (NAVO) has been running a particle tracing model (originally developed for oil spill modeling) based on the high resolution NCOM models for point releases of material at FDNPP, but not including atmospheric deposition as intended for the NCEP model. These modeling efforts are essentially complimentary, and NCEP has had access to the NAVO results. This model was no longer operated, when it was super-seeded by the model described in the next paragraph.

The Defense Treat Reduction Agency (DTRA) has been running a dispersion model for the near-coast area using offshore observations to address local water quality for use by Navy ships. This approach used offshore observations to estimate source areas and levels of coastal releases of pollutants. This modeling effort was complimentary to the NCEP effort, and was considered to provide NCEP with proxy source data needed for the large sale modeling effort. NCEP and DTRA established an active dialog on all modeling efforts.

NOS Office of Response and Restoration (OR&R) has the GNOME model with particle tracing capabilities. NCEP has provided OR&R with the 1km NCOM data. OR&R did assess possible support for the coastal modeling problem. As in the deep ocean, any modeling effort here is severely hamstrung by lack of data.

NOS Coastal Survey Development Laboratory (CSDL) is an established partner of NCEP with respect to building the ocean modeling backbone capability for NOAA, with NCEP focusing on basin scales and NOS focusing on coastal areas. For the plume modeling, NOS is engaging their partners in academia to inventory capabilities. In this context, the FVCOM modeling group is developing and adopting a global unstructured grid model with extremely high resolution to model the Japanese tsunami. This model may also provide some tracing capability for retrospective modeling. NOS and NCEP are also partnering on developing regional tracer modeling capabilities as part of long-term capability development.

NCEP relied on EPA to provide threshold contamination levels needed for effective communication of contamination levels to the decision makers. EPA provided such estimates on May 11, 2011 (see Appendix A).

The Department of State facilitated active dialog with our Japanese colleagues, which led to a fact-finding visit to Tokyo in May 2011. Discussion with our Japanese colleague have been very constructive with respect to exchange of modeling findings, and with exchange of observational data.

In October 2011, NOAA was represented at meetings at the International Atomic Energy Agency (IAEA) in Monaco to work on a draft request for proposals for benchmarking ocean plume models. This interaction fosters possible future international collaboration on ocean plume modeling.

All physical modeling of the radioactive plume in the ocean will be critically dependent on observation partnership inside and outside of NOAA, and with the international community.

1.3 Outline of report

In Section 2 the basic modeling approach will be described. Section 3 describes model inputs, and model errors are addressed in Section 4. Initial model results are presented in Section 5, and products generated for the IWG are discussed in Section 6. Conclusions are presented in Section 7.

2 Model description

2.1 General considerations

As described in the introduction, the modeling approach described here is intended to provide rapid actionable information to decision makers. It should be noted that it is not intended to be the most sophisticated scientific approach available. The present approach is based on particle tracing, done as a post-processing step after a full ocean model has been run. The particle tracing approach is suitable for the present purpose because:

i) Particle tracing is cheap compared to running a full model with embedded tracers, and can be done quickly in retrospective mode using model output archives. Note that this approach does not require modifications to the computation-intensive operational models, which allows for rapid response even in a highly regimented operational environment.

ii) Particle tracing can be done without detailed information on contamination sources, and will give actionable information on where pollutants may travel to. It will also identify areas that are not directly threatened by contamination.

iii) A major initial uncertainty in modeling pollution is obtaining accurate estimates of contamination sources, particularly near the time of the releases. However, particularly in the time directly following release of contaminants, it is essential to obtain actionable information to determine which areas might be at risk. Particle tracing can be used to do 'what-if' scenarios, using hypothetical release patterns and intensities.

iv) If particle archives are maintained, it becomes relatively easy to estimate pollution levels from various source scenarios, as this only requires post-processing of particle tracks, but no full re-running of models or particle tracing (also highly beneficial for what-if scenarios).

It is well understood that computing contaminant concentrations from particle tracing is difficult, particularly for long term monitoring where (virtual) particle densities in the model generally become too low, and where physical behavior of discrete particles compared to dissolved material becomes too different. This will be discussed in more detail in Sections 4, 5 and 7.

2.2 RTOFS-Global (HYCOM)

The cornerstone of this modeling effort is the global eddy-resolving version of NCEP's Real-Time Ocean Forecast System (RTOFS-Global). This model was

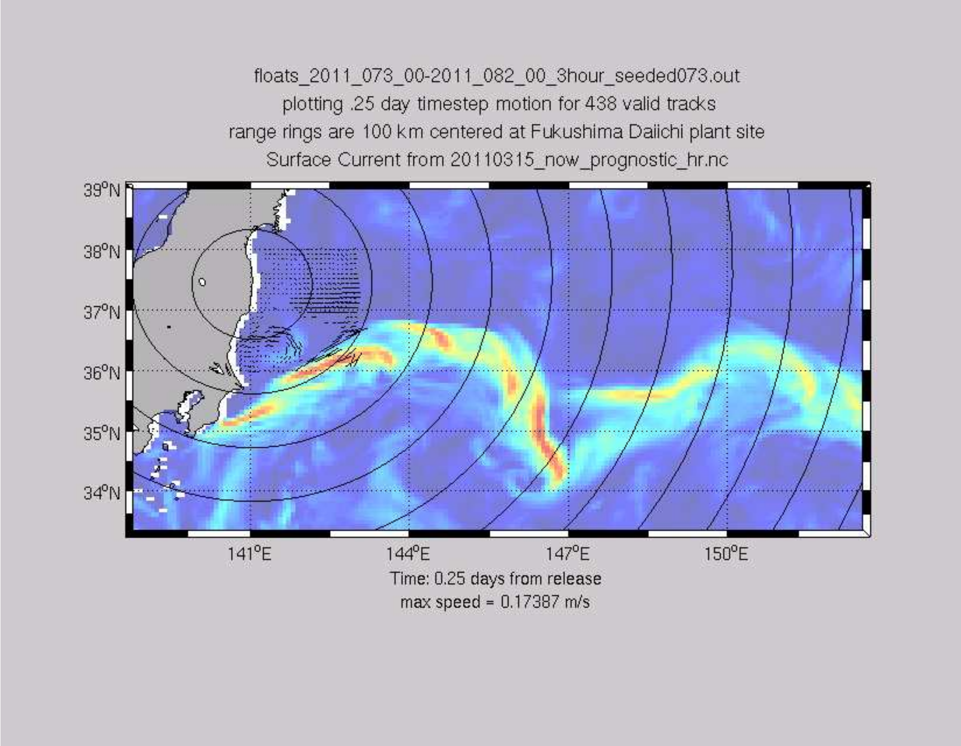

Fig. 2.1 : Example surface currents from RTOFS-Global around Japan for March 15, 2011, 00 UTC.

undergoing pre-operational testing at NCEP Central Operations (NCO) when the initial disaster occurred. For all practical purposes, the pre-operational model was running daily as if it was a fully operational model. The model became fully operational on October 25, 2011. RTOFS-Global is based on an eddy resolving 1/12° global HYCOM (HYbrid Coordinates Ocean Model) model (Chassignet et al., 2009), and is part of a larger national backbone capability of ocean modeling at NOAA that is being developed at the NWS and the National Ocean Services (NOS). This NOAA effort is a part of a larger national effort in a strong partnership with US Navy.

RTOFS-Global runs once per day to produce a eight day forecast[3], starting from daily initialization fields produced at NAVO using the Navy Coupled Ocean Data Assimilation (NCODA) system, a 3D multi-variate data assimilation package (Cummings, 2005). As configured in RTOFS, HYCOM has a horizontal equatorial resolution of 1/12°, or approximately 9 km. The HYCOM grid is on a Mercator projection from 78.64°S to 47°N, and north of this it employs an Arctic dipole patch where the poles are shifted over land to avoid a singularity at the North Pole. This gives a mid-latitude horizontal resolution of approximately

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[3] A six day forecast at the time of the incident.

7km, and a polar resolution of approximately 3.5km. The coastline is fixed at the 10m isobath with open Bering Straits. RTOFS-Global employs 32 hybrid vertical coordinate surfaces (Bleck, 2002), with potential density referenced to 2000m and it includes the effects of thermobaricity (Chassignet et al., 2003). Vertical coordinates can be isopycnals, often best for resolving deep water masses, levels of equal pressure (fixed depths), best for the well mixed unstratified upper ocean and sigma-levels (terrain-following), often the best choice in shallow water. The model employs the time-variant layered continuity equation to make a dynamically smooth transition between the vertical coordinate types. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. The dynamic ocean model is coupled to a thermodynamic energy loan ice model and uses the KPP mixed layer formulation (Large et al., 1994). The forecast system is forced with 3-hourly momentum, radiation and precipitation fluxes from the NCEPS's operational Global Forecast System (GFS, Moorthi et al., 2001) fields. Figure 2.1 shows an example surface current field from RTOFS-Global around Japan, identifying the Kuroshio and Kuroshio Extension as the major (surface) current systems in this area.

2.3 Particle tracking

The second critical element of this modeling approach is the particle tracking model. Tracking ocean motions by means of in-situ drifters or by floats has been extensively used to obtain information about the ocean pathways, velocities, and transports. In particular the global surface drifter data set (Sybrandy and Niiler, 1991) monitors velocities and transports by means of drifters maintained at 15m depth (Lumkin and Pazos, 2006). Griffa et al. (2008) analyze eddy signatures, separating by size and polarity, from the global drifter data set. Particle tracking in ocean models has also been extensively used (Garraffo et al., 2001a,b; Halliwell et al., 2003) An example of recent insight on the ocean circulation as obtained by both in-situ and synthetic floats is presented in Bower et al. (2009).

In the present study, an off-line approach has been used to follow synthetic floats and drifters using archived output from RTOFS-Global, which is available at 3 hour intervals for the surface, and at 6 hour intervals for the full three-dimensional ocean. The synthetic float off-line code is the off-line version of the in-line code available in HYCOM. The in-line version was developed by Halliwell et al. (2003) and was later extracted as an off-line code. It is based in part on previous schemes for Miami's Isopycnal Coordinate Ocean Model (MICOM, see Garraffo et al., 2001a,b, for early tracing algorithms). Several types of particles can be tracked: 3-dimensional Lagrangian (advected with the model diagnosed vertical velocity), isopycnic, and isobaric (diagnostics at fixed moorings is also

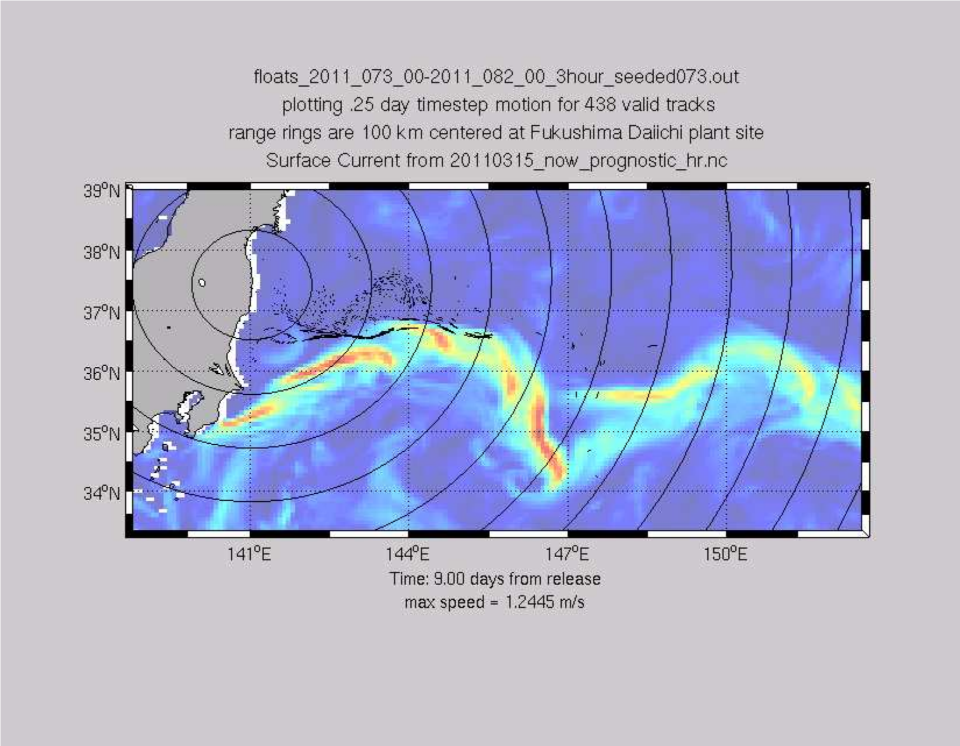

Fig. 2.2 : Example of particle tracing in the upper ocean mixed layer. Currents as in Fig. 2.1. Black lines identify particle tracks in the last 9 *days of the simulation; hence, length of tracks corresponds to recent speed of particle. Note that snapshot of current field represents the start of the integration only, so that tracks do not exactly line up with current features.*

supported). A description of the code is also available online[4]. Note that the code supports the HYCOM curvilinear grids.

In the particle tracing algorithm, for each particle a search is performed of the 16 surrounding grid points to perform two-dimensional polynomial interpolation of the model variables (within a vertical given layer). If insufficient water points are available around the particle position, only the nearest neighbors are used. The model layer containing the float is identified by interpolating the layer depths to the horizontal particle position. First the float is advected with the horizontal interpolated velocities (at the float layer), then it is moved to a new vertical layer as needed.

In the present approach, we will assume that the contamination is contained in the upper mixed layer of the ocean. Initial experiments showed that isobaric floats deployed in the upper model layer at a depth of 1 to 3m are reasonably

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[4] http://www.hycom.org/attachments/067_float.pdf

representative for the horizontal motion in the mixed layer. Particularly for generating actionable information quickly, and considering the large uncertainties in contamination loads, this assumption appears reasonable. This approach maintains the particles at a chosen depth (layer1, upper 3 meters) and does not include vertical motions or vertical diffusion of particles as "synthetic" drifters. Furthermore, using surface floats only allows us to use the higher time resolution of RTOFS-Global archives for the surface layer. The float time step is 3 hours, using 3 hourly archives with no further time interpolation. Initial experiments with higher time resolution velocity fields showed no significant impact on particle trajectories. Motion unresolved by the resolution of the ocean model can be modeled by adding a random turbulent component to the velocity fields of the model. This has not been considered here. The float time stepping is performed using a 4^{th} order Runga-Kutta scheme. Figure 2.2 shows an example of tracked virtual particles. In the Kuroshio Extension, particles move fast (long recent tracks), whereas outside the Kuroshio extension particles may be virtually at rest (single points in plots rather than tracks).

2.4 HYSPLIT

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model is a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations (Draxler and Hess, 1998; Draxler, 2007). It includes modules for chemical transformations and computes the advection of a single pollutant particle, or simply its trajectory. The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. In the particle model, a fixed number of particles are advected through the model domain by the mean wind field and spread by a turbulent component. The model's default configuration assumes a 3-dimensional particle distribution (horizontal and vertical).

HYSPLIT computations track 20 different isotopes. Here, only the three most abundant Iodine and Cesium isotopes (^{131}I, ^{134}Cs, and ^{137}Cs) are considered. These isotopes have half lives of 8 days, 2 years and 30 years, respectively. The computational techniques for ocean contamination used here, together with the particle archives maintained, make it relatively easy to provide similar products for the other 17 isotopes in HYSPLIT at a later time.

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3 Model input

3.1 RTOFS-Global (HYCOM)

As described in the previous section, RTOFS-Global system was initially deployed at NCEP Central Operations (NCO) as an experimental forecast system, and is now a fully operational system. It is run daily to produce a 2 day analysis and a eight day long forecast. Results include three dimensional global fields for Temperature, Salinity, Velocity components and Sea Surface Height. Atmospheric forcings from GFS/GDAS (GFS, Moorthi et al., 2001) are used to produce these forecasts with the ocean surface relaxed to Sea Surface Salinity from Polar science center Hydrographic Climatology (PHC) climatology.

3.2 Particle tracking

The particle tracking model requires two types of input. One represents the physical state of the ocean, the other is a seeding scheme for particles,

Surface (top layer) velocity components in the North Pacific from from RTOFS-Global as described above have been used as input for the particle tracking model.

Several particle seeding schemes were used for this study. All particles were seeded daily, and followed for a length of time up to 170 days from the initial event. The following seeding schemes have been used.

1) High resolution grid near Japan: particles with daily initial positions in a fixed 1/8° regular Mercator grid covering a region off the coast of Japan, centered at 37.25° N, and extending 2.5° in latitude and longitude. This grid was initially used to represent both coastal runoff and ocean deposits relatively close to FDNPP.

2) Low resolution grid: particles with daily initial positions in a fixed 1° Mercator grid covering the region 130°E - 160°E, 20°N - 45°N. This grid was used initially to assess large scale ocean surface flow patterns and speeds, covering areas with the main atmospheric deposits.

3) Dynamic seeding, intermediate resolution: Regular 1/4° grid, particles deployed daily at locations where according to HYSPLIT atmospheric tracer model, radiative deposition was larger than 1000 B/m^2. Two versions of the HYSPLIT load were followed as particles were seeded daily where activity is larger than the chosen threshold.

Results from these schemes are presented in Section 5. Note that all seeding was stopped after April 26, as no significant new contamination is believed to have been deposited in the ocean after this date. This implies that the approach presented here does not account for groundwater contamination sources as reported in the summer of 2013, nor does it deal with deposited and re-suspended material in the coastal areas around FDNPP.

3.3 HYSPLIT

For HYSPLIT, three different inputs for surface deposits of ^{137}Cs, ^{134}Cs, and ^{131}I radionuclides are used from three independent runs of HYSPLIT. These data sets were based on source information from three different sources: namely NRC (US Nuclear Regulatory Commission), DOE (US Department of Energy) and NSC (Japan's Nuclear Safety Commission). Henceforth, these will be referred to as case NRC (Nuclear Regulatory Commission), case DOE (Department of Energy) and case NSC (Nuclear Safety Commission) receptively.

At present, the emission estimates from the case NSC are believed to the best, based upon model air concentration predictions compared with the US EPA (Environmental Protection Agency) monitoring data. For this case, the in-cloud wet deposition removal rate was reduced based on comparisons with atmospheric measurements, resulting in more deposition further downwind. The simulation duration is longer: 12 March through 20 April, with emissions ending a few days prior. At the end of the simulation period, all of the ^{137}Cs (10 pBq) was deposited (of which 6 pBq went into the ocean) and two-thirds of the total ^{131}I (100 pBq) was deposited. Unfortunately, this version of HYSPLIT was made available at a much later time and could not be used for particle tracking. The other two versions of HYSPLIT deposits for ^{137}Cs, ^{134}Cs, and ^{131}I considered in the following sections are sources for the (dynamically seeded) ocean particle models. Note that the third scenario is used in the more recent modeling effort outlined in Garaffo et al. (2013).

For each of these cases, HYSPLIT was run for a certain time period starting at 0000 UTC 12 March, 2011. Emissions were specified for 20 radio-nuclides, released at a continuous rate starting at 0600 UTC 12 March as per the source information for the three cases. Although there is a temporal variation in the emissions, this level of detail was not included. The calculation used the 1/2 ° resolution global GFS model with an integration time step of 15 min. A total of 170 tracer particles were released each hour, with each particle containing the appropriate mass of each radio-nuclide. The calculation included decay, dry, and wet deposition. Air concentration and deposition was computed on a 0.25 ° resolution grid as 24 h averages for concentration and 24 h totals for deposition. Particles were followed for 120 h (5 days) and then deleted from the calculation. Approximately 80,000 particles are on the computational domain at any one time. The GFS/GDAS precipitation rates used for wet depositions were also verified against the precipitation rates from satellite analysis.

4 Model uncertainties

The models used in this study are components of operational (or pre-operational) forecast systems. There are a set of uncertainties which are generic in nature and apply to all such operational or research prediction systems.These are described below.

4.1 Numerical Errors

Operational forecast systems are built around a core which consists of a numerical engine (model). This numerical engine has been designed to interpret an analog environment with the use of discretization methods. Since these methods are applied to finite length grids and finite time intervals, they suffer from numerical rounding and truncation errors. These errors are based on the properties of the selected numerical scheme and tend to produce model drift and both spatial and temporal aliasing. For example, a grid size of approximately 9 km can only resolve a feature which is at least covered by 5 grid points or 36 km. In this context,

Reducing the size of these grids will result in smaller numerical errors but at the cost of greater computational costs in time and available resources (CPU, storage). Given that a limited time window exists for providing operational products with the use of available computational resources, the computational efficiency of any such forecast forecast system has to be optimized within these constraints.

RTOFS-Global is considered to be 'eddy-resolving' in the deep ocean, meaning that it has sufficient resolution to resolve dominant oceanic mesoscale features. However, on the coast and the continental shelves, such features may have scales of the order of 1 km or less, which are not properly resolved by RTOFS-Global. Hence, higher resolution ocean model are needed to address dispersion of pollution near the FDNPP, as discussed in Section 1.

Similarly, GFS and HYSPLIT have resolutions tailored to large-scale or global forecast problems. Mesoscale feature of the atmosphere are generally resolved, particularly over the ocean. However, small scale weather features associated with orography are not well resolved.

With this in mind, the modeling system used here is suitable for assessing ocean contamination from the atmosphere over large spatial scales in the North Pacific Ocean, but is less suitable for modeling dispersion of contaminants due to coastal releases at FDNPP, as discussed in Section 1.

An additional type of numerical error is introduced when model results are saved at given spacial and temporal resolution for later processing. This is the case for the particle tracking performed here. Whereas the ocean model results are save on the native spatial resolution, they are only available every 3 hours for the top layer, and every 6 hours for the entire volume. This requires interpolation to times in between, which generates some additional uncertainty in the computed particle tracks.

4.2 Modeling Assumptions

The discretization methods used by forecast methods apply parameterizations to help account for dynamical processes which are not resolved by the chosen grid size and time steps for integration. These are either sub-grid scale processes which are approximated using "bulk" formulations or assumptions which help simplify the formulations using semi-empirical relationships to represent complex or non-linear dynamics. Moreover, any mathematical model always is an approximation of nature, and hence will have implicit limitations. Such limitations can only be addressed by calibration and validation of such models. The models used here have extensively been validated for the application scales applied here, and can be considered state-of-the-art in their respective fields.

4.3 Observations and data assimilation

The weather and ocean models used here (GFS, HYCOM) describe initial value problems with a chaotic nature. This implies that good forecast guidance critically depend on an accurate assessment of the present state of the atmosphere and ocean, and that the accuracy of the forecast naturally deteriorates with forecasts time due to errors in our understanding of the present, and due to the inherent chaotic behavior of the problem.

At the center of such forecast problems is the data assimilation model used to provide estimates of initial conditions for the models. This is by itself a complex mathematical task which introduce errors as described for the models in the previous section. More complex assimilation methods are also more accurate but computationally expensive. Uncertainties introduced in such problems are generally captured in ensemble approaches, where a combination of different initial states and numerical models is used to estimate the uncertainty in the model results.

For the atmosphere these methods are generally mature and well developed, with an enormous amount of in-situ and remotely sensed data. Whereas different state-of-the-art forecasts systems typically show increased differences with forecast time, the present study is mainly depending on analysis and short term forecasts. For these, the atmospheric state is generally well know at the scales considered here. Whereas atmospheric forecasts by no means are perfect, uncertainties in the analyses and short term forecasts are small compared to many other uncertainties identified for this study

For ocean modeling, the same issues exist as with the atmosphere. However, methods are generally less mature, and ocean data is much more sparse than atmospheric data. In fact, the case can be made that there is insufficient ocean data available to fully constrain the ocean state in the models. This could be observed when comparing ocean conditions around Japan from various state-of-the-art systems. All systems show similar general ocean current patterns, but with clear differences in details. For instance, US Navy, NOAA and the European Mercator models all showed an eddy off Sendai, but with large differences in intensities between models. Also, some of the initial high-resolution Japanese models showed the Kuroshio Extension a little more to the North (closer to the FDNPP) than most other model. This implies that the ocean models provide good to excellent qualitative guidance, but that care has to be taken to using and interpreting details (quantitative) aspects of the guidance.

The plume modeling presents an amalgamation of the ocean and weather forecasts, particularly if the contamination reaches the ocean through the atmosphere. Three additional uncertainties / errors occur here.

First, as the contamination in the atmosphere or from coastal releases essentially comes from a point source, and as the weather and ocean models used here have insufficient resolution to resolve air and water flow close to the FDNPP, initial dispersion errors are unavoidable.

Second, and more important, enormous uncertainties exists in the quantity of material that is released, particularly shortly after the accident (see Section 3.3). The latter errors are expected to dominate the quantitative errors in the plume modeling, and may even influence dispersion patterns discussed in the following sections.

Third, there are virtually no observations for radioactive contamination that can be used for the development, calibration and validation of the plume models. As these model have inherent uncertainties, great care has to be taken with the use and interpretation of effectively unvalidated models.

4.4 Summary

Numerical modeling by definition includes a wide range of uncertainties as has been identified in the previous Sections. In the present context, errors and uncertainties of three major efforts can be identified; those of weather models, ocean models and ocean plume models.

Like all modeling efforts, weather models have errors and uncertainties. In the present context, however, weather analysis and forecast errors are small compared to the errors in the other two main models.

The ocean models are detailed as weather models are, but are limited in their accuracy mostly due to a lack of observational data to constrain the models. This implies that the ocean model results should be considered more qualitative than quantitative, and that obtaining real-time directed observations of the physical ocean state can greatly improve the accuracy of ocean models where needed most. Unfortunately, only a few additional observations have been made near the FDNPP.

Large uncertainties occur in the modeling of the ocean plume. These uncertainties are mostly driven by uncertainty in the source of contamination. These uncertainties justify the simple (rapid response and scenario driven) plume modeling techniques used here. Plume modeling is particularly limited due to the almost complete lack of validation data for plume models (see following sections). In this context, it is more reasonable to produce limiting (upper and lower bound) contamination estimates, than a best-guess deterministic or probabilistic products. As outlined in Section 3.3, the two source scenarios used here fortunately can be considered as two bounding cases.

5 Results

5.1 Product evolution time line

As mentioned in the introduction of this report, the modeling work presented here was mostly performed to provide actionable information to the US Government through an Interagency Working Group. Providing such information in near real time and as soon as possible after the event represents a different challenge than a conventional scientific modeling exercise. In this semi-operational context, the development of a formal Concept Of Operations (CONOPS) is essential to balance information contents, accuracy and speed of delivery of products. A draft CONOPS was developed at the onset of this project, and naturally is a living document. A frozen version of this CONOPS from April 15 is retained to document the historical evolution of products, and is reproduced here in Appendix B.

At the onset of the event, it was decided that development of advisory ocean forecast products was to proceed even though there was no initial actionable information on ocean or atmospheric radionuclide composition or release rates. This decision initially resulted in the evolution of a two-phase program. The first phase was ocean model forecasting of an idealized plume of material released to he water in and around the FNPP area. The second phase began once numerical estimates of atmospheric wet deposition of radionuclides on the ocean surface began to arrive, and focused on radionuclide release from the atmosphere to the ocean.

As the event progressed, limited geospatial information derived from ocean measurements at selected ocean stations near the FDNPP site were received from Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Tokyo Electric Power Company (TEPCO). These were used as "ground truthing" guidance on the modeled plume time-dependent estimates of radionuclide activity. These data were not part of the input data for the forecast products.

Two separate unverifiable model data sets of atmospheric wet deposition radionuclide deposition fluxes were received within a few weeks of the event (see Section 3.3) and were used in the production of initial plume forecast products. A third verifiable data set was received near the end of the event (see Section 3.3) and was used in the development of ocean tracer forecast products, but not for the particle-density based plume estimates. Note that this third set of products is mentioned in the CONOPS (Appendix B), but will be presented elsewhere (Garaffo et al., 2013).

5.2 Methodology

The Fukushima plume event modeling response was a combination of straightforward application of existing forecasting tools and an evolutionary process that leveraged the existing tools and incorporated additional data and modeling methods to create new prognostic tools. The twin driving principles were that (1) it had to be flexibly designed to respond to rapidly shifting requirements, and (2) the computational requirements must not be too large as frequent re-running of the process was expected.

5.2.1 Plume Modeling from Particle Tracks

The first step in forecasting the Fukushima plume was to engage the HYCOM Lagrangian particle tracking capability. This was first developed by the HYCOM Consortium at the University of Miami's Rosenstiel School of Marine and Atmospheric Science and used in applications such as predicting the drift and trajectories of rafts in search and rescue operations as well as oil spill and pollution plume tracking programs.

The model grid was seeded with a number of particle positions, and over the course of the run the positions were re-seeded with new particles, thus gradually increasing the total number of particles. The re-seeding simulated continued contamination releases from the incident site into the particle release area and allowed us to simulate a plume formed over a period of time instead of a simple static release. The starting positions of the particles were initially constrained to a grid box located just offshore from the FDNPP (see Fig. 5.1 on page 23). The first goal of the project was to model the plume of contaminated water released into the ocean at the reactor site, and the initial particle seeding points were selected with that in mind.

The model tracked the individual particles in time and the first analysis package aggregated the thousands of particle tracks into hourly and daily estimates of the extant and concentration of the dispersion plume. Two approaches were used: particle density estimation and particle activity estimation. Central to the design of the analysis system was the need for fast data processing. Brute force methods of geo-locating, binning and regridding the data were discarded in favor of more efficient algorithms. The resulting reduction in processing time gave us the flexibility to run the analyses repeatedly as the model track data was refined and external data sets were updated.

5.2.2 Particle Density Estimation (Tracks to Plume)

Particle density estimation of a plume of water is, at its core, just a time-dependent two-dimensional histogram of particle locations on the model grid. We followed a two-step process of aggregation and binning. Aggregation reconciled the multiple particle track data files into a single time-consistent data structure. Three structures were created corresponding to the seeding method employed by the particle tracking initialization: low-resolution wide area, high-resolution centered just offshore of the incident location, and dynamic seeding which followed the general shape of the atmospheric plume determined from the HYSPLIT data. Detection and editing of anomalous track data was also performed at this time, mostly for occasional particle “jumps” of several degrees in a single time interval.

Additionally, the high-resolution particle seeding was grouped into four categories according to each particle’s initial radial distance from the reactor location.

Next, for each diurnal or semi-diurnal time realization, all particles available at that time were located on a reduced model grid of 0.125^o resolution using a fast binning method (FFNDGrid) by Oyvind Breivik and Per Brodtkorb, obtained from the MathWorks^{tm} Community File Exchange.

The resulting 2-dimensional grid was then interpolated back to the RTOFS Global $1/12^o$ grid and a light smoothing applied using the graphics toolkit.

As the event proceeded, the decision was made to concentrate on processing only the high-resolution seeding particle set.

5.2.3 Particle Plume Activity Estimation (Tracks to Radionuclide Concentrations

As the event progressed questions were raised about the radionuclide composition of the plume and what types of isotopic plume estimates could be created from the plume density studies. NCEP/MMAB requested and received two HYSPLIT atmospheric model-based data sets that gave the spatio-temporally dependent surface deposition rates of a number of radioisotopes of interest. From the list three were selected for analysis: ^{134}Cs, ^{137}Cs, and ^{131}I. The goal of the study was to couple the HYSPLIT surface deposition data with HYCOM particle track data as an initial condition, and then to use the particle trajectory data with radioactive decay coefficients to estimate the time and spatially dependent isotopic concentrations of nuclear decay. The accepted unit of nuclear decay concentration is given as Becquerels per liter or Becquerels per cubic meter (Bq/l or Bq/m^3) where a Becquerel is one nuclear decay per second.

Initially, a low-resolution and a high-resolution particle seeding domains from the water plume tracking effort were used. The plume density analysis was designed to track a plume of water released from the proximity of the plant and was not expected to be particularly accurate in estimating a plume created by an atmospheric plume of gases released by the plant, but it gave us the opportunity to prototype the software needed to incorporate the three different data streams. Two improved (dynamic) particle seeding schemes were implemented: the first used an early estimate of the aggregate atmospheric plume extant based on the Department of Energy HYSPLIT data (DOE-HYSPLIT), the second used an improved atmospheric plume estimate based on Nuclear Regulatory Council HYSPLIT data (NRC-HYSPLIT). A third version of HYSPLIT (NSC-HYSPLIT) that was made available at a later time was not used for particle tracking Detection and editing of anomalous track data was also performed at this time, mostly for occasional particle “jumps” of several degrees in a single time interval.

Next, for both of the HYSPLIT isotopic deposition data sets, the particles were initialized with time and spatially dependent estimates of the radionuclide concentration matched to the RTOFS grid. As the deposition was given in terms of surface flux values, the concentration was estimated by incorporating the RTOFS Global mixed layer depth values and assuming that any isotope that came into contact with the surface of the ocean would quickly dissolve and be instantaneously distributed throughout the mixed layer depth. Horizontal mixing of the particles was not rigorously accounted for, instead it was assumed that the chemical concentration of the isotopic burden at the particle location would not interact with other particles’ migrations. As a crude proxy of mixing and entrainment, the mixed layer depth scaling was only allowed to reduce a particle’s isotopic value, never increase it.

The particle tracks as well as the HYSPLIT time and space data match-up used a KD-Tree Nearest Neighbor search algorithm to rapidly align the atmospheric and oceanic locations of the two data sets. The KD-Tree routines by Steven Michael were obtained from the MathWorks^{tm} Community File Exchange.

Once the time and spatially aligned data structures were completed, each particles’ isotopic concentration was computed using the half-life value as

$$N(t) = N(0)e^{(\frac{log(2)t}{t_{1/2}})}$$

where N is the concentration and $t_{1/2}$ is the half-life value of the radioisotope.

The resulting time series of isotopic concentrations scaled with mixed layer depth was smoothed with a double-passed 7-point moving average (boxcar) filter to remove high-frequency noise, mostly due to rapid fluctuations in the mixed layer depth values.

The 2-dimensional spatial histogram of activity was then determined as in the plume density case by using the FFNDGrid tool on a reduced resolution model grid. Graphics were loaded into a JavaScript image viewer, with separate views for each isotope of interest, and three different spatial domains in the North Pacific area, including close-up images of region around the sampling stations set up by MEXT.

5.3 Seeding Strategies and associated products

Two principal particle seeding strategies were employed during the event, static (idealized) and dynamic (temporal-spatially dependent seeding based on atmospheric plume estimates). Static seeding was used for both simple (non-isotopic) plume diffusion analysis as well early attempts at isotopic plume activity studies.

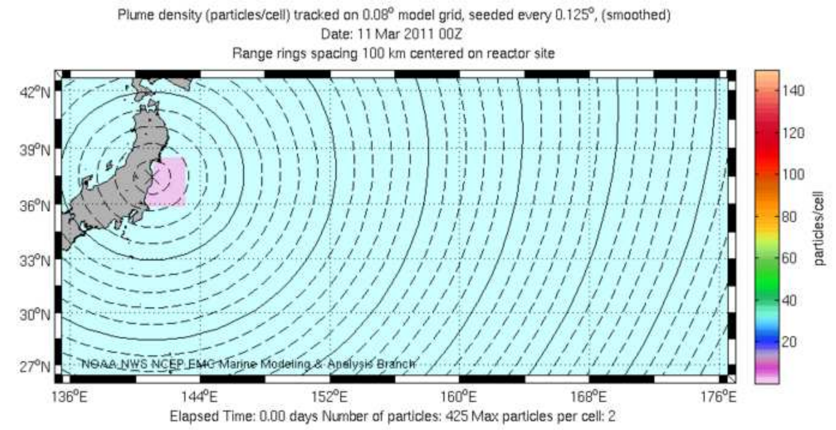


Fig. 5.1 : Initial high-resolution static seeding locations

5.3.1 Static (idealized) seeding in and around FNPP

Two domains were selected for static seeding, a $1/4^o$ low-resolution grid $140 - 162^oE \times 34 - 44^oN$, and a $1/8^o$ high-resolution grid $140.8 - 143.0^oE \times 36 - 38.4^oN$. Fig. 5.1 and Fig. 5.2 map the two seeding domains.

The intent of the static seeding was to capture the Lagrangian dispersion of the ocean current flows in the vicinity of the FNPP site (high-resolution seeding), and in on a North-West Pacific basin scale (low-resolution seeding). Fig 5.3 shows a snapshot of the Kuroshio Current as it separates from the nearshore east of Japan and moves out into the North Pacific. Note the profusion of rings and eddy activity in and around the main jet of the current. It was important that these major flow characteristics of the current system were captured by the seeding strategy in order for the plume dispersion to be accurately modeled.

Balancing the need for resolving the major current features, entrainment, and overall eddy activity was the additional computational cost of tracking the very large number of particles injected into the model grid over the course of the analysis period. In this sense the competing design parameters of the seeding strategies were to cover as much area with as many particles as possible without overloading the computer resources available. The high and low resolution seeds were seen as an attempt at bracketing the range of potential seedings, High resolution and small initial domain, or low resolution and large initial domain. Although the low resolution domain covered a much larger area, the resolution was barely able to capture even the gross features of the Kuroshio. Thus it was

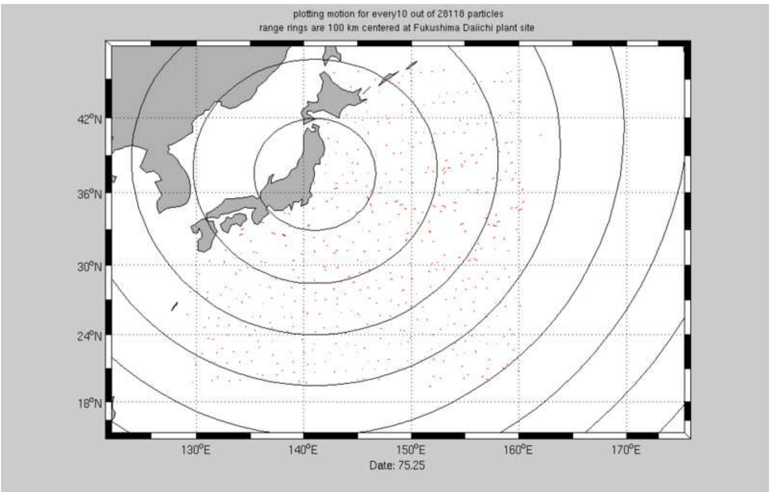


Fig. 5.2 : Initial low-resolution static seeding locations

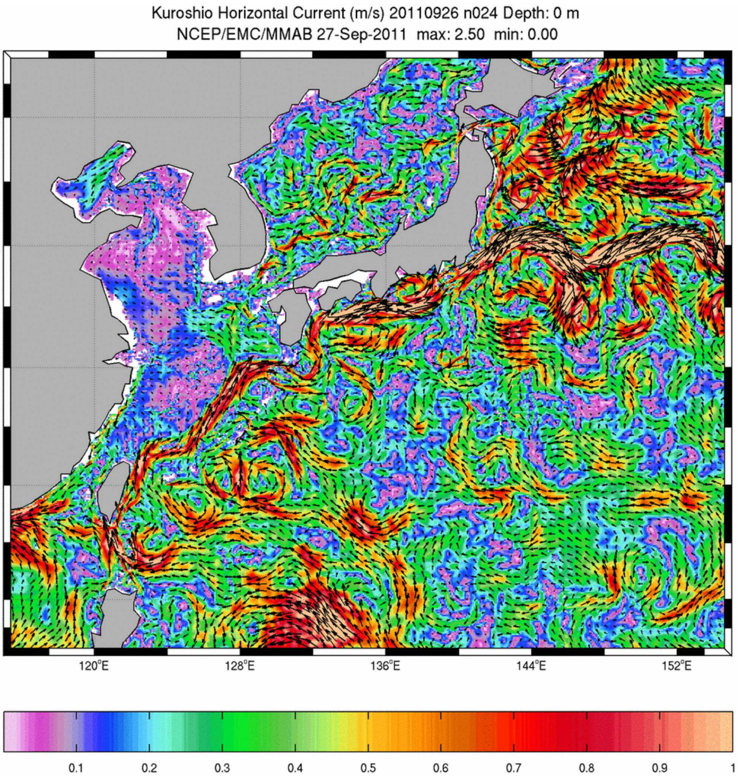


Fig. 5.3 : Global HYCOM representation of the Kuroshio Current at the surface

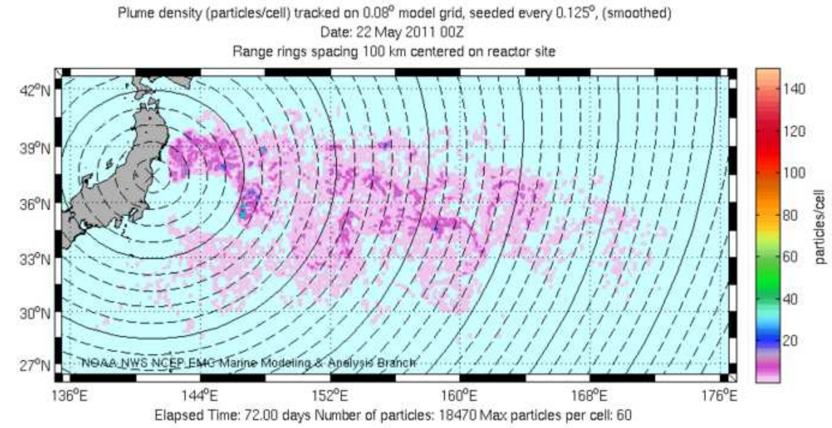


Fig. 5.4 : High-resolution particle plume after 72 days. Note that now new particles have been seeded after April 26, 2011

decided to concentrate our efforts on the high resolution strategy for the plume dispersion analysis. The low resolution seed was used for the initial plume activity study prior to the implementation of the dynamic seeding.

Fig. 5.4 shows the full particle plume from the high resolution seeding strategy after 72 days (May 22, 2011) from a seeding of 18,420 particles starting on 11 March 2011 and ending on April 26, 2011. The particle locations were analyzed at 3 hour intervals.

Concentrating on the high-resolution seeding strategy, an attempt was made at isolating the various parts of the plume. The rationale was that lacking any information on the amount of contamination entering the ocean, we would assume that the concentrations of contaminants would drop rapidly as a function of distance from the reactor site. Preliminary assessments of the water-borne activity levels measured by emergency personnel of the water flowing out from the plant showed a drop in radioactivity concentrations of several orders of magnitude over very short (in terms of several meters) length scales.

In order to crudely assess the drop-off in concentrations at the initial seeding locations and to compute the resulting extent of the dispersion of those portions of the plume, the high-resolution grid was further subdivided into 5 subgroups depending on the radial distance from the FNPP site: 0-25 km, 25-50 km, 50-100 km, 100-200 km, and greater than 200 km. Each group was individually analyzed in an early effort to gage the relative dispersion of reactor contamination as a function of release distance from the plant.

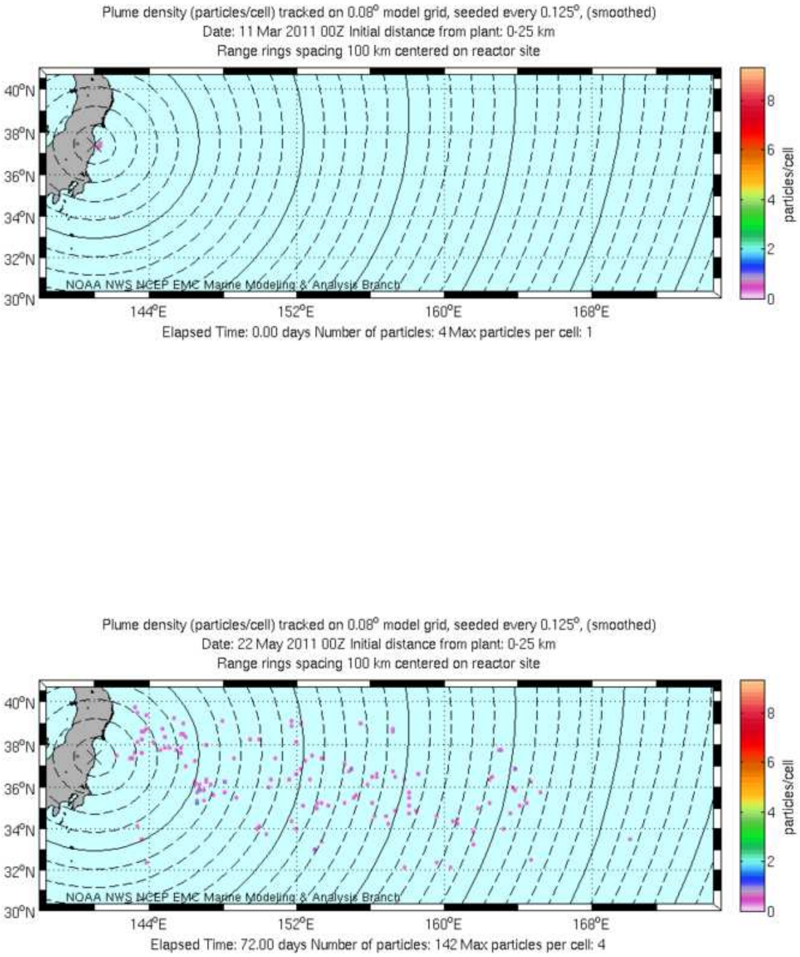


Fig. 5.5 : Group 1 (0-25 km) plume initial position and after 72 days

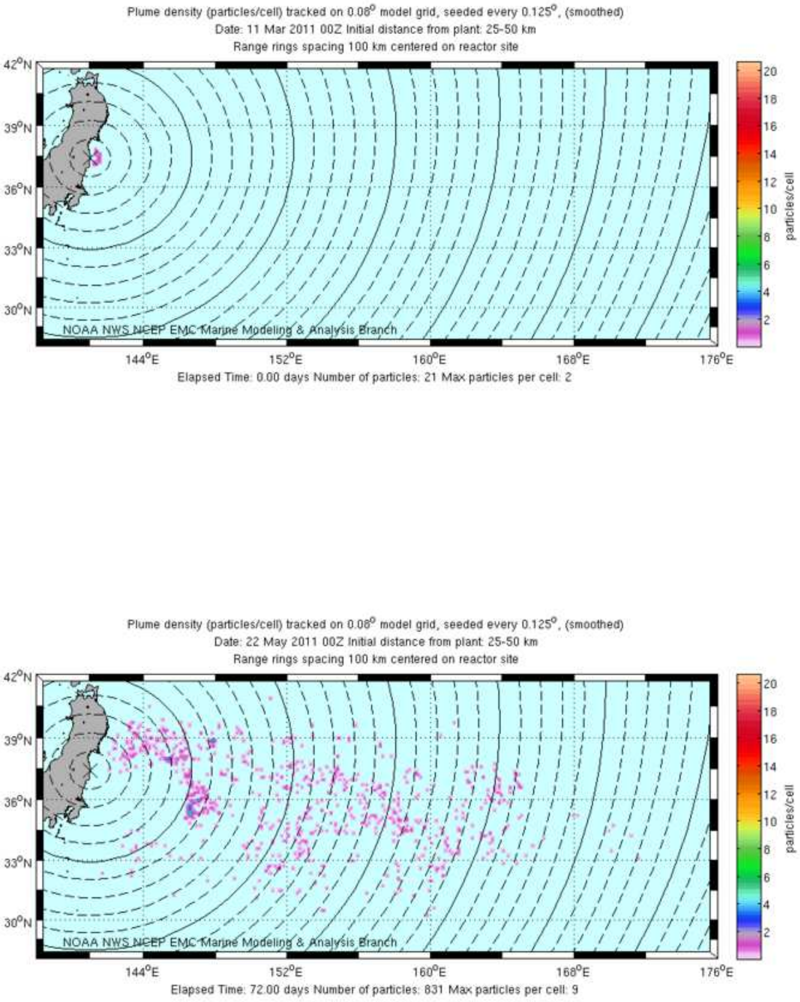


Fig. 5.6 : Group 2 (25-50 km) plume initial position and after 72 days

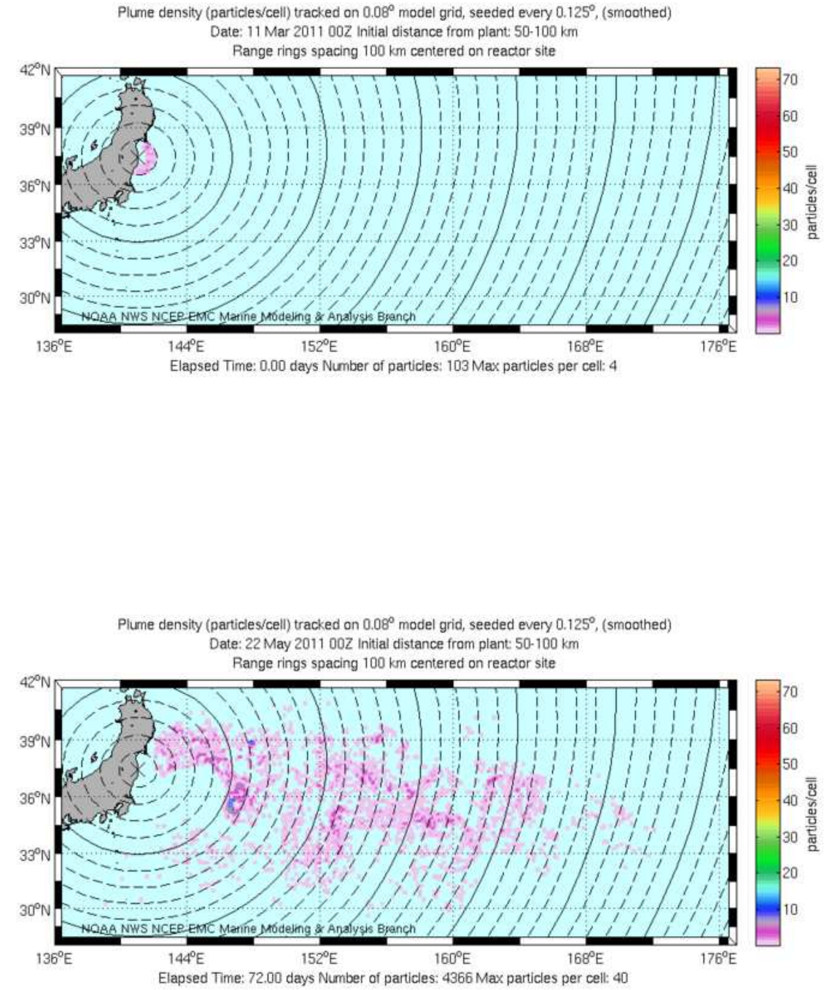


Fig. 5.7 : Group 3 (50-100 km) plume initial position and after 72 days

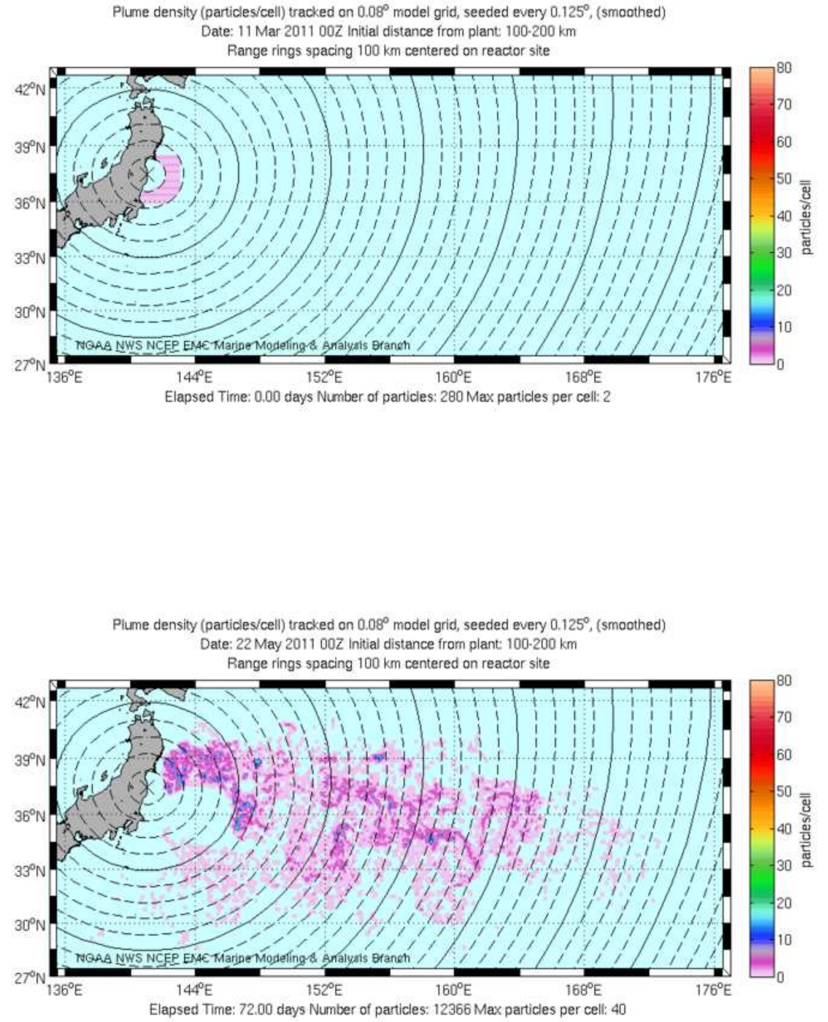


Fig. 5.8 : Group 4 (100-200 km) plume initial position and after 72 days

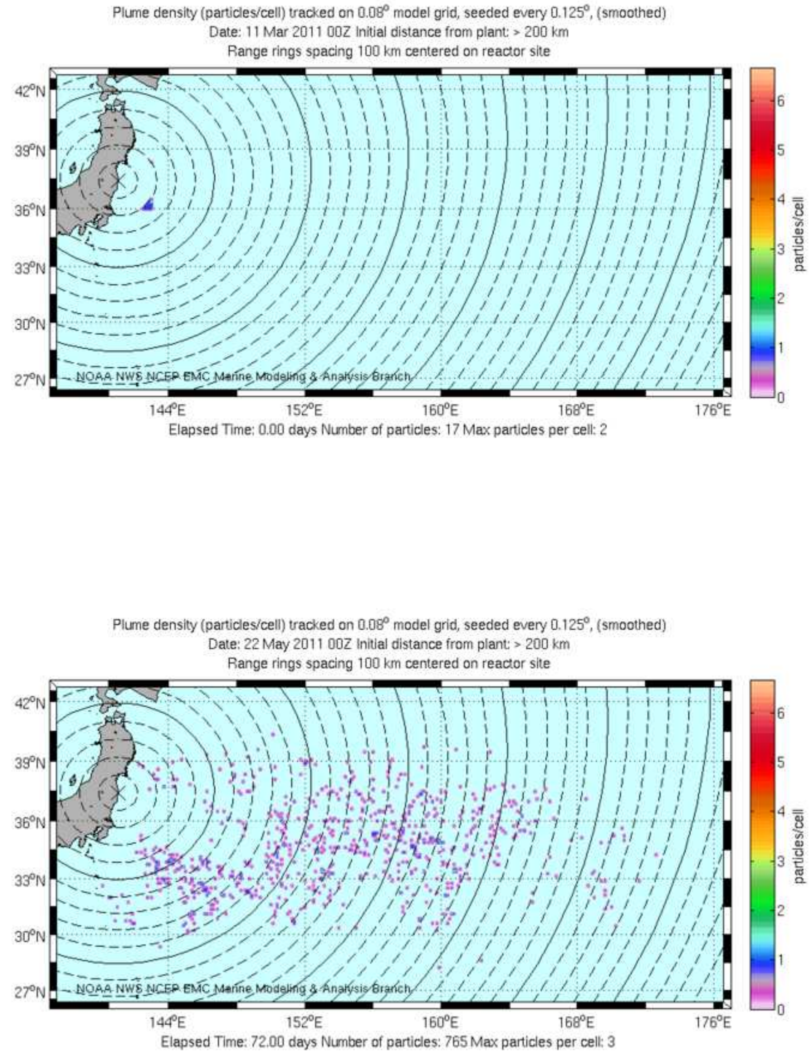


Fig. 5.9 : Group 5 (> 200 km) plume initial position and after 72 days

Figs 5.5 through 5.9 show the initial locations of the sub sampled plumes and the dispersal after 72 days.

5.3.2 Idealized coastal seeding with limited atmospheric wet depositions

Soon after the plume density was underway we received the first set of atmospheric wet deposition model results based on the Nuclear Regulatory Commission release estimates (NRC HYSPLIT-1). Analysis of the data showed that the atmospheric plume from the FNPP site was considerably larger than our initial seeding areas. Rerunning of the model with new seeding positions was expected to take several days to complete. During the interregnum we began work on the analysis system to combine the particle track data with the static plume seeding data. This was not intended to be an accurate modeling of the ocean plume as it was severely misaligned with the atmospheric plume. Nevertheless it did give us an opportunity to test the analysis procedures.

The following maps show the results of low and high-resolution static seeding and the two sets of HYSPLIT atmospheric wet depositions.

The HYSPLIT data was composed of twenty separate radionuclides, each individually tracked in the atmospheric plume. Three isotopes of interest were chosen, ^{134}Cs (half-life 2.1 years), ^{137}Cs (half-life 30.2 years), and ^{131}I (half-life 8 days). The following maps track the initial concentrations of the three radioisotopes in units of Becquerels/liter (Bq/l) and their concentrations after 37 days. Becquerel is an SI unit of radioactivity where 1 Bq = 1 decay/second.

The static seeding was well positioned to try and model the surface activity levels measured at several ocean station locations by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). The analysis was performed for both the low-resolution and high-resolution static seeds. Subsequent to the receipt of the NRC HYSPLIT-1 data set, a second wet deposition atmospheric model data set was received from the Department of Energy (DOE HYSPLIT-2). The plume analysis was repeated with the new data set, and the MEXT time series was also redone. Below is a list of Figures presented on the following pages.

1. Figs. 5.10 through 5.12 (pages 33 through 35) show the upper ocean layer radiation concentrations (Bq/l) obtained from the low-resolution static seed combined with the NRC HYSPLIT-1 data set.

2. Fig. 5.13 shows the ocean surface radioactivity concentration time series based on NRC HYSPLIT-1 atmospheric isotopic data and the RTOFS Global low-resolution static seed, sampled at locations and times to correspond with MEXT station locations and times

3. Figs. 5.14 through 5.16 (pages 37 through 39) show the ocean surface radioactivity concentration (Bq/l) obtained from combining the low-resolution static seed with the NRC HYSPLIT-2 data set.

4. Fig 5.17 (page 40) shows the ocean surface radioactivity concentration time series based on DOE HYSPLIT-2 atmospheric isotopic data and the RTOFS Global low-resolution static seed, sampled at locations and times to correspond with MEXT station locations and times

5. Figs. 5.18 through 5.20 (pages 41 through 43 show the ocean surface radioactivity concentration (Bq/l) from the high-resolution seed combined with the NRC HYSPLIT-1 data sets.

6. Fig. 5.21 (page 44) shows the ocean surface radioactivity concentration time series based on NRC HYSPLIT-1 atmospheric isotopic data and the RTOFS Global high-resolution static seed, sampled at locations and times to correspond with MEXT station locations and times

7. Figs. 5.22 through 5.24 (pages 45 through 47) show the ocean radioactivity concentration (Bq/l) from the high-resolution seed combined with the DOE HYSPLIT-2 data sets.

8. Fig. 5.25 (page 48) shows the ocean surface radioactivity concentration time series based on DOE HYSPLIT-2 atmospheric isotopic data and the RTOFS Global high-resolution static seed, sampled at locations and times to correspond with MEXT station locations and times.

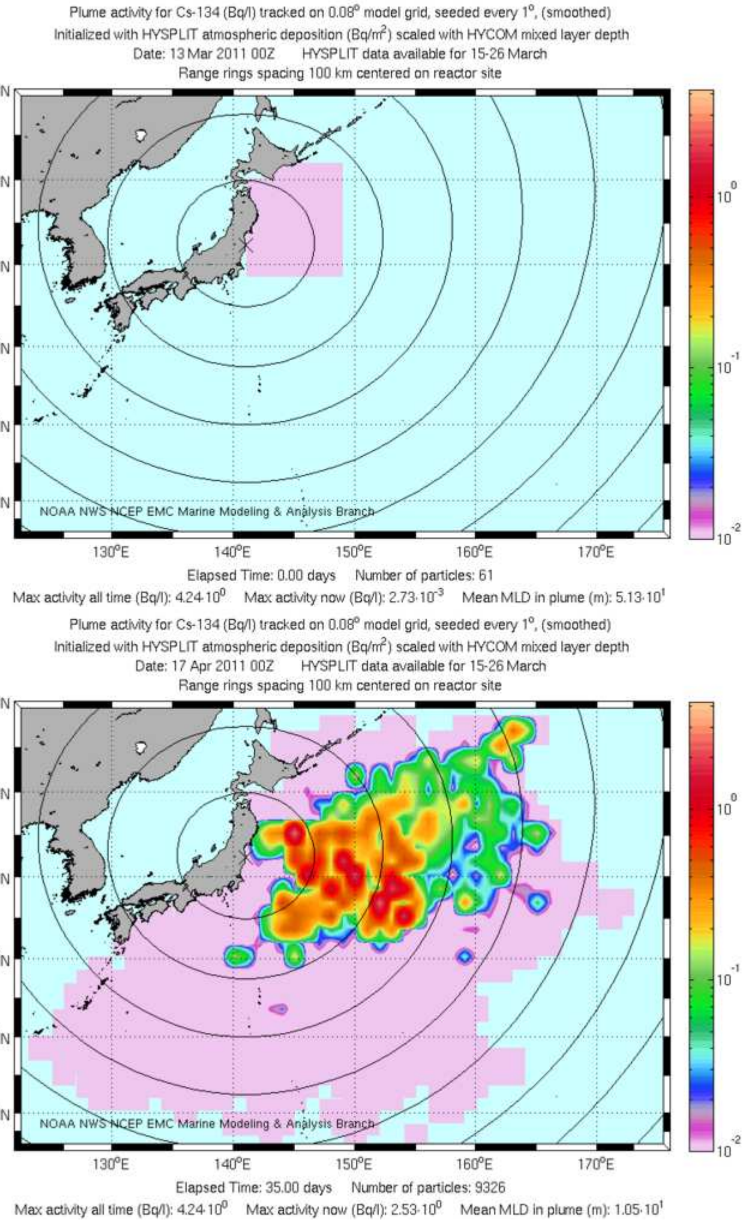


Fig. 5.10 : Low resolution seed, ^{134}Cs, HYSPLIT-1, initial plume and after 37 days.

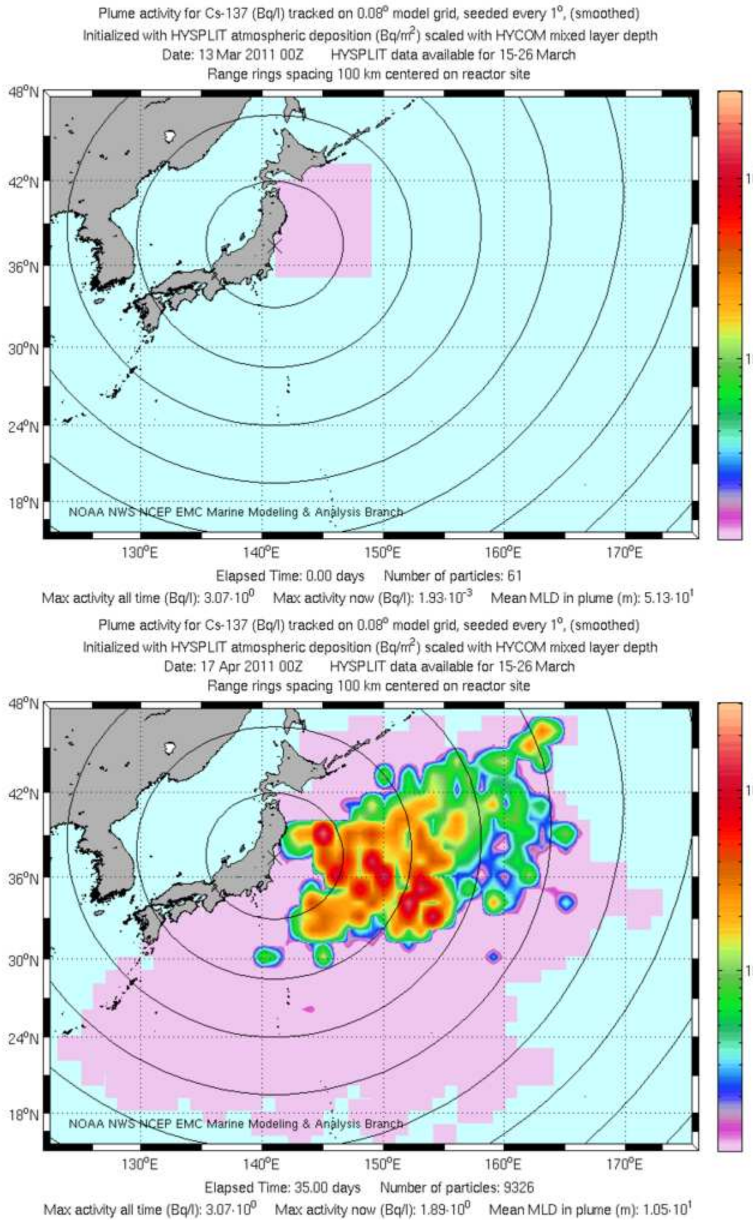


Fig. 5.11 : Low resolution seed, ^{137}Cs, HYSPLIT-1, initial plume and after 37 days.

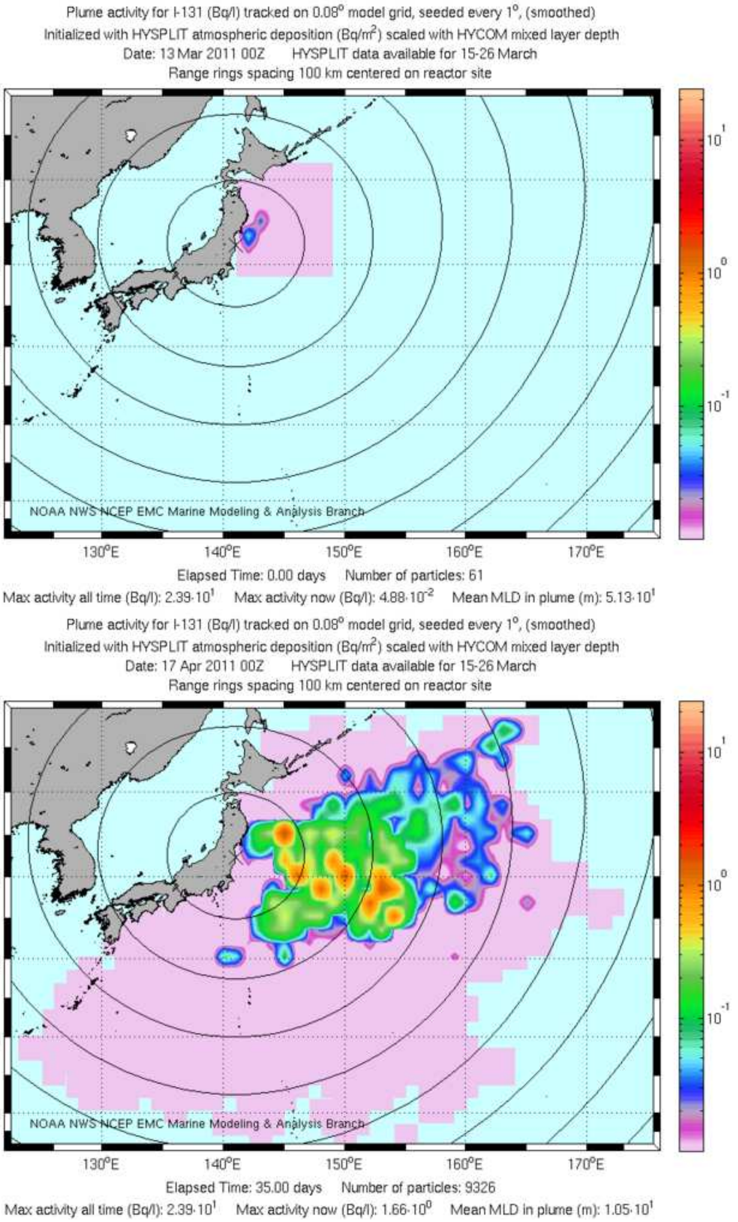


Fig. 5.12 : Low resolution seed, ^{131}I, HYSPLIT-1, initial plume and after 37 days.

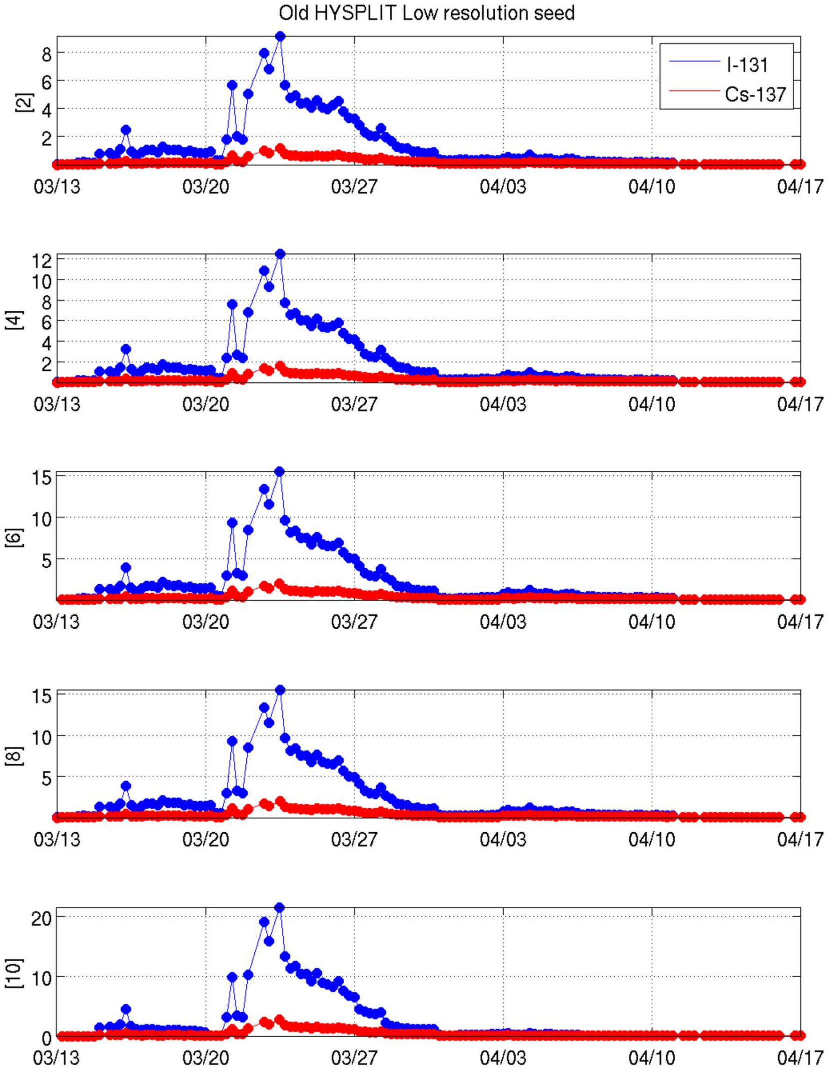


Fig. 5.13 : Low resolution seed, MEXT station time series, even station numbers only.

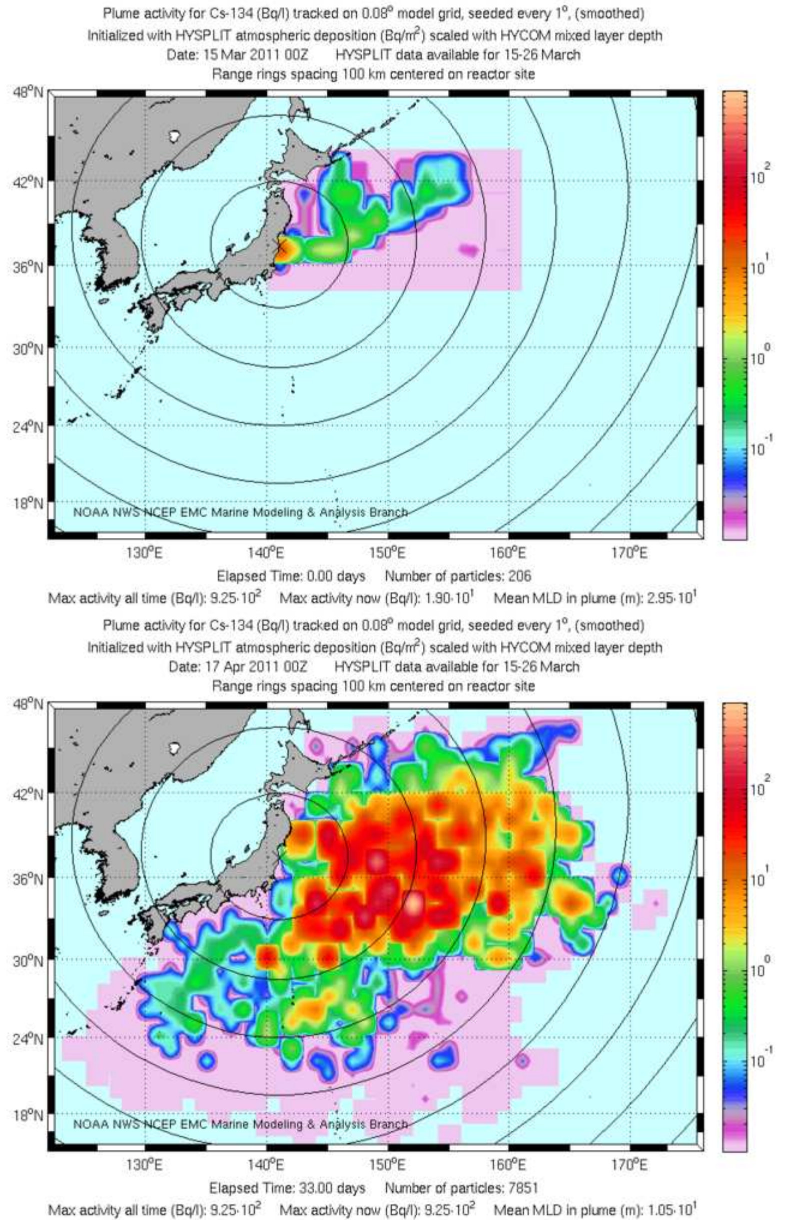


Fig. 5.14 : Low resolution seed, ^{134}Cs, HYSPLIT-2, initial plume and after 37 days.

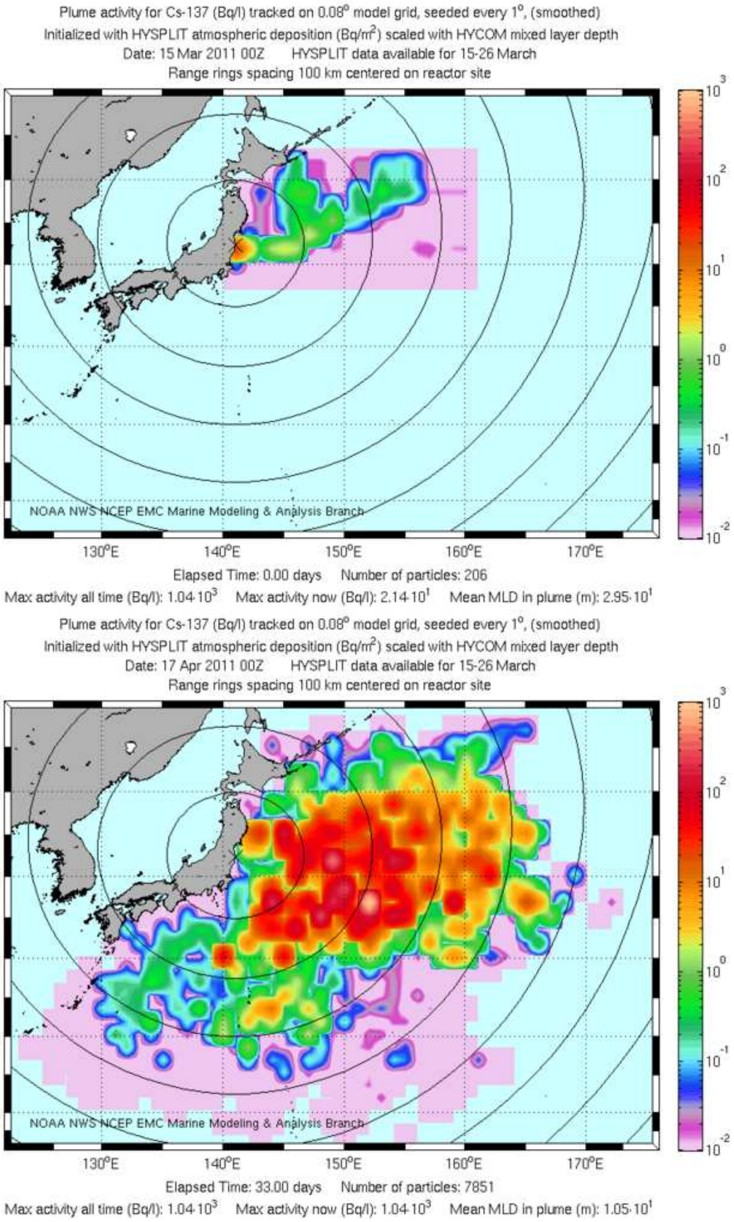
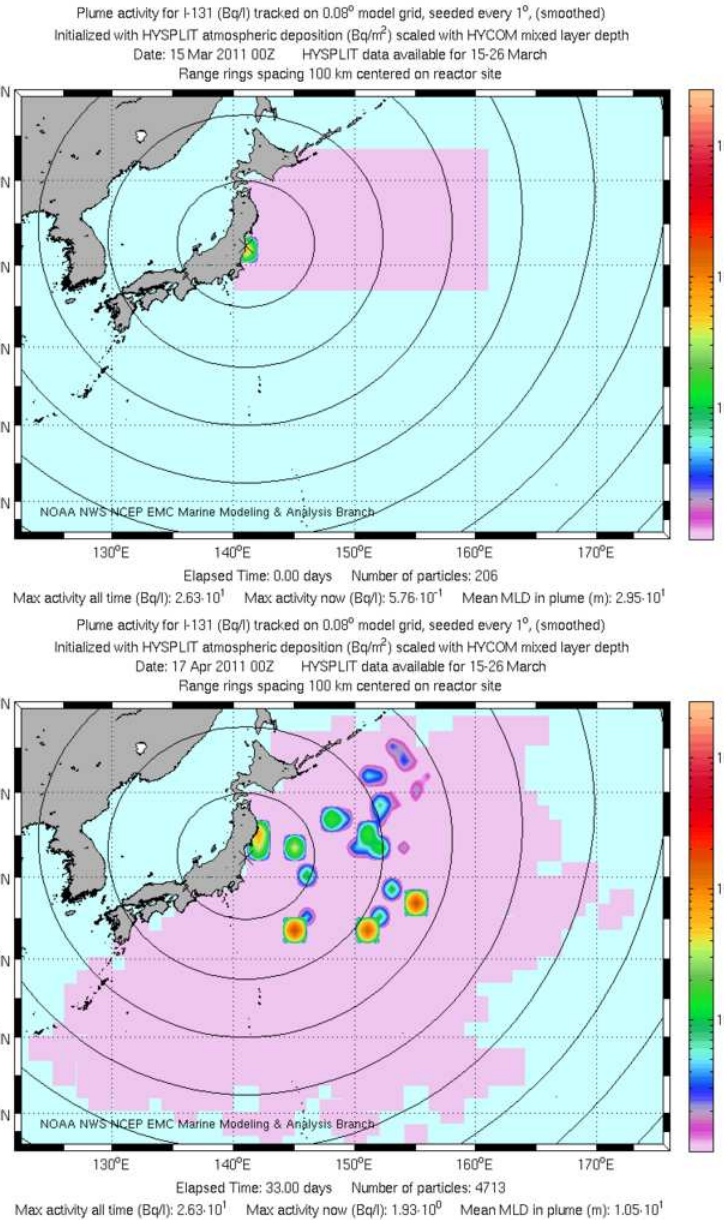


Fig. 5.15 : Low resolution seed, ^{137}Cs, HYSPLIT-2, initial plume and after 37 days.



Plume activity for I-131 (Bq/l) tracked on 0.08° model grid, seeded every 1°, (smoothed)
Initialized with HYSPLIT atmospheric deposition (Bq/m²) scaled with HYCOM mixed layer depth
Date: 15 Mar 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 100 km centered on reactor site

Elapsed Time: 0.00 days Number of particles: 206
Max activity all time (Bq/l): $2.63\cdot10^1$ Max activity now (Bq/l): $5.76\cdot10^{-1}$ Mean MLD in plume (m): $2.95\cdot10^1$

Plume activity for I-131 (Bq/l) tracked on 0.08° model grid, seeded every 1°, (smoothed)
Initialized with HYSPLIT atmospheric deposition (Bq/m²) scaled with HYCOM mixed layer depth
Date: 17 Apr 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 100 km centered on reactor site

Elapsed Time: 33.00 days Number of particles: 4713
Max activity all time (Bq/l): $2.63\cdot10^1$ Max activity now (Bq/l): $1.93\cdot10^0$ Mean MLD in plume (m): $1.05\cdot10^1$

Fig. 5.16 : Low resolution seed, ^{131}I, HYSPLIT-2, initial plume and after 37 days.

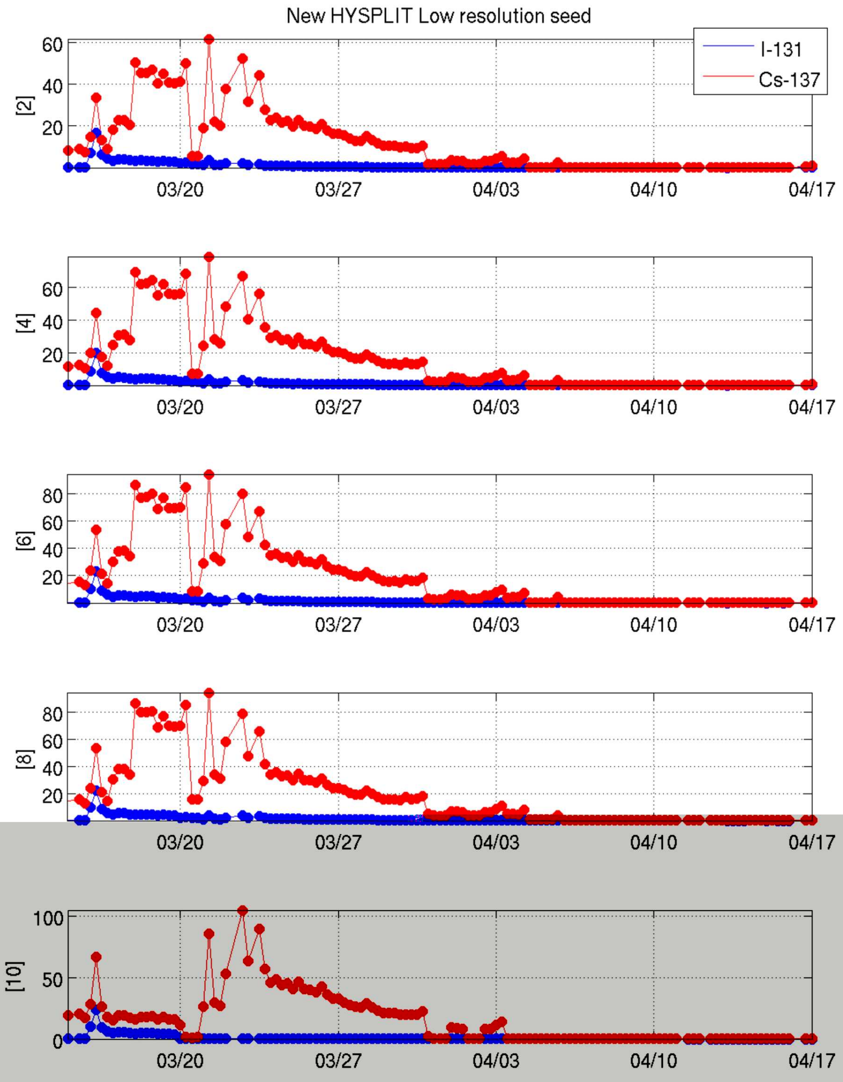


Fig. 5.17 : Low resolution seed, MEXT station time series, even numbered stations only.

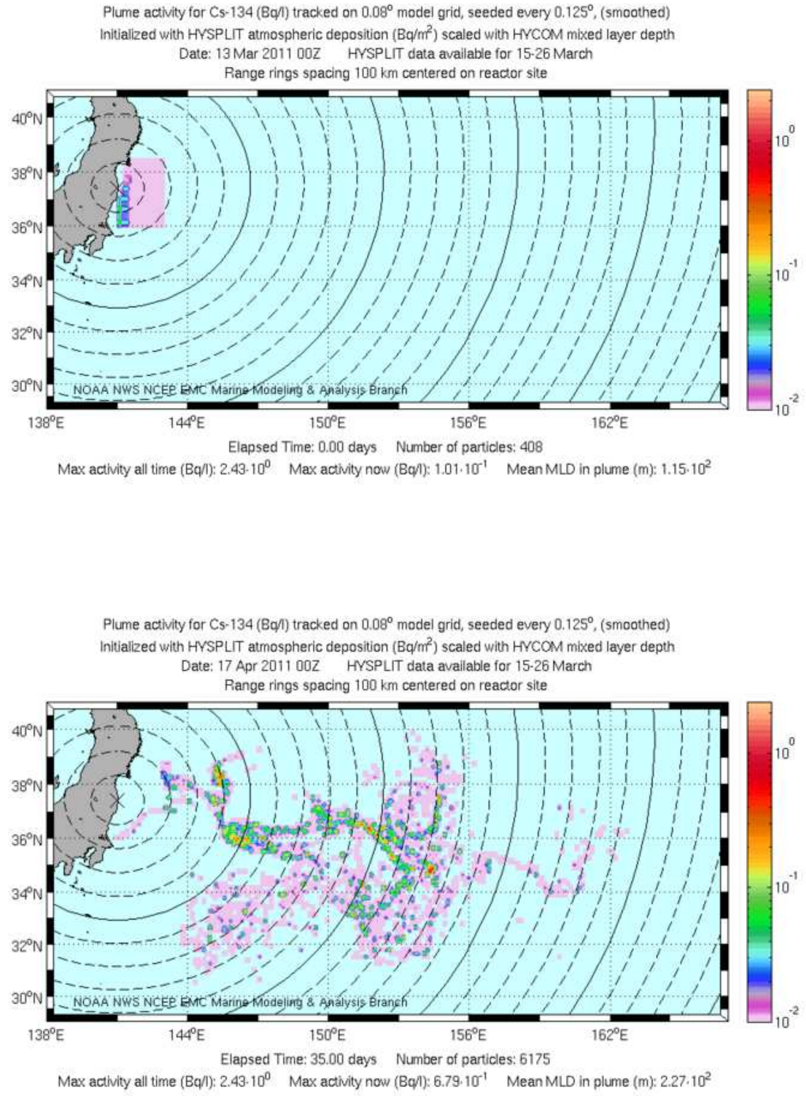


Fig. 5.18 : High resolution seed, ^{134}Cs, HYSPLIT-1, initial plume and after 37 days.

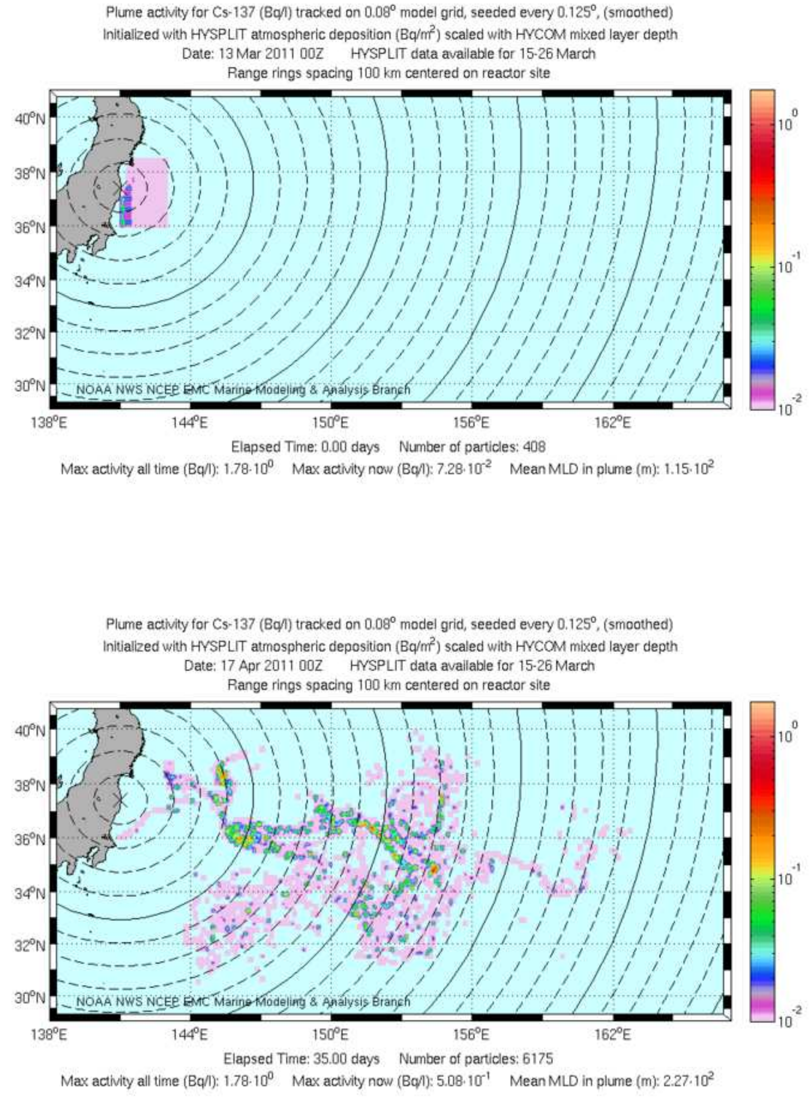


Fig. 5.19 : High resolution seed, ^{137}Cs, HYSPLIT-1, initial plume and after 37 days.

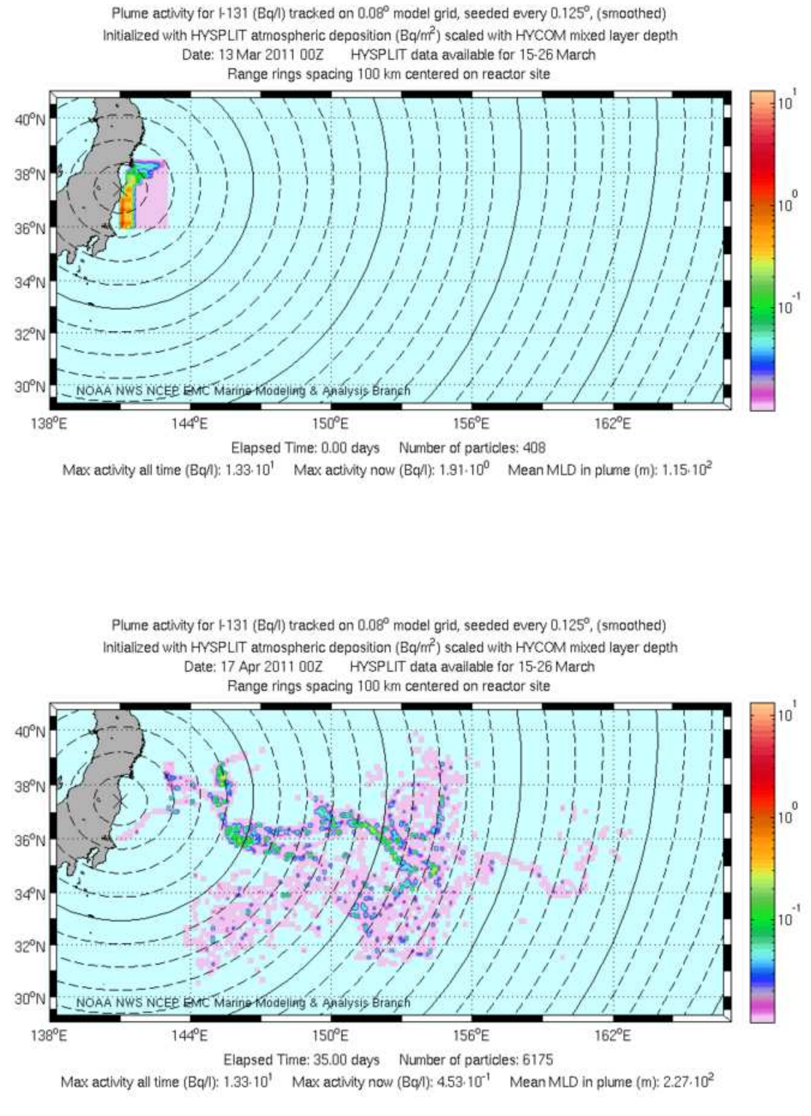


Fig. 5.20 : High resolution seed, ^{131}I, HYSPLIT-1, initial plume and after 37 days.

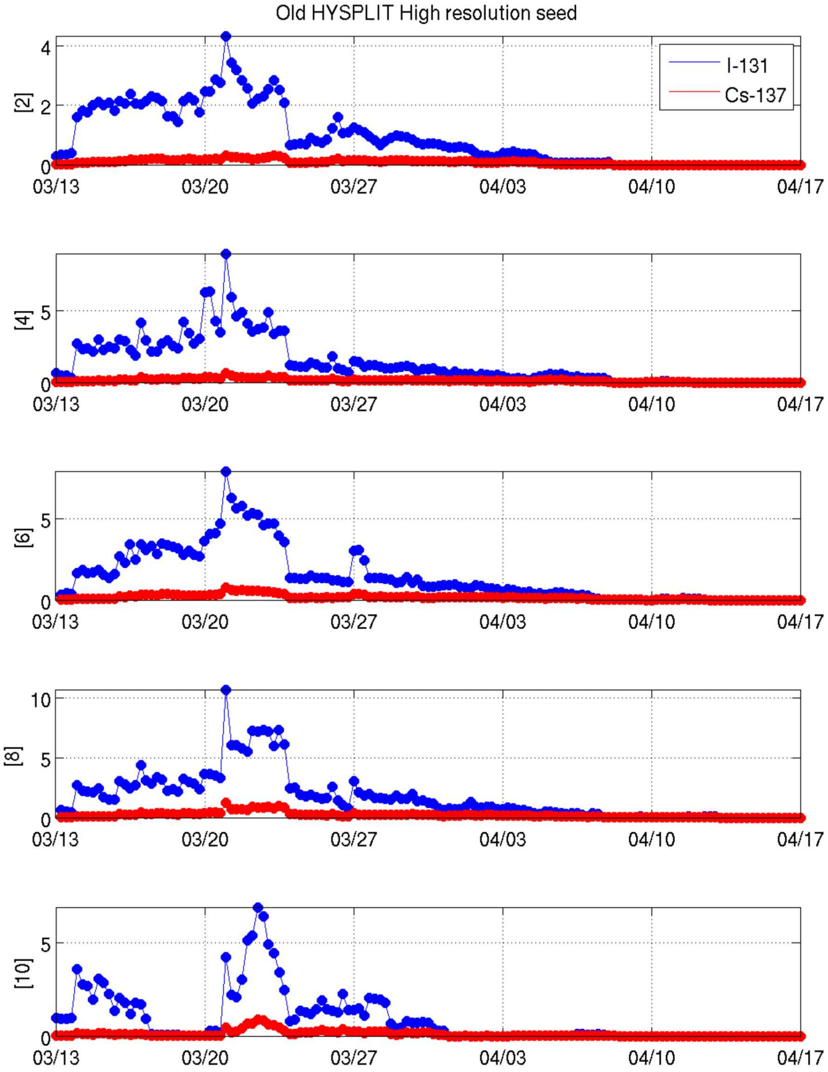


Fig. 5.21 : High resolution seed, MEXT station time series, even numbered stations only.

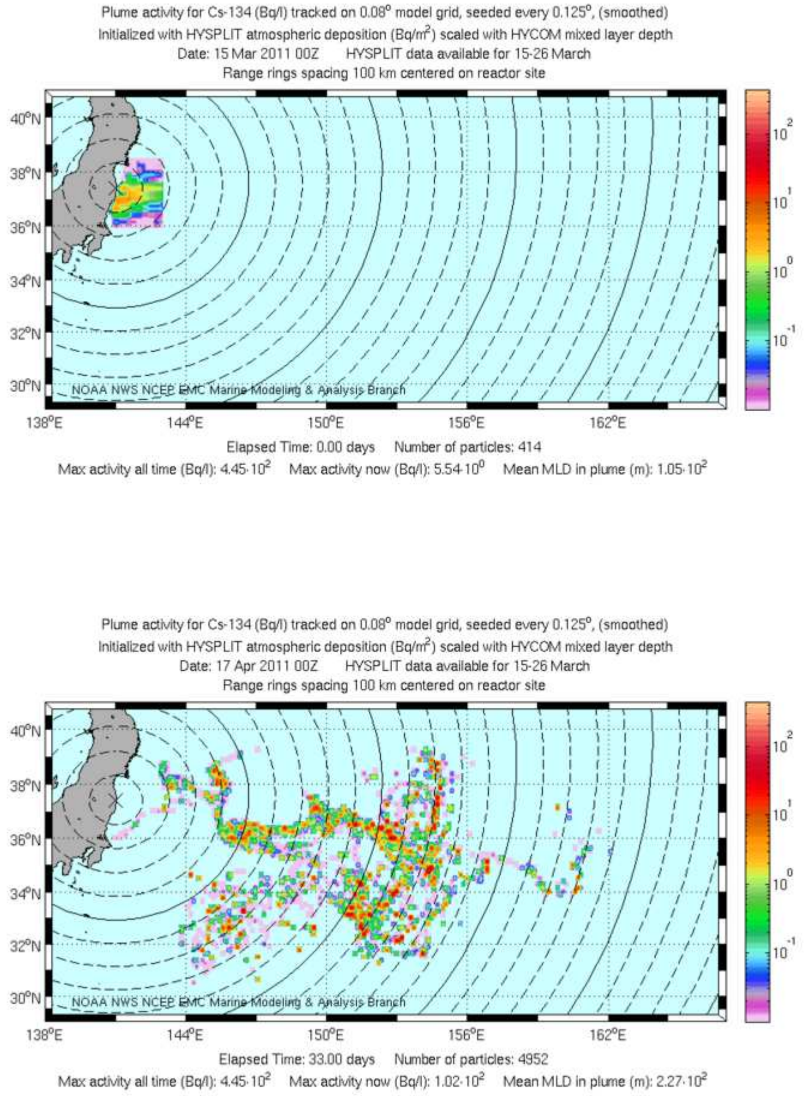
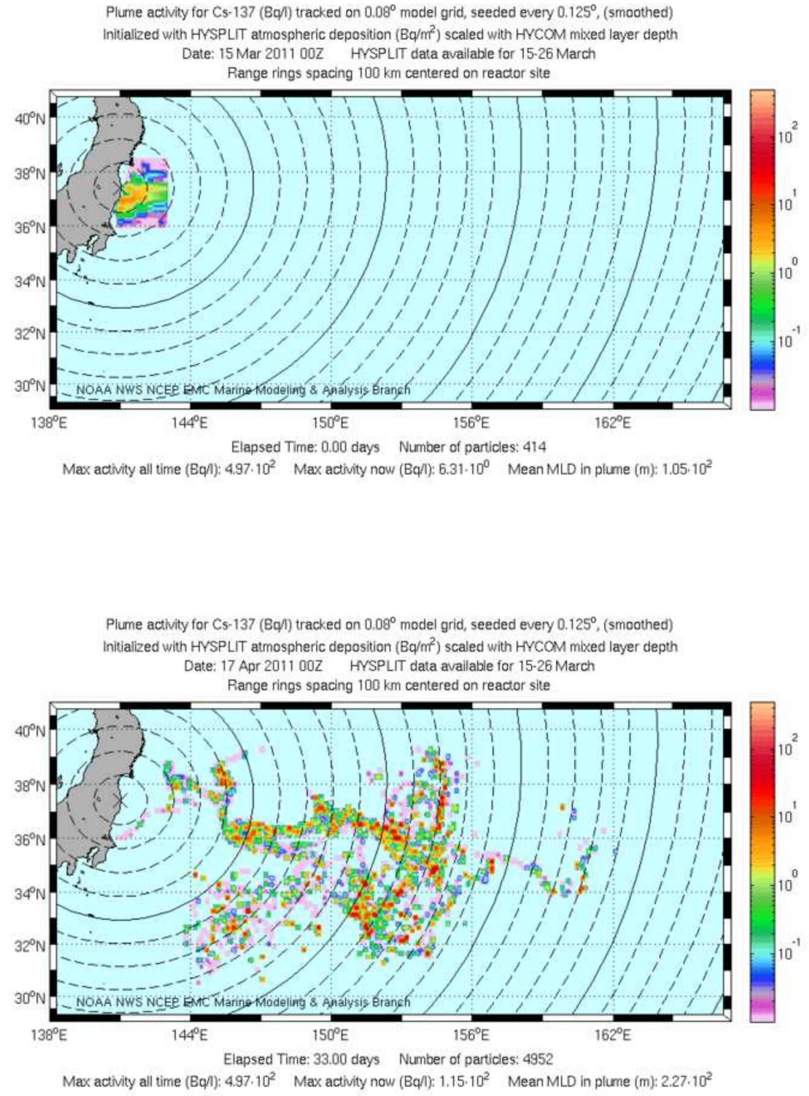


Fig. 5.22 : High resolution seed, ^{134}Cs, HYSPLIT-2, initial plume and after 37 days.



Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Initialized with HYSPLIT atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 15 Mar 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 100 km centered on reactor site

Elapsed Time: 0.00 days Number of particles: 414
Max activity all time (Bq/l): $4.97 \cdot 10^2$ Max activity now (Bq/l): $6.31 \cdot 10^0$ Mean MLD in plume (m): $1.05 \cdot 10^2$

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Initialized with HYSPLIT atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 17 Apr 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 100 km centered on reactor site

Elapsed Time: 33.00 days Number of particles: 4952
Max activity all time (Bq/l): $4.97 \cdot 10^2$ Max activity now (Bq/l): $1.15 \cdot 10^2$ Mean MLD in plume (m): $2.27 \cdot 10^2$

Fig. 5.23 : High resolution seed, ^{137}Cs, HYSPLIT-2, initial plume and after 37 days.

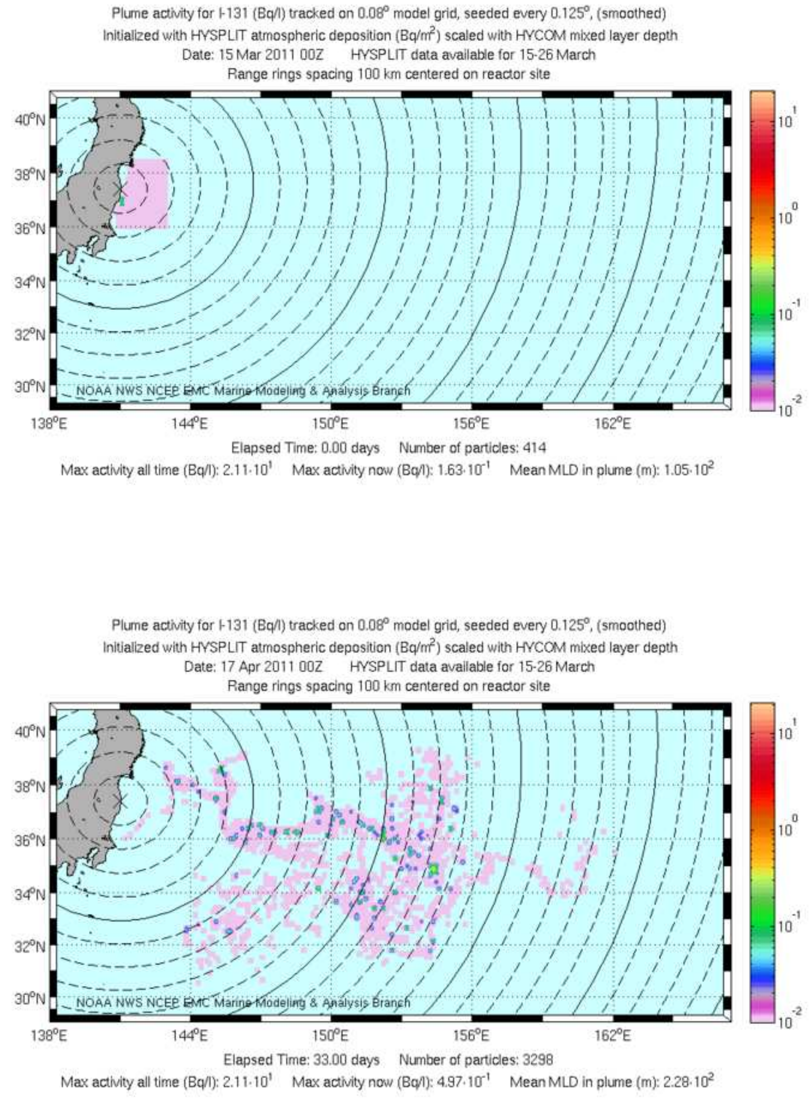


Fig. 5.24 : High resolution seed, ^{131}I, HYSPLIT-2, initial plume and after 37 days.

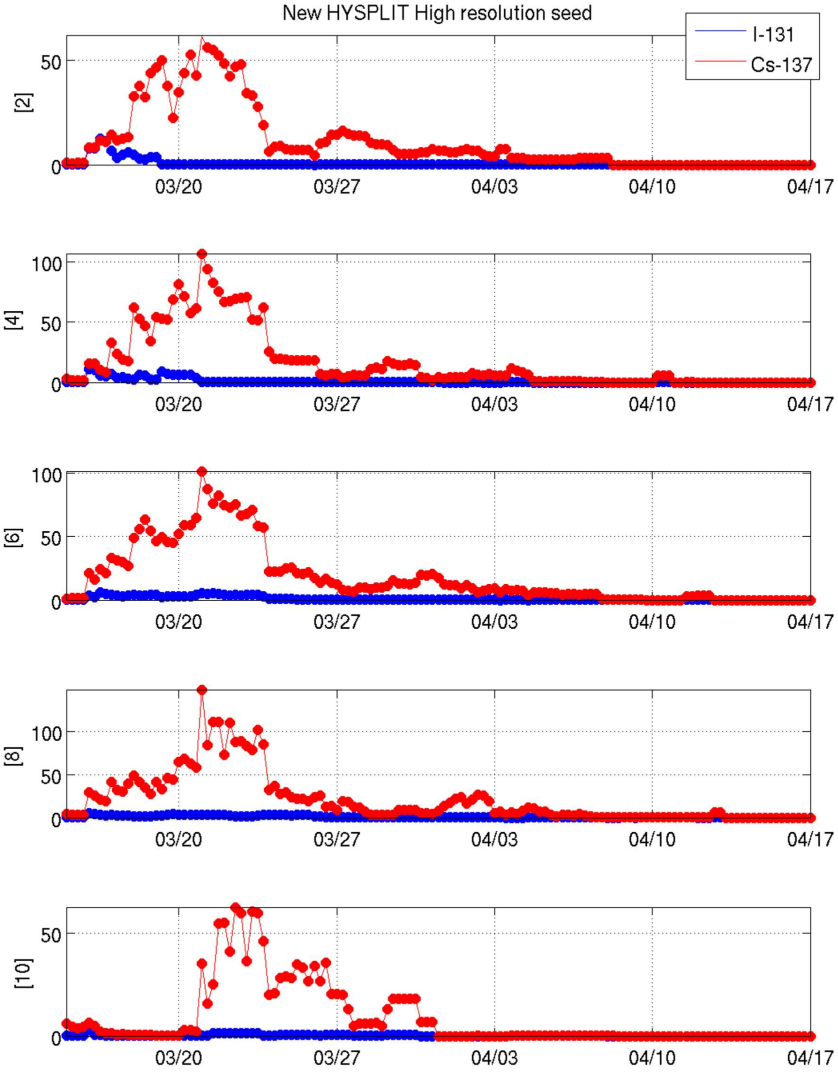


Fig. 5.25 : High resolution seed, MEXT station time series, even numbered stations only.

5.3.3 Full atmospheric wet depositions only

To capture as much of the atmospheric fluxes of radionuclides depositing on the surface of the ocean, two new dynamic seeding strategies were employed. Both were based on the NRC HYSPLIT-1 plume data, with the second strategy consisting of a refinement of the first. The dynamic seeding method shifts the initial positions of the seeded particles as a function of time, using the atmospheric plume data as a guide. Unlike the static seeding positions located close to the FNPP location, the dynamic particle tracks in this method can begin at locations throughout the North Pacific.

The following maps show first the results of the first dynamic seeding matched with the two sets of HYSPLIT atmospheric wet depositions, and then the revised dynamic seeding is combined with the NRC HYSPLIT-1 data set. The DOE HYSPLIT-2 data set was not used with the revised dynamic seeding.

1. Figs. 5.26 through 5.28 (pages 50 through 52) show the ocean radioactivity concentration (Bq/l) from the initial dynamic seed combined with the NRC HYSPLIT-1 data sets.

2. Figs. 5.29 through 5.31 (pages 53 through 55) show the ocean radioactivity concentration (Bq/l) from the revised dynamic seed combined with the NRC HYSPLIT-1 data sets. Note that is these Figures, we are also changing the representation to “stoplight chart” approach, where green means contamination below any critical level (existing drinking water acceptable levels, yellow mean some caution, between drinking water levels and new exposure levels established by EPA (Appendix A), and red means exceeding the acceptable EPA levels (i.e., potential danger).

3. Figs. 5.32 through 5.34 (Pages 56 through 58) show the ocean radioactivity concentration (Bq/l) from the initial dynamic seed combined with the DOE HYSPLIT-2 data sets.

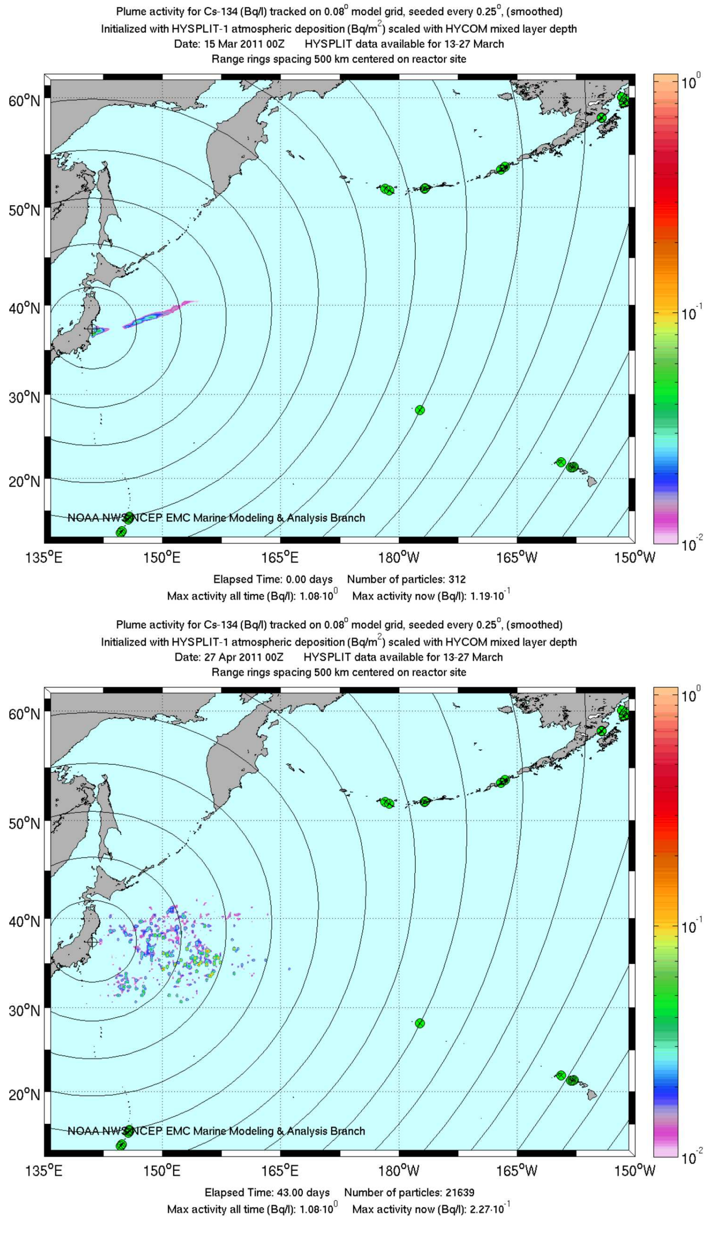


Fig. 5.26 : Initial dynamic seed, ^{134}Cs, HYSPLIT-1, initial plume and after 37 days.

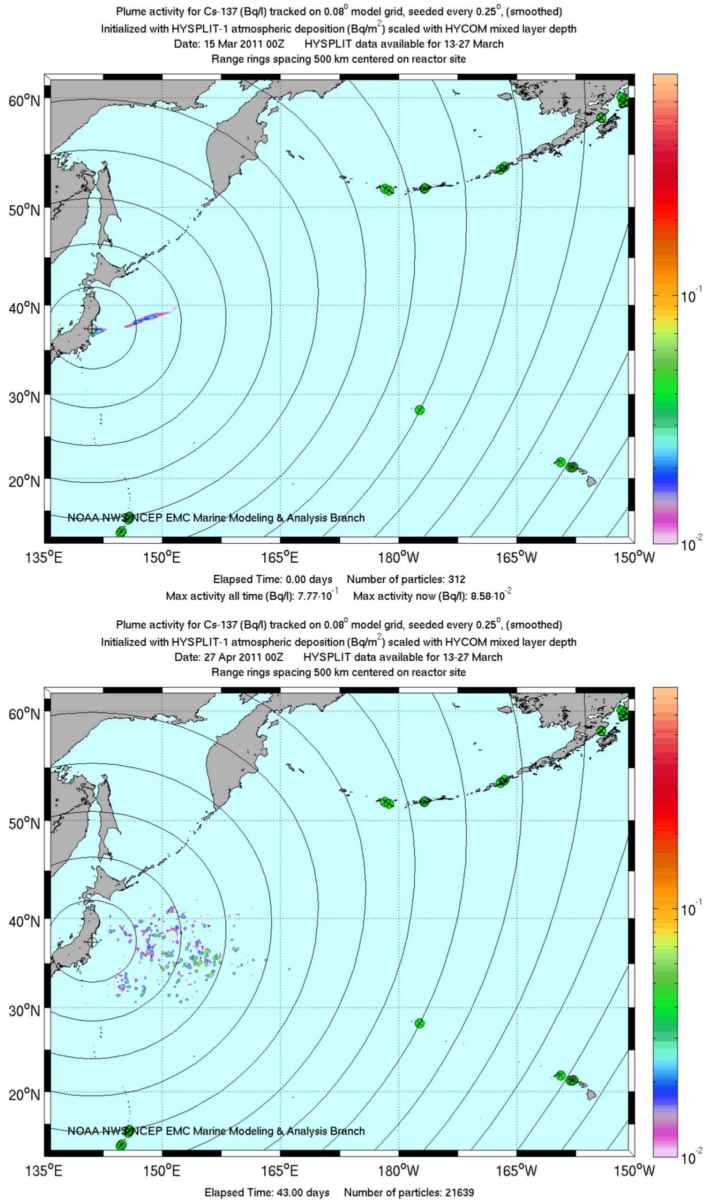


Fig. 5.27 : Initial dynamic seed, ^{137}Cs, HYSPLIT-1, initial plume and after 37 days.

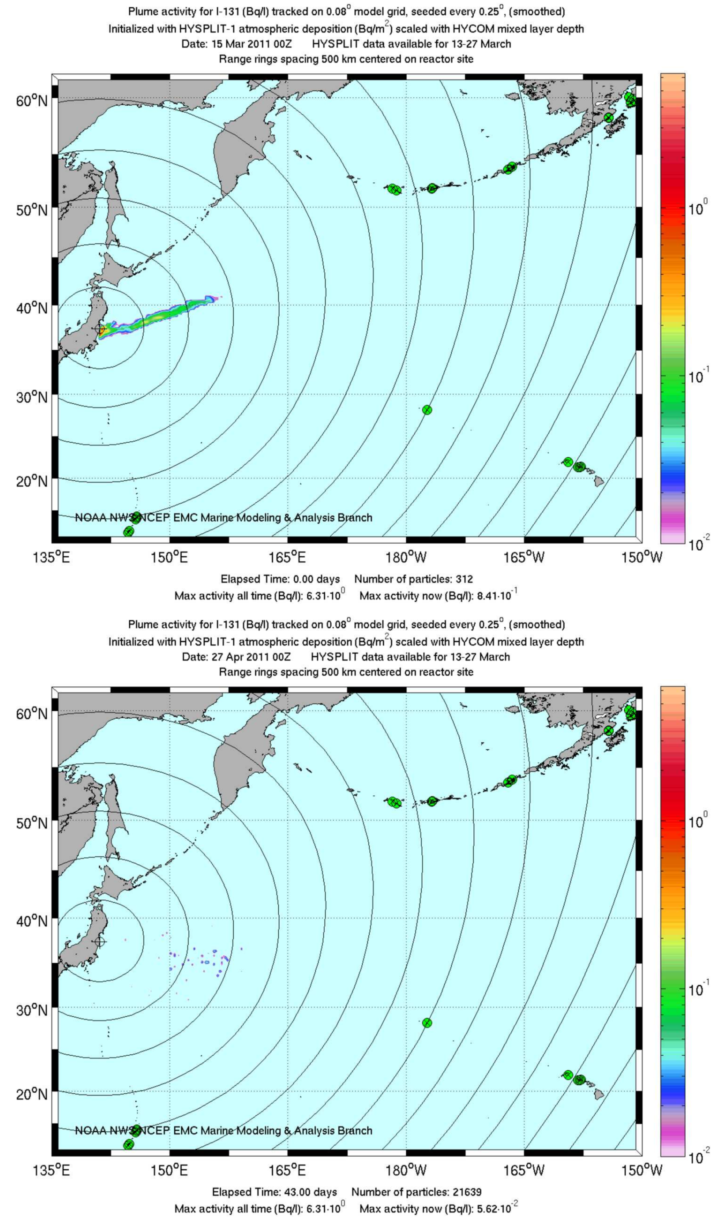
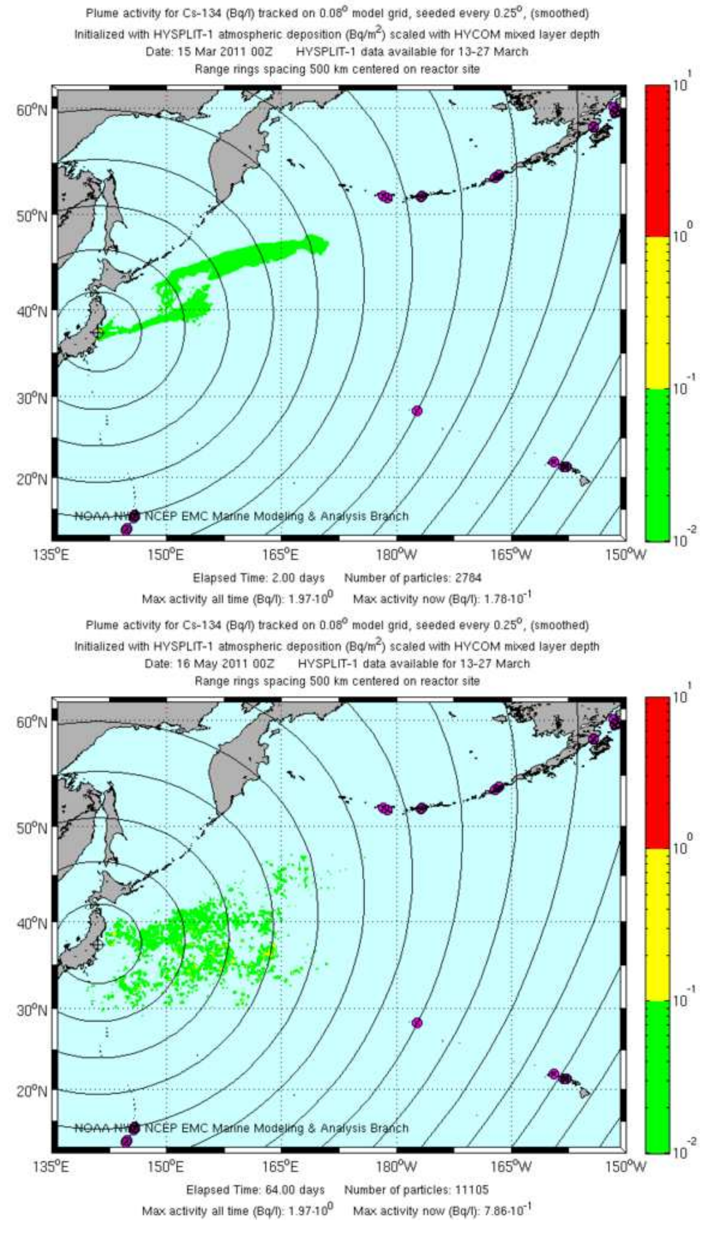


Fig. 5.28 : Initial dynamic seed, ^{131}I, HYSPLIT-1, initial plume and after 37 days.



Plume activity for Cs-134 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-1 atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 15 Mar 2011 00Z HYSPLIT-1 data available for 13-27 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 2.00 days Number of particles: 2784
Max activity all time (Bq/l): $1.97 \cdot 10^0$ Max activity now (Bq/l): $1.78 \cdot 10^{-1}$

Plume activity for Cs-134 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-1 atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 16 May 2011 00Z HYSPLIT-1 data available for 13-27 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 64.00 days Number of particles: 11105
Max activity all time (Bq/l): $1.97 \cdot 10^0$ Max activity now (Bq/l): $7.86 \cdot 10^{-1}$

Fig. 5.29 : Revised dynamic seed, ^{134}Cs, HYSPLIT-1, initial plume and after 37 days. First attempt at three-color presentation of results.

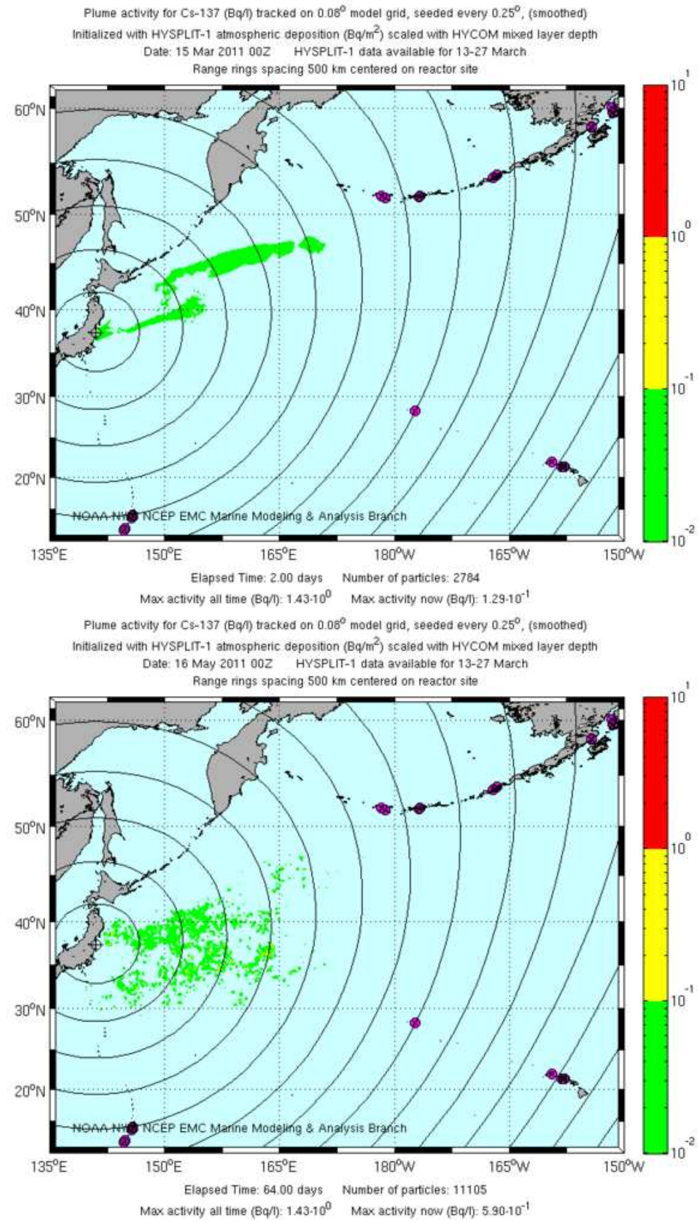


Fig. 5.30 : Revised dynamic seed, ^{137}Cs, HYSPLIT-1, initial plume and after 37 days, using three-color representation.

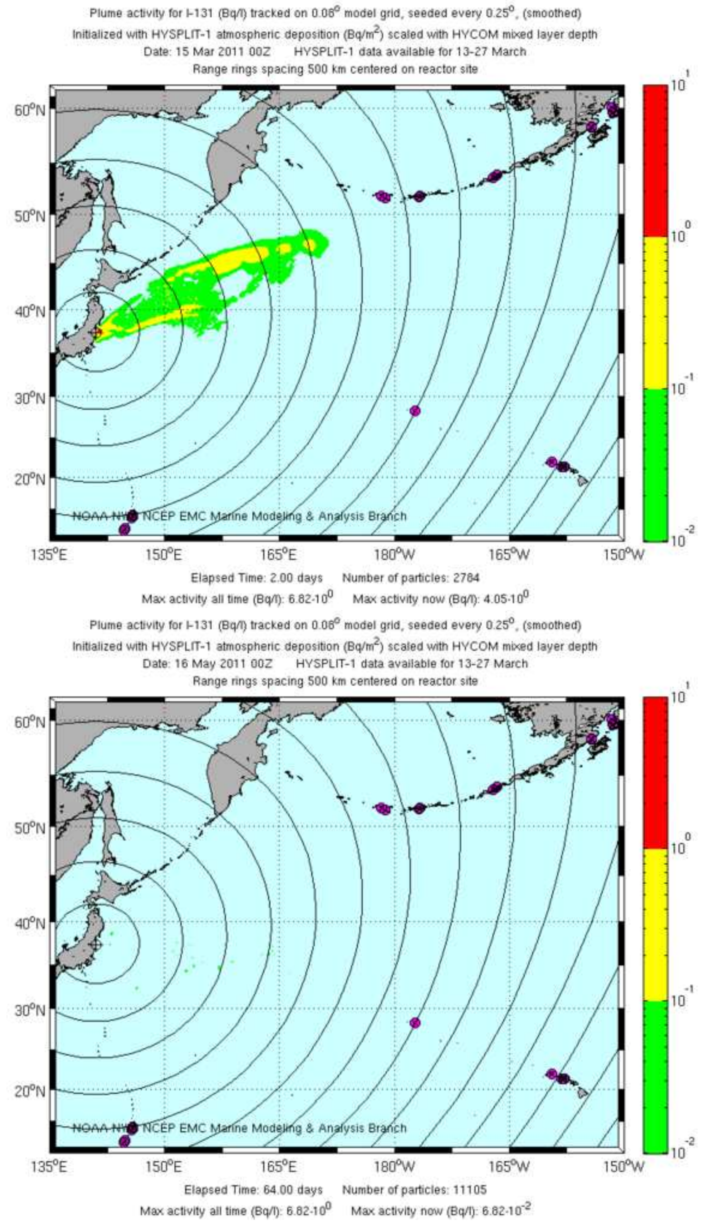


Fig. 5.31 : Revised dynamic seed, ^{131}I, HYSPLIT-1, initial plume and after 37 days, using three-color representation.

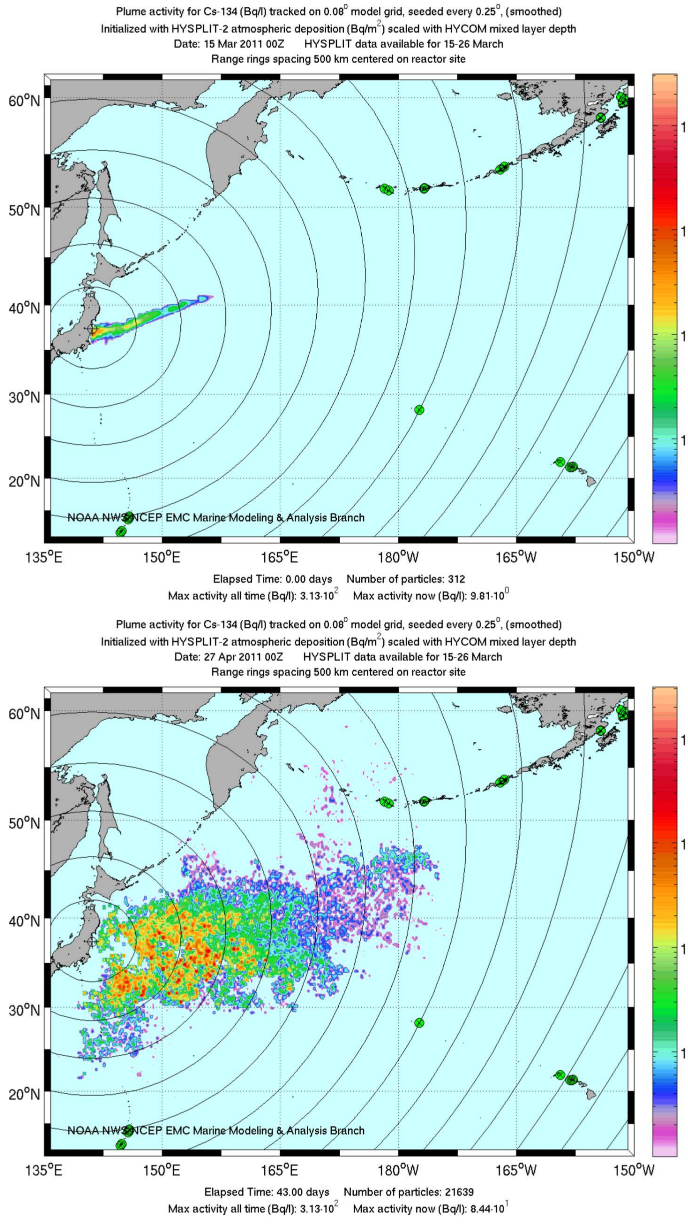


Fig. 5.32 : Initial dynamic seed, ^{134}Cs, HYSPLIT-2, initial plume and after 37 days.

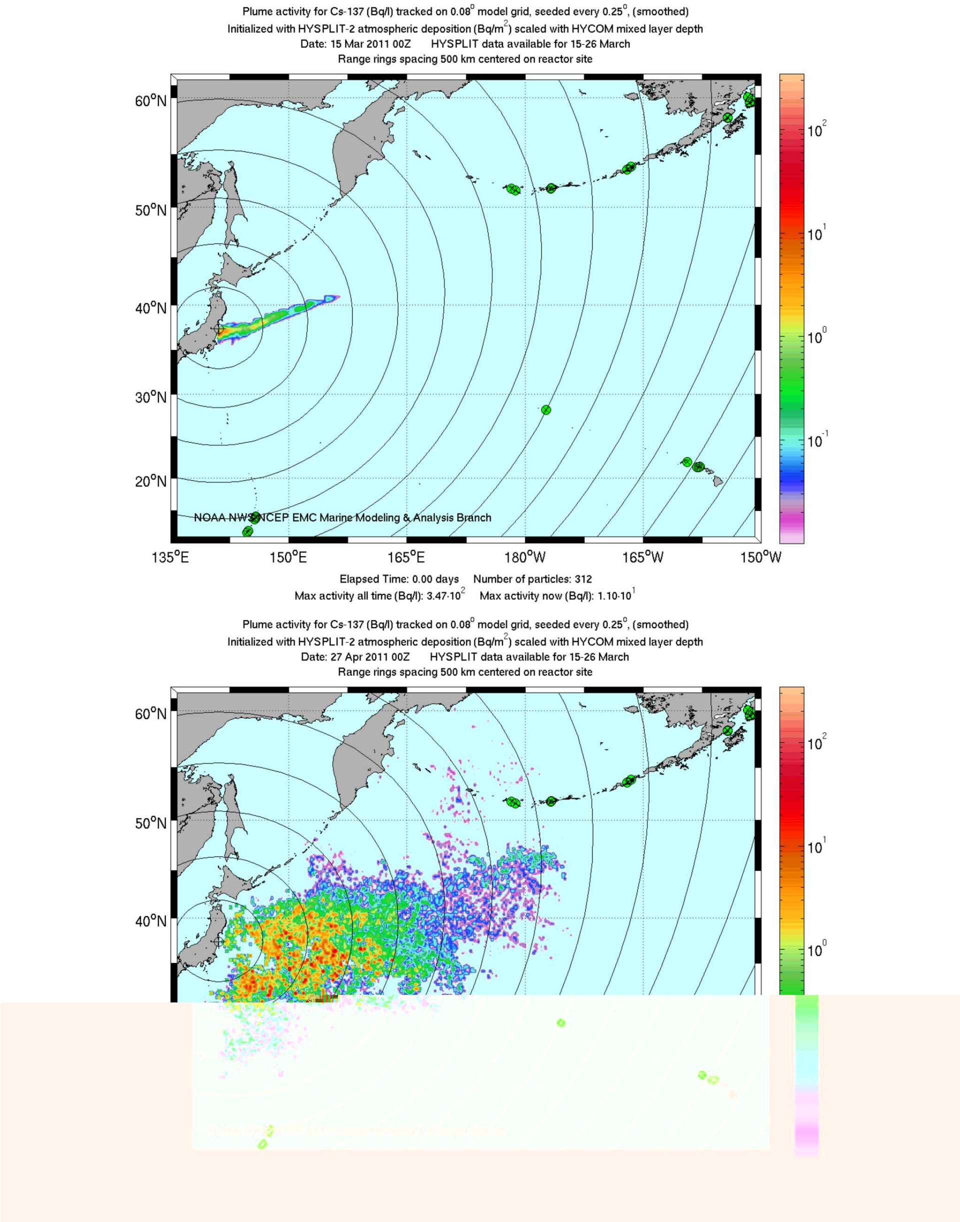


Fig. 5.33 : Initial dynamic seed, ^{137}Cs, HYSPLIT-2, initial plume and after 37 days.

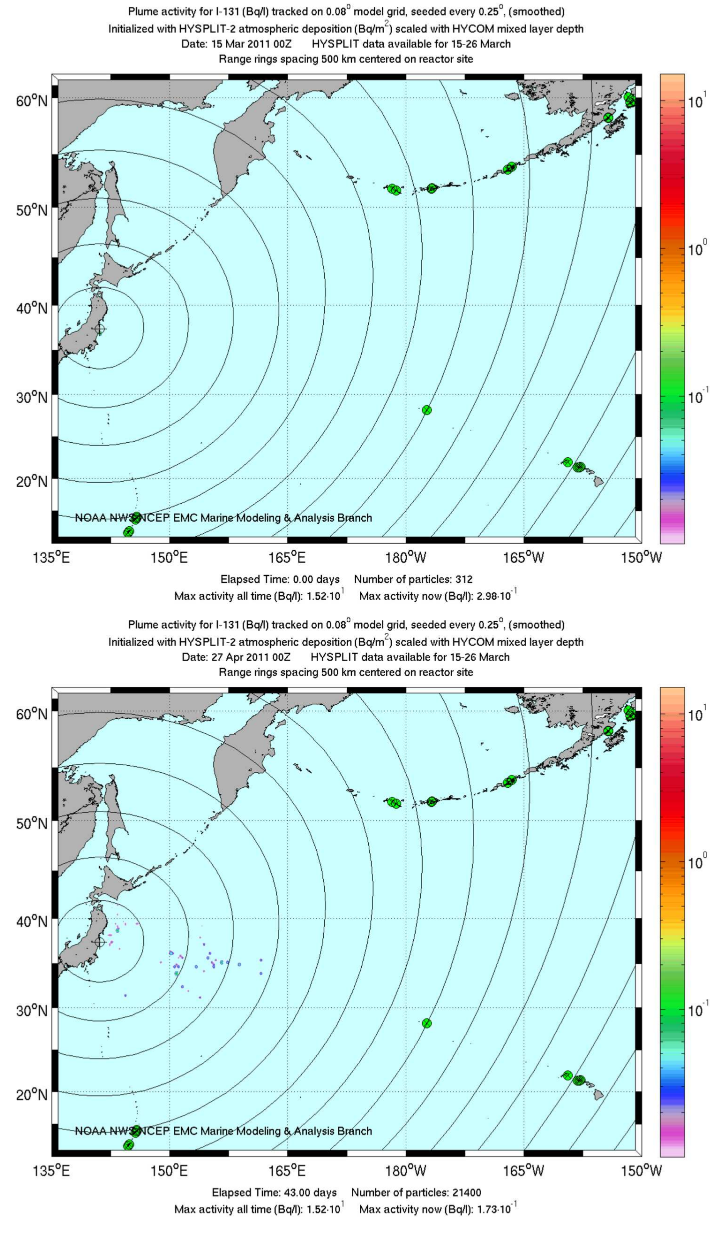


Fig. 5.34 : Initial dynamic seed, ^{131}I, HYSPLIT-2, initial plume and after 37 days.

6 Products

So far, the report has described the evolution of the modeling for the FDNPP disaster as it unfolded, but has not yet identified the final products as distributed to the IWG, and later to the general public. The various products have been distributed to the IWG initially as PowerPoint presentations (Appendices C and D), and later through web sites that will be identified below. The products were comprehensively described in a presentation at the Ocean Sciences meeting in Salt Lake City, in February 2012. The corresponding presentation is reproduced here in Appendix E, and still represents a concise overview of the products generated for the IWG. As outlined in the CONOPS (Appendix B), three products were envisioned, and all these three have been delivered.

The first product is the particle tracing approach based on the high-resolution seeding around FDNPP, and only considers the movement of particles using forecasted surface currents, without assessing the level of contamination. This product was designed to provide situational awareness about where contamination in the ocean would move and how fast. This product was provided to the IWG as biweekly PowerPoint presentations from April 15 through May 26, 2011. As an example of this product, the presentation for April 29, 2011 is reproduced here in Appendix C (without the animation on page 4). In late May, the animations in the presentation became prohibitively large, and the graphics were distributed through a web site, that was updated weekly

http://polar.ncep.noaa.gov/global/plume

The web version of the first product can be displayed by clicking on the "Particle Density" box. This particle tracking was continued for 172 days, in line with the plans outlined in the CONOPS (Appendix B). General conclusions from this product are found on the last page of the example in Appendix C. Moreover, these early product helped greatly to alleviate concerns about ocean pollution in US areas of interest such as Guam, Saipan, Hawaii and Alaska.

The second product is a rough estimate of pollution levels based on particle tracking and mixing of contamination in the ocean's mixed layer, as described in the previous sections. Early versions of this product were provided as PowerPoint presentation, the last of which was provided on May 6, 2011 (Appendix D). In this early product version. results are still presented in a "scientific" format, showing a large range of contamination. Unique to this specific presentation is the addition of pollution estimates for ^{90}Sr. Due to the low levels of contamination for this radioisotope, it was not considered after this presentation. An obvious observation from the presentation in Appendix D is the enormous uncertainty in total amount of contamination released at FDNPP; the NRC and DOE estimates used with HYSPLIT differed by nearly three orders of magnitude. This is symptomatic for early response to such disasters; even at the Ocean Sciences meeting nearly a year after the incident, best estimates from different source still differed by a factor of 5. Even with the simple modeling approaches used here, it is clear that the uncertainty of the source dominates the uncertainty in the modeling. Whereas the large differences between the NRC and DOE sources are crippling from a scientific perspective, they proved useful from the perspective of decision making; as outlined in the presentation, they became a natural upped and lower estimate of pollution levels.

A more mature version of the second product can be found in the presentation given at the February 2012 Ocean Science meeting (Appendix E). This presentation introduces the contamination level provided by EPA (Appendix A) used to generate a "stoplight chart" presentation of the data, using only three colors. Green identifies notable pollution levels but without considerations for safety issues (contamination from 1-100% of allowed contamination for drinking water). Red identifies potential safety issues regarding human contact with the water. Yellow identifies the transition between green and red. The fact that the high source estimate from DOE resulted in red coloring only close to the source in the first two weeks indicated within 6 weeks after the incident that contamination levels would be notable, but not dangerous over large parts of the Pacific Ocean. Contamination maps for Cesium were made available to the IWG on a regular basis on the above web site (click "Plume Activity" box) in the stoplight format for the first 100 days after the tsunami.

The third product produced for the IWG consisted of full three-dimensional dispersion modeling of ^{137}Cs in the North Pacific Ocean. This product became a fully operational product of NCEP on October 1, 2011, and was also presented in the Ocean Sciences presentation (Appendix E). This product provides a more scientific approach, benefiting from better source estimates, and is prepared for presentation in peer-reviewed scientific literature (Garaffo et al., 2013). The results from this approach are available on line at

http://polar.ncep.noaa.gov/global/tracer

The third product will not be discussed here in detail.

7 Conclusions

The present report provides an overview of ocean modeling activities at NCEP in response to the FDNPP disaster in March 2011.This effort represents a somewhat unconventional mix between science, engineering and providing actionable information to decision makers. Within four weeks after the event, decision makers were provided with particle tracing results, that could be used effectively to separate safe ocean areas from potentially threatened areas. After six weeks, the first contamination estimates of ocean surface water for the North Pacific were produced. Finally, full dispersion modeling products became available after approximately six months, and become fully operational at NCEP approximately a year after the event. These products are a culmination of collaboration between many agencies in the IWG. Particularly noteworthy are the efforts of the US Navy providing ocean modeling results at a large range of scales, the National Ocean Services (NOS) providing coastal modeling linked to our third st of products, and the Environmental Protection Agency (EPA), establishing water quality standards that were essential to provide a “stop light” representation of model results. Also unique to this approach is the explicit Concept of Operation (CONOPS, Appendix B, specifically developed for these products and the IWG.

The approach presented here could be used as a blueprint for emergency response ocean modeling. When properly funded, and available as a standby capability, the first set of products (particle tracking only), could be produced for decision makers within two working days. The second set of products (particle based pollution estimates) depend on source estimates of pollution, as well as physics of pollution dispersion. Initial products could be expected in three to six weeks. These first two products can typically be produced for three to six months, after which they would be replaced by full dispersion modeling products.

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[1] http://www.nws.noaa.gov/om/tpb/

APPENDICES

A EPA radiation dose estimates

As part of the Interagency Working Group (IWG), the Environmental Protection Agency (EPA) has provided estimated of radiation doses for Recreational Ocean Use. The main use for providing such doses is to be able to provide model results in terms of radiation thresholds, in order to provide meaningful graphics for decision makers. The corresponding document is reproduced here with permission of the EPA on the following two pages. Throughout the report, threshold values used are based on the 1 mrem exposure examples.

Contact information for this document:

Daniel Schultheisz (Schultheisz.Daniel@epamail.epa.gov)

Methodology for Estimating Radiation Dose from Recreational Ocean Use
May 17, 2011

The following simple methodology can be used to derive a rough estimate of the radiation dose to an individual from recreational ocean use in order to assist in evaluating the potential impacts on U.S. coastal waters from a radiological release. The methodology was first developed to assess potential exposures from radioactive materials released by the Fukushima Daiichi Nuclear Power Plant in Japan for the purpose of informing decisions regarding ocean monitoring. The methodology can be used to calculate doses from iodine-131, cesium-134 and cesium-137 using a simple swimming scenario in which a person incurs the majority of the dose from external exposure, but also incidentally ingests some small amount of water containing radioactive material. The methodology could be expanded to address other radionuclides as appropriate, and could also be adjusted as necessary to apply to releases of radionuclides into other water bodies (e.g., lakes, rivers).

Methodology:
Immersion and ingestion doses are calculated using the following equations:

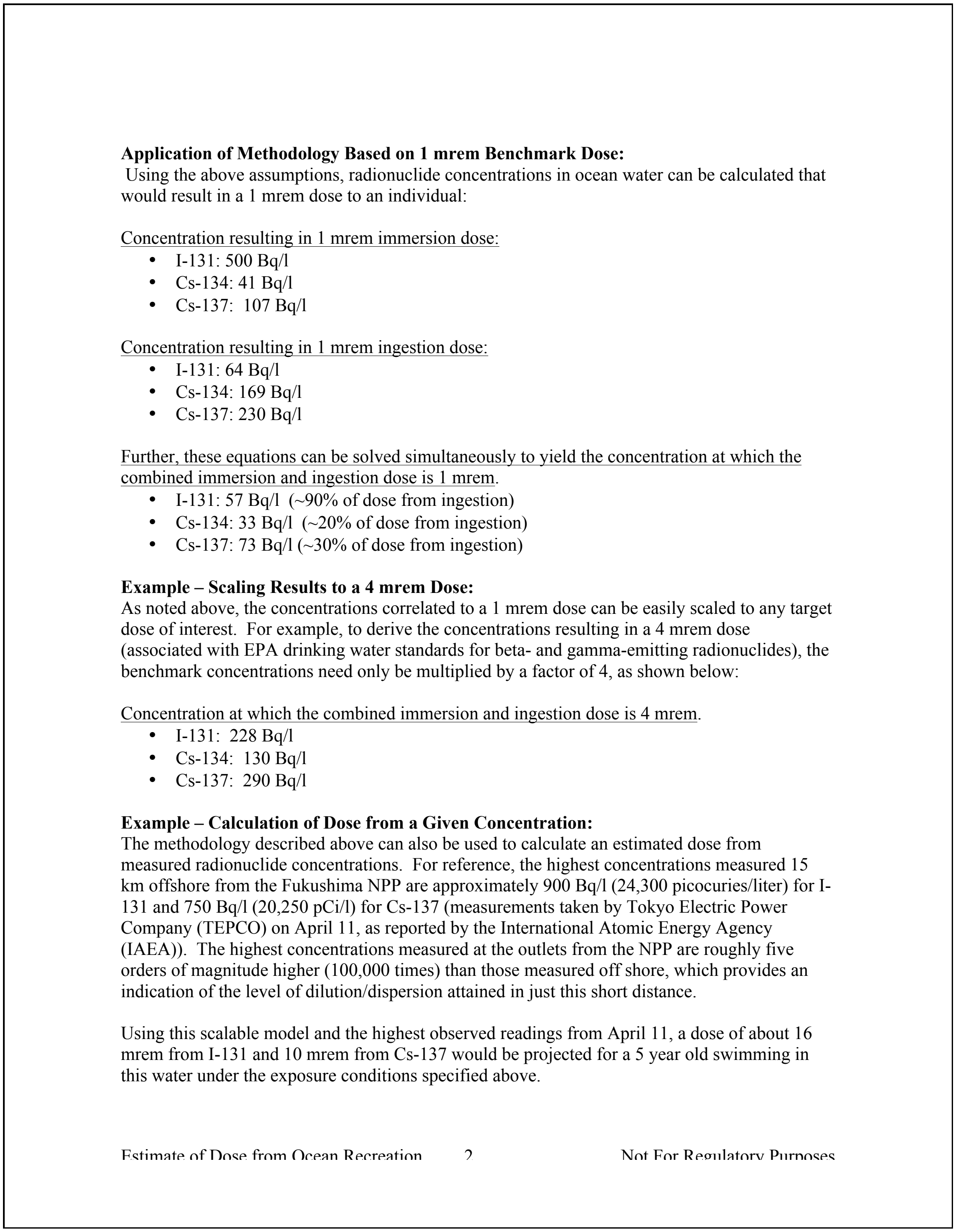
(1) Immersion dose = exposure time x dose conversion factor x concentration

(2) Ingestion dose = ingestion volume x dose conversion factor x concentration

Where dose is in units of millirem (mrem) and concentration is in units of Becquerels per liter (Bq/l).

Assumptions for Sample Application of Methodology:

1. A person swims five hours per day for 30 days (for I-131) or 90 days (for Cs-134 and Cs-137)
    - Accounts for shorter half-life of I-131 (8 days vs. 2 yrs and 30 yrs)
    - Estimate selected by EPA from similar scenario used for BP spill
2. Total exposure time is 150 hours (for I-131) or 450 hours (for Cs-134 and Cs-137)
3. Dose conversion factors for immersion (independent of age) in I-131, Cs-134, and Cs-137 from DCFPACK2:
    - I-131: 3.7×10^{-15} rem/sec per Bq/m^3
    - Cs-134: 1.53×10^{-14} rem/sec per Bq/m^3
    - Cs-137: 5.83×10^{-15} rem/sec per Bq/m^3
4. Dose conversion factors for ingestion by a five-year old child of I-131, Cs-134, and Cs-137 from DCFPACK2:
    - I-131: 1.03×10^{-5} rem/Bq
    - Cs-134: 1.32×10^{-6} rem/Bq
    - Cs-137: 9.67×10^{-7} rem/Bq
5. Ingestion of ocean water is 50 ml per day (EPA Exposure Factors Handbook)
6. Total ingestion is 1.5 liters (for I-131) or 4.5 liters (for Cs-134 and Cs-137)
7. A combined immersion and ingestion dose of 1 mrem is selected as an example for calculating corresponding radionuclide concentrations in ocean water. A 1 mrem dose is a very conservative benchmark. These calculations are easily scalable to any target dose of interest.



Application of Methodology Based on 1 mrem Benchmark Dose:
Using the above assumptions, radionuclide concentrations in ocean water can be calculated that would result in a 1 mrem dose to an individual:

<u>Concentration resulting in 1 mrem immersion dose:</u>

- I-131: 500 Bq/l
- Cs-134: 41 Bq/l
- Cs-137: 107 Bq/l

<u>Concentration resulting in 1 mrem ingestion dose:</u>

- I-131: 64 Bq/l
- Cs-134: 169 Bq/l
- Cs-137: 230 Bq/l

<u>Further, these equations can be solved simultaneously to yield the concentration at which the combined immersion and ingestion dose is 1 mrem</u>.

- I-131: 57 Bq/l (~90% of dose from ingestion)
- Cs-134: 33 Bq/l (~20% of dose from ingestion)
- Cs-137: 73 Bq/l (~30% of dose from ingestion)

Example – Scaling Results to a 4 mrem Dose:
As noted above, the concentrations correlated to a 1 mrem dose can be easily scaled to any target dose of interest. For example, to derive the concentrations resulting in a 4 mrem dose (associated with EPA drinking water standards for beta- and gamma-emitting radionuclides), the benchmark concentrations need only be multiplied by a factor of 4, as shown below:

<u>Concentration at which the combined immersion and ingestion dose is 4 mrem</u>.

- I-131: 228 Bq/l
- Cs-134: 130 Bq/l
- Cs-137: 290 Bq/l

Example – Calculation of Dose from a Given Concentration:
The methodology described above can also be used to calculate an estimated dose from measured radionuclide concentrations. For reference, the highest concentrations measured 15 km offshore from the Fukushima NPP are approximately 900 Bq/l (24,300 picocuries/liter) for I-131 and 750 Bq/l (20,250 pCi/l) for Cs-137 (measurements taken by Tokyo Electric Power Company (TEPCO) on April 11, as reported by the International Atomic Energy Agency (IAEA)). The highest concentrations measured at the outlets from the NPP are roughly five orders of magnitude higher (100,000 times) than those measured off shore, which provides an indication of the level of dilution/dispersion attained in just this short distance.

Using this scalable model and the highest observed readings from April 11, a dose of about 16 mrem from I-131 and 10 mrem from Cs-137 would be projected for a 5 year old swimming in this water under the exposure conditions specified above.

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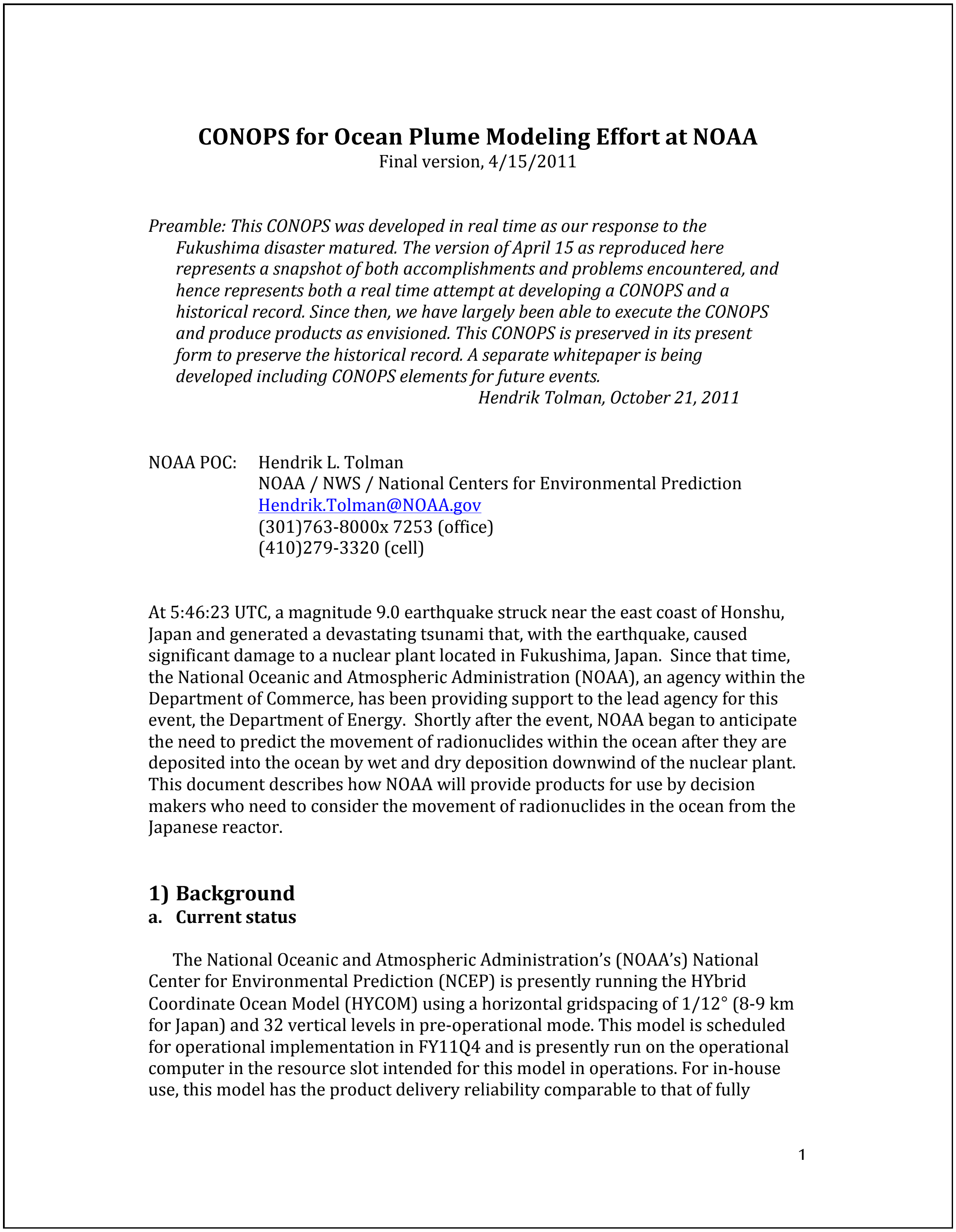
B Concept of Operations (CONOPS)



CONOPS for Ocean Plume Modeling Effort at NOAA

Final version, 4/15/2011

Preamble: This CONOPS was developed in real time as our response to the Fukushima disaster matured. The version of April 15 as reproduced here represents a snapshot of both accomplishments and problems encountered, and hence represents both a real time attempt at developing a CONOPS and a historical record. Since then, we have largely been able to execute the CONOPS and produce products as envisioned. This CONOPS is preserved in its present form to preserve the historical record. A separate whitepaper is being developed including CONOPS elements for future events.

Hendrik Tolman, October 21, 2011

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At 5:46:23 UTC, a magnitude 9.0 earthquake struck near the east coast of Honshu, Japan and generated a devastating tsunami that, with the earthquake, caused significant damage to a nuclear plant located in Fukushima, Japan. Since that time, the National Oceanic and Atmospheric Administration (NOAA), an agency within the Department of Commerce, has been providing support to the lead agency for this event, the Department of Energy. Shortly after the event, NOAA began to anticipate the need to predict the movement of radionuclides within the ocean after they are deposited into the ocean by wet and dry deposition downwind of the nuclear plant. This document describes how NOAA will provide products for use by decision makers who need to consider the movement of radionuclides in the ocean from the Japanese reactor.

1) Background

a. Current status

The National Oceanic and Atmospheric Administration's (NOAA's) National Center for Environmental Prediction (NCEP) is presently running the HYbrid Coordinate Ocean Model (HYCOM) using a horizontal gridspacing of 1/12° (8-9 km for Japan) and 32 vertical levels in pre-operational mode. This model is scheduled for operational implementation in FY11Q4 and is presently run on the operational computer in the resource slot intended for this model in operations. For in-house use, this model has the product delivery reliability comparable to that of fully operational models. Since NCEP identifies products rather than the models used to generate the products, this model is also identified as the Real Time Ocean Forecast Model – Global (RTOFS-Global). This model has been run at NCEP since December 2010, and full archive data of the 1/12° grid spacing data is available starting March 8, 2011.

To predict the movement of radionuclides in the ocean, NOAA has considered several options using HYCOM and determined that one option provides an estimate that can be obtained relatively quickly and easily. The most direct way to predict the concentration of radionuclides throughout the ocean would be to use the HYCOM's model capability for full tracer computations (comparable to HYSPLIT in the atmosphere). This capability, however, has not yet been tested at NCEP, and would require modifications to the pre-operational model. Furthermore, this approach will require re-running the full ocean model for each scenario considered, and hence will be computationally expensive. Finally, it will require data on deposits and behavior of radionuclides, which NOAA currently does not have. All these considerations make dispersion modeling of an ocean not suitable for producing rapid response actionable information on radioactive contamination of seawater.

Alternatively, particle tracing can be performed using output of the ocean model. NCEP has a tested capability to trace particles, and started experimenting with this approach shortly after the news of damage to the Fukushima Daiichi reactor was made public. Presently NOAA is using the 1/12° HYCOM model output to track inert particles at the ocean surface, assuming that the surface behavior is reasonably representative for the ocean mixed layer, and that the radionuclides will mostly be contained in and distributed by the upper mixed layer of the ocean.

With the particle tracing information, NOAA can only produce estimates of retention time of radionuclides near the coast, as well as dispersion time scale of these materials by the Kuroshio Current. The latter will identify both potentially safe areas in the Pacific, and areas of potential exposure on the time scales of weeks to months. To provide additional information on the radiation levels from the particle tracing, NOAA will need:

- Deposit rates of radionuclides (preferably in Bq/m^2/day), as georeferenced numerical information.
- Estimates of point sources at the coast, and development of methods to convert this into a proxy load per model particle.
- Estimates of vertical dispersion of radionuclides within the ocean that will need to be validated / assessed by measurements. Tentatively, model predicted mixed layer depth can be used for this.
- Horizontal diffusion rates in the ocean associated with low particle density far away from source. Dispersion modeling may be helpful and a reasonable assumption can be made to estimate the associated uncertainty with such an assumption .
- Radioactive decay information of material involved and the composition of that material. Decay information on Iodine and Cesium is available. However,

it is not clear if these materials should be considered as dissolved or particulate.

- Observed radionuclides in the ocean. The modeling activities described in this CONOPS document includes significant uncertainty, making it of paramount importance that in-situ observations of radionuclides are available to develop as well as validate the model with respect to predicted levels of radioactivity.
- Additional observations of the physical state of the ocean (temperature, salinity and current velocity, including profile data). These data are particularly critical near the coastal sources of the pollution, as they describe the initial containment or dispersion of pollution from the coast. Generally, better description of ocean currents will result in more realistic dispersion patterns. Because the Navy preforms the data integration in the modeling for this effort, additional ocean state observations should be coordinated with the Navy (Naval Oceanographic Office (NAVO), Naval Research Laboratory (NRL)).

There are several important limitations of this approach that need to be understood by any user of NOAA's information. First, the resolution of the NCEP ocean model is insufficient to address the detailed dispersion of radioactive material in coastal areas near the power plant. This limitation can be mitigated by using high-resolution ocean models as run by our partners, particularly the U.S. Navy Operational Global Ocean Model (NCOM) using a horizontal gridspacing of 1 km (see following section). The data of the latter model are currently being distributed by NOAA's Ocean Prediction Center (OPC). The Navy routinely runs the NCOM for the West Pacific including Japan, using a horizontal gridspacing of 3.5 km. These data have also been archived at NCEP. The archive of ocean model data from the Navy at NCEP contains data starting at March 6.

Second, this modeling approach deals with dispersion on weather time scales, and is suitable (and feasible) to be run for time scales of up to a few months. For Iodine, this is not an issue, because it's half live is 8 days. For Cesium or other pollutants associated with catastrophic failure at the reactor, climate scale dispersion modeling is required to address long-term impacts.

Third, NOAA is only modeling the physical dispersion radioactive material and does not have the knowledge or capability to address human or biological impacts.

b. Partners

The HYCOM model is a community model, developed with major contributions of the Navy, academia and NOAA. The RTOFS-Global implementation is an operational partnership between NCEP and NRL/NAVO. NCEP adopted the model configuration developed at NRL and being operationalized at NAVO, and NAVO provides daily initialization data for the NCEP model. This partnership allowed NCEP to accelerate the model implementation. Navy ocean modelers are available for discussion of the physical ocean state as needed.

NCEP is starting to become a distribution point for Navy (NAVO) ocean models. OPC is distributing global 1/8° resolution NCOM data for selected areas. NAVO has a 3.5 km NCOM model running routinely for the Japanese waters. NAVO has set up a high resolution (1 km horizontal grid spacing) nested NCOM model for the area around the Fukushima Daiichi reactor. These data are transitioned to NCEP through operational communication channels, and NCEP acts as the archive and distribution point of these model data.

NCEP has the capability to provide any other partners with boundary and initialization data for local models from the HYCOM and NCOM models described above.

NCEP is considering standing up particle tracing capabilities based on the 1km NCOM model, particularly to address behavior of continuous or catastrophic releases of radioactive material at the coast. NCEP is coordinating with both the Navy and National Ocean Services (NOS) to leverage coastal modeling capabilities. The following potential collaborations have been identified:

The Navy (NAVO) has been running a particle tracing model (originally developed for oil spill modeling) based on the high resolution NCOM models for point releases of material at the plant, but not including atmospheric deposition as intended for the NCEP model. These modeling efforts are essentially complimentary, and NCEP will have access to the NAVO results. This model is no longer operated, as it is super-seeded by the model described in the next paragraph.

The Defense Treat Reduction Agency (DTRA) is running dispersion model for the near-coast area using offshore observations to address local water quality for use by Navy ships. This approach uses offshore observations to estimate source areas and levels of coastal releases of pollutants. This modeling effort is complimentary to the NCEP effort, and may provide NCEP with proxy source data needed for the large sale modeling effort. NCEP and DTRA have established an active dialogue on all modeling efforts.

NOS Office of Response and Restoration (OR&R) has the GNOME model with particle tracing capabilities. NCEP has provided OR&R with the 1km NCOM data. OR&R is assessing possible support for the coastal problem. As in the deep ocean, any modeling effort here is severely hamstrung by lack of data.

NOS CSDL is an established partner of NCEP with respect to building the ocean modeling backbone capability for NOAA, with NCEP focusing on basin scales and NOS focusing on coastal areas. For the plume modeling, NOS is engaging their partners in academia to inventory capabilities. In this context, the FVCOM modeling group is developing a adopting a global unstructured grid model with extremely high resolution to model the Japanese tsunami. This model may also provide some tracing capability for retrospective modeling. NOS and NCEP are also partnering on developing regional tracer modeling capabilities as part of long-term capability development.

We have not yet engaged the Japanese modeling community. From our international connections in GODAE OceanView, we do believe that the Japanese do have high resolution regional ocean models. We have been monitoring results presented from foreign sources such as French plume modeling based on the Mercator system, and will contact relevant producers of model results as necessary.

All physical modeling of the radioactive plume in the ocean will be critically dependent on observation partnership inside and outside of NOAA, and with the international community.

2) Intended products

Two levels of products can be identified from the particle tracing, with different levels of uncertainties and different level of needs for information external to NCEP in order to produce these products. Each consecutive product builds upon the previous product.

a. Model virtual particle density products

Description: The physical ocean model (HYCOM) is seeded with virtual model particles at a resolution no higher than that of the model (up to one particle per 8x8 km grid box, or 1x1 km grid box for coastal NCOM model). Seeding takes place at a regular time intervals (initially 24h, may be increased later) resulting in a linear growth in time of the number of virtual particles in the model. From the track information virtual particle density plots can be produced anywhere in the world.
Interpretation: Such products will show where deposited material could potentially go, depending on where the material is deposited initially, but will give no information on local level of contamination.
Actionable information: By running "what-if" scenarios by considering virtual particles seeded at different distances from the source (Fukushima Daiichi plant, tentatively at <25km, 25-50km, etc.), we will have a first estimate of how long coastal contamination will be contained in coastal areas or will be dispersed through the larger ocean, how far and fast material is moved through the ocean, and which general areas in the Pacific are at risk for water based pollution and which are not. Note that the seeding closest to the source can be used as a proxy to deal with present runoff from the plant, and catastrophic by spatially contained events.
Uncertainties: Accuracy will depend on (i) accuracy of ocean model, and (ii) assumption of surface behavior of the being representative for mixed layer and that material is retained in the upper ocean (iii) particles will not represent horizontal diffusion far away from the source where virtual particle densities are low. Uncertainties (i) and (ii) imply that details of the distribution may be inaccurate, but general patterns are more reliable. Uncertainty (iii) can be mitigated somewhat by horizontally diffusing virtual particle densities away from the source, or by properly interpreting the resulting data. Experience with dispersion modeling (off-line, input from academia) could help address the last issue.
Risks: Such products show where material might go, depending on its source, but do not mean that material will go to each source. In the DWH event, similar products resulted in panic reactions from the media/public when some models showed particles tracing all the way up to Europe.

Mitigation: Such products should not be publicly disseminated in real time, and only be used within the government.
Essential external information: None, can be done with presently available modeling results.
Product available: This product is presently available, but not yet on an automated schedule.

b. Estimate of radioactive material per volume.

Description: Starting from the virtual particle density in the model, contamination per volume can be estimated by using contamination loads at the starting point of the virtual particles, radioactive decay information, and possibly particle settlement on the bottom or out of the mixed layer, and additional estimates of vertical mixing..
Interpretation: Detailed physical description of total contamination per volume of water in the upper ocean (representative for ocean surface).
Actionable information: initial safety assessment compared to acceptable thresholds. Input for additional human and biological threat assessment.
Additional uncertainties: Uncertainties in atmospheric and coastal pollution loads result in uncertainties in ocean pollution estimates. Uncertainties in behavior of pollutants (dissolved versus particulate) result in uncertainties in ocean pollution estimates. Assumption will be made on vertical mixing depth, of which not much is known yet. Limited measurement near plant shows some vertical mixing but are far from conclusive.
Risks: cumulative uncertainty through range of products.
Mitigation: worst case scenarios should give actionable information.
Essential external information: profile measurements of radioactive material further away from the plant than presently monitored by JAMSTEC, and in Kuroshio cross sections will l reduce uncertainty on vertical mixing. Observations closer to the coast will help reduce uncertainties in coastal sources of pollution. Observations of radionuclides in sediment near the plant will help assess if pollutants behave as particulate or as dissolved material.
Product available: NCEP has initial versions of all data needed, and expects to have initial product in 1-2 weeks.

3) Product dissemination

Due to the uncertainty implicit to these products, and due to the need of proper interpretation, it will be essential to tightly control the dissemination of outputs from this modeling effort (consider DWH lessons learned). All NCEP modeling personnel (EMC) has been informed of the sensitive nature of this modeling effort. Ocean model results are not critical and are kept on the operational NOAA super computer. Raw track data for virtual particles is also kept at the same machines.

Products are generated on desktop machine at NCEP/MMAB with tightly controlled access.

Acceptable dissemination of these products will be addressed at the highest levels of NOAA and the interagency efforts.

4) Scheduling

The modeling capability described herein consists of three identifiable processes.

- Running of RTOFS-Global (HYCOM) model.
- Generating virtual particle tracks.
- Generation of products

RTOFS-Global is run daily by NCEP Central Operations (NCO) in pre-operational mode on the operational supercomputer using resources reserved for this model in full operational implementation (scheduled for FY11Q4). The pre-operational model version includes the full model run. Full operational implementation requires finalization of model output dissemination, not relevant for the present effort. For the preset effort, and practical purposes RTOFS-Global can be considered as an operational model. However, the present project does elevate the need for the RTOFS-Global model to be monitored, which has been discussed between NCEP Central Operations (NCO) and EMC. The necessary RTOFS-Global data is available for processing before 6:30pm EDT each day.

The tracking of virtual particles presently requires manual processing by MMAB personnel. Presently, this requires several hours, including visual inspection of results as quality control. These programs run on the central super computer as single processor jobs, and can be run reliably on presently available resources. Note that each set of virtual particles generated represent a single tracking job, implying a linear growth of number of jobs with time. This will effectively limit this approach to be feasible for tracking material to several months. We expect to be able to automate this procedure, reducing the time to execute this part of the system to under 2 hours. A critical part here will be to automate quality control NCO will provide 7/24 support for running and monitoring codes as needed.

Product generation is performed on desktop hardware it EMC/MMAB using Matlab software. Initially product generation will be run manually. Automation will take up to two weeks, including building in redundancy by generating the products on both primary and secondary resources.

The above has the following implications for product delivery schedules when there is a need for daily forecast products (see discussion below). Due to the non-shift status of MMAB personnel, initial product delivery will be the next morning. With sufficient automation, product delivery will be accelerated as indicated in the table below. EMC will provide necessary monitoring this system outside of core operating hours for this ad-hoc application. EMC and NCO intend on work on fully operationalizing this capability, but that is not feasible in within the scope of the present project.

Job step	Initial	Target	Execution
RTOFS-Global (HYCOM) + archiving	6:30 pm EDT	6:30 pm EDT	NCO
Tracking virtual particles	10:00 am next day	8:30 pm EDT	EMC (→ NCO ?)
Products generation	11:00 am next day	9:30 pm EDT	EMC

Due to the time scales involved with dispersing pollutants through the Pacific Ocean, it is presently not clear what a preferred time schedule of product generation will be, and if it is necessary to provide forecasts complementary to an estimate of the present conditions. For longer term monitoring (weeks to months) of existing pollution, it may be sufficient to proved hindcast updates several times per week. In case of catastrophic events, daily product delivery (including forecasts) will be essential.

At the April 14 meeting of the IWG on Ocean Plume Modeling it was decided that the virtual particle density map provides useful actionable information, and will be produced on a regular schedule to the IWG. Because this plot shows cumulative effects of dispersion build up over many weeks, adding forecast capability of up to 6 days was presently not deemed necessary. Similarly, it was concluded that a bi-weekly update would be sufficient for now. NCEP intends to provide updates to the IWG on Monday and Friday, with data included up to the previous Saturday and Wednesday, respectively.

5) Event driven response.

In case of catastrophic events at the Fukushima Daiichi plant, a feasible first response will be to generate virtual particle density plots based on particles seeded close to the plant to address potential expansion in time of highly contaminated areas. Any other products can only be generated if some observed ocean data is available. High resolution modeling based on the 1km NCOM model will also be needed.

NCEP can tentatively produce the virtual particle density (forecast) products several (3?) hours after notification, depending on availability of regular staff at EMC/MMAB, that normally works an 8-hour standard workweek schedule (no 7/24 shift support). EMC will set up a stand-by capability to reduce dependency on critical skill of individual personnel in EMC/MMAB, once an initial set of actionable products has been developed.

6) Critical data.

The ocean modeling efforts use all available data through Navy data assimilation resources. Additional observations of the ocean state, particularly in the very complex current environment near the reactor site, will be beneficial to estimate retention times of pollutants in the shallow water near the plant, as well as time scales of dispersion to offshore areas, and eventually the Kuroshio extension.

Available radiological data in the ocean as presented in various Japanese web sites presently include:

- JAMSTEC observations approximately 30km offshore of surface and near-bottom concentrations of Iodine-131 and Cesium-137.
- Occasional similar observations roughly 15km offshore at three location (source presently not clear).
- Similar coastal observations near the plant, and 10 and 16km south of the plant (TEPCO).

These data provide some capability to calibrate and validate models, as well as some capability to estimate coastal releases of these two isotopes. Additional needs include:

- The present JAMSTEC data line is useful as a sentry line to assess offshore dispersion of the pollutants from coastal sources, but appears to far away from the coast for accurate estimates of the total volume of coastal sources. To fill this gap we either need.
    - Additional observation points closer to the coastal source.
    - Other volume estimates of point sources at the coast.
- DTRA modeling suggests that the coastal sources are particulate rather than dissolved. This needs to be addressed either by detailed analysis of water samples, more detailed profile information at present observations points, or information on settling of radionuclides from sediment samples.
- Far-field observations of radionuclides are needed to calibrate and validate modeling of dispersion at large scales. Tentatively, cross-sections of the Kuroshio extension are needed. Cross section could be around 145°E as a well-defined gateway of pollution leaving the direct vicinity of the plant, or otherwise should be directed by initial modeling results of concentrations of radionuclides.

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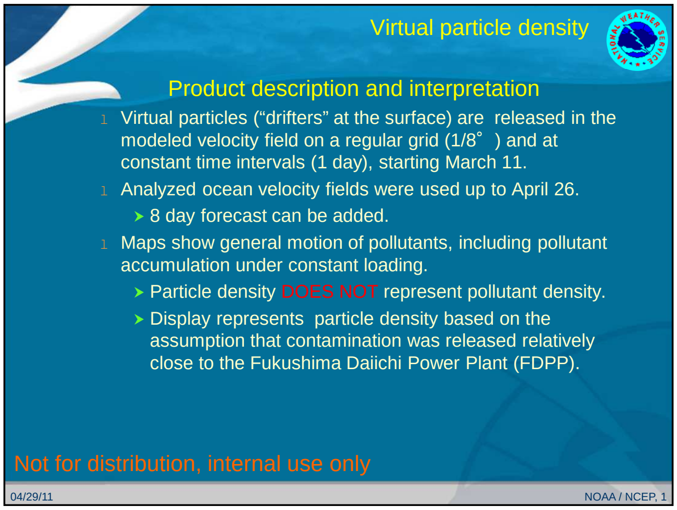
C First product (plume density)



Virtual particle density

Product description and interpretation

- Virtual particles (“drifters” at the surface) are released in the modeled velocity field on a regular grid (1/8˚) and at constant time intervals (1 day), starting March 11.
- Analyzed ocean velocity fields were used up to April 26.
  - 8 day forecast can be added.
- Maps show general motion of pollutants, including pollutant accumulation under constant loading.
  - Particle density DOES NOT represent pollutant density.
  - Display represents particle density based on the assumption that contamination was released relatively close to the Fukushima Daiichi Power Plant (FDPP).

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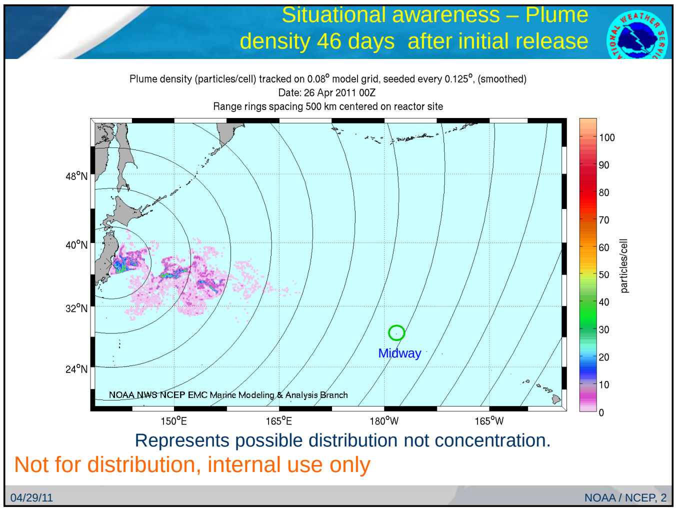
04/29/11 NOAA / NCEP, 1



Situational awareness – Plume density 46 days after initial release

Plume density (particles/cell) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Date: 26 Apr 2011 00Z
Range rings spacing 500 km centered on reactor site

Represents possible distribution not concentration.

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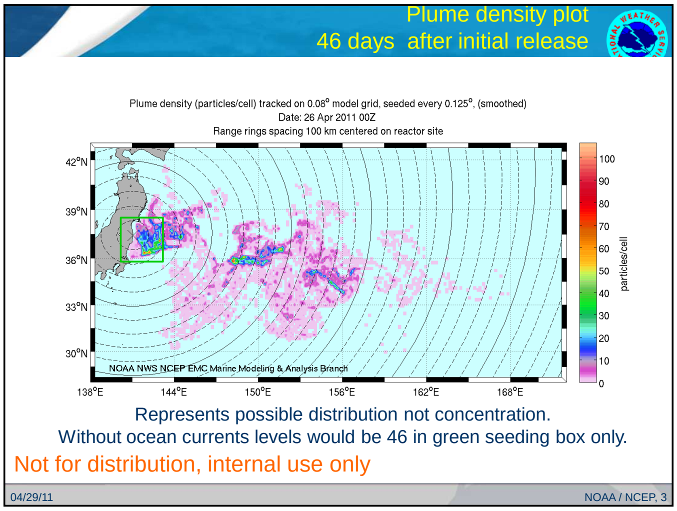
04/29/11 NOAA / NCEP, 2



Plume density plot 46 days after initial release

Plume density (particles/cell) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Date: 26 Apr 2011 00Z
Range rings spacing 100 km centered on reactor site

Represents possible distribution not concentration.
Without ocean currents levels would be 46 in green seeding box only.

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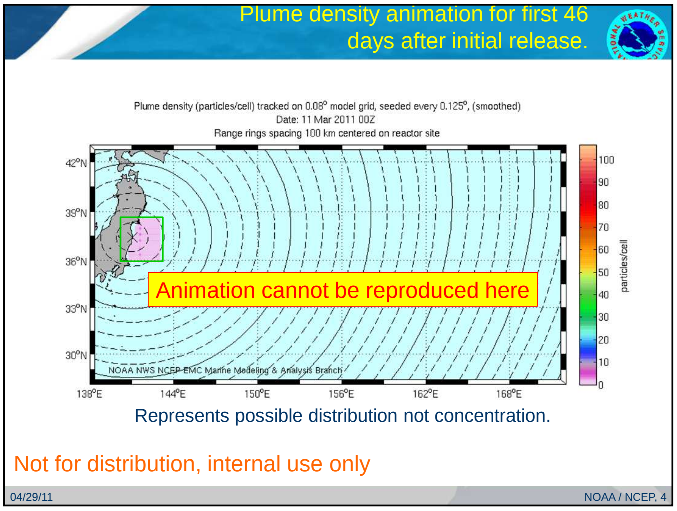
04/29/11 NOAA / NCEP, 3



Plume density animation for first 46 days after initial release.

Plume density (particles/cell) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Date: 11 Mar 2011 00Z
Range rings spacing 100 km centered on reactor site

Animation cannot be reproduced here

Represents possible distribution not concentration.

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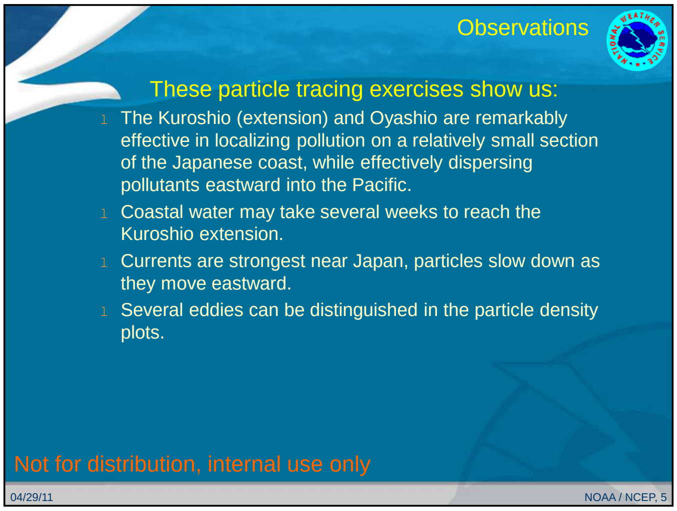
04/29/11 NOAA / NCEP, 4



Observations

These particle tracing exercises show us:

- The Kuroshio (extension) and Oyashio are remarkably effective in localizing pollution on a relatively small section of the Japanese coast, while effectively dispersing pollutants eastward into the Pacific.
- Coastal water may take several weeks to reach the Kuroshio extension.
- Currents are strongest near Japan, particles slow down as they move eastward.
- Several eddies can be distinguished in the particle density plots.

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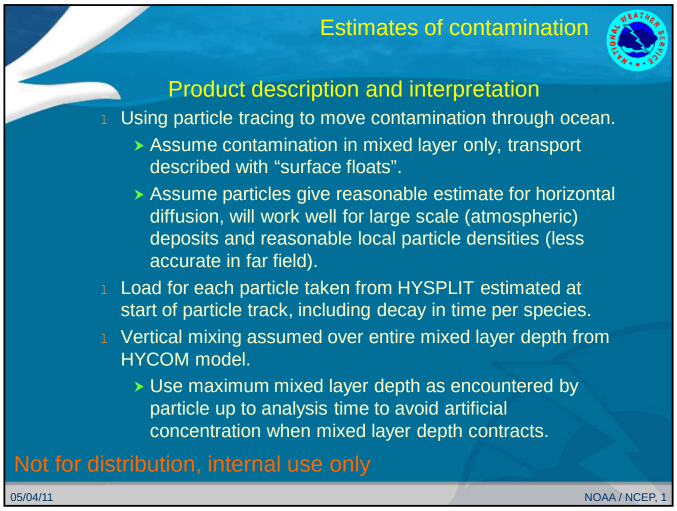
NOAA / NCEP, 5

D Second product (contamination from particles)



Estimates of contamination

Product description and interpretation

- Using particle tracing to move contamination through ocean.
  - Assume contamination in mixed layer only, transport described with “surface floats”.
  - Assume particles give reasonable estimate for horizontal diffusion, will work well for large scale (atmospheric) deposits and reasonable local particle densities (less accurate in far field).
- Load for each particle taken from HYSPLIT estimated at start of particle track, including decay in time per species.
- Vertical mixing assumed over entire mixed layer depth from HYCOM model.
  - Use maximum mixed layer depth as encountered by particle up to analysis time to avoid artificial concentration when mixed layer depth contracts.

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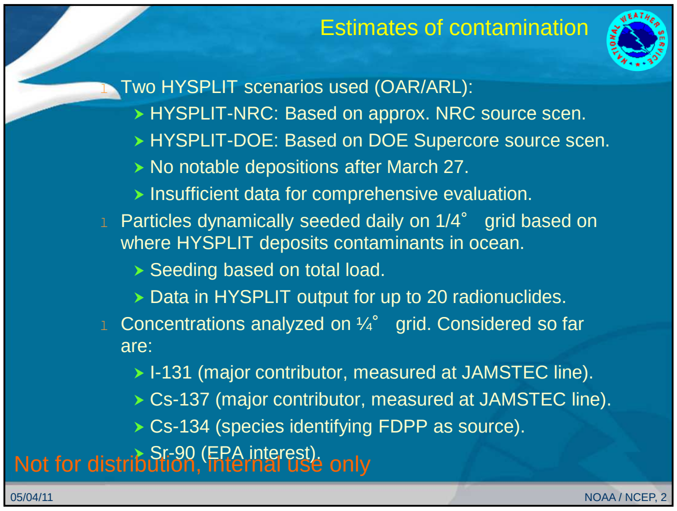
05/04/11 NOAA / NCEP, 1



Estimates of contamination

- Two HYSPLIT scenarios used (OAR/ARL):
  - HYSPLIT-NRC: Based on approx. NRC source scen.
  - HYSPLIT-DOE: Based on DOE Supercore source scen.
  - No notable depositions after March 27.
  - Insufficient data for comprehensive evaluation.
- Particles dynamically seeded daily on 1/4° grid based on where HYSPLIT deposits contaminants in ocean.
  - Seeding based on total load.
  - Data in HYSPLIT output for up to 20 radionuclides.
- Concentrations analyzed on ¼° grid. Considered so far are:
  - I-131 (major contributor, measured at JAMSTEC line).
  - Cs-137 (major contributor, measured at JAMSTEC line).
  - Cs-134 (species identifying FDPP as source).
  - Sr-90 (EPA interest).

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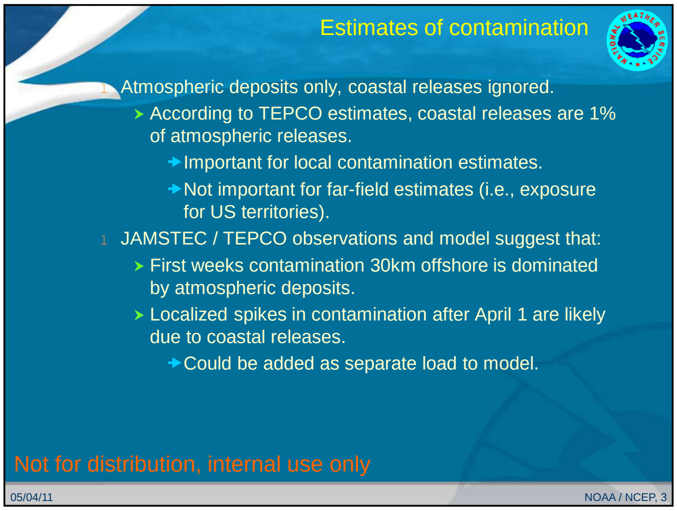

Estimates of contamination

- Atmospheric deposits only, coastal releases ignored.
  - According to TEPCO estimates, coastal releases are 1% of atmospheric releases.
    - Important for local contamination estimates.
    - Not important for far-field estimates (i.e., exposure for US territories).
- JAMSTEC / TEPCO observations and model suggest that:
  - First weeks contamination 30km offshore is dominated by atmospheric deposits.
  - Localized spikes in contamination after April 1 are likely due to coastal releases.
    - Could be added as separate load to model.

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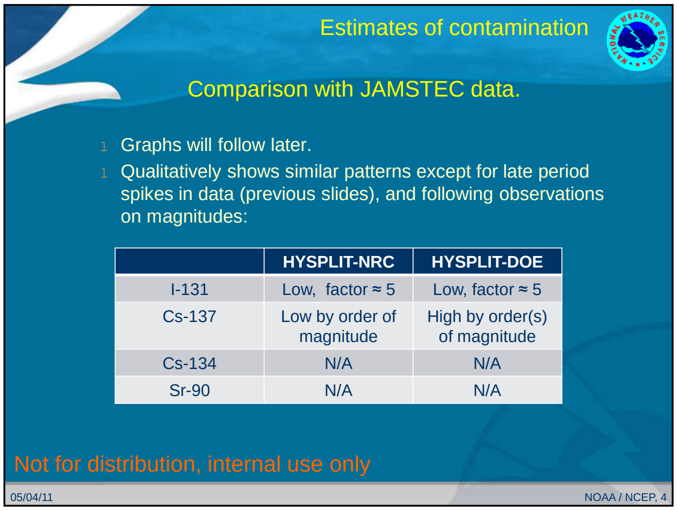

Estimates of contamination

Comparison with JAMSTEC data.

- Graphs will follow later.
- Qualitatively shows similar patterns except for late period spikes in data (previous slides), and following observations on magnitudes:

	HYSPLIT-NRC	HYSPLIT-DOE
I-131	Low, factor ≈ 5	Low, factor ≈ 5
Cs-137	Low by order of magnitude	High by order(s) of magnitude
Cs-134	N/A	N/A
Sr-90	N/A	N/A

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Estimates of contamination

- Particularly for Cesium, there is an enormous uncertainty in the total source size.
- Simple model introduces uncertainties, but it appears that source uncertainties dominate uncertainties in model results.

NOTE:

FOLLOWING SLIDES ARE IN Bq/L SHOWING RANGE OF RESULTS UP TO UNDETECTABLE LEVELS. FOR PUBLIC USE, RESULTS NEED TO BE NORMALIZED AND THRESHOLDED..

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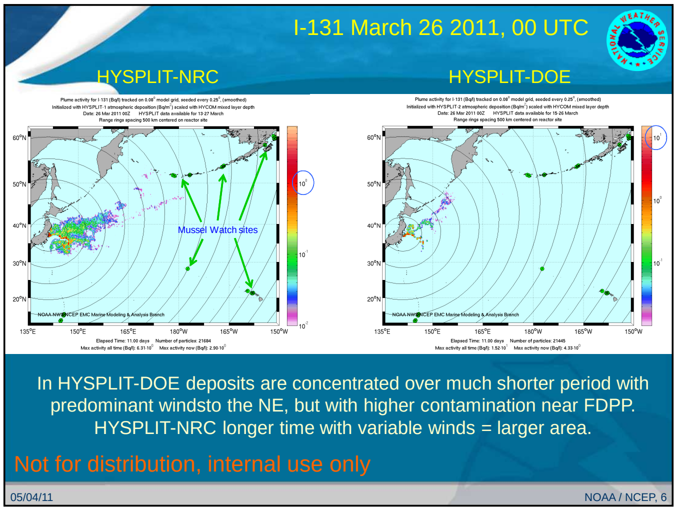

I-131 March 26 2011, 00 UTC

HYSPLIT-NRC

HYSPLIT-DOE

In HYSPLIT-DOE deposits are concentrated over much shorter period with predominant windsto the NE, but with higher contamination near FDPP. HYSPLIT-NRC longer time with variable winds = larger area.

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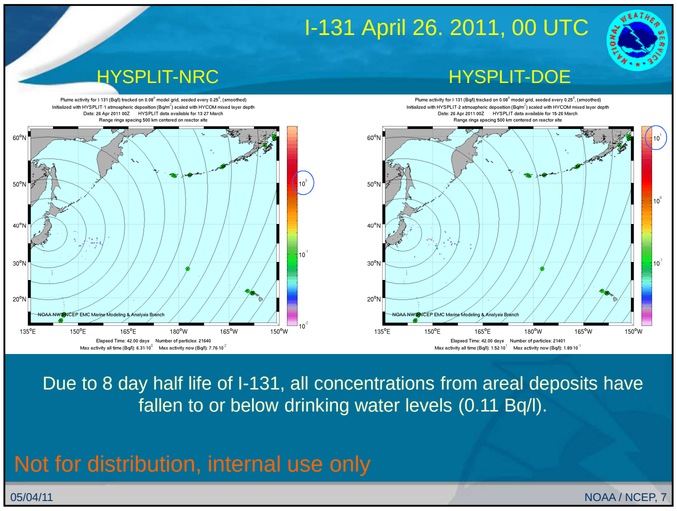

I-131 April 26. 2011, 00 UTC

HYSPLIT-NRC

Plume activity for I-131 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-1 atmospheric deposition (Bq/m²) scaled with HYCOM mixed layer depth
Date: 26 Apr 2011 00Z HYSPLIT data available for 13-27 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 42.00 days Number of particles: 21640
Max activity all time (Bq/l): $6.31 \cdot 10^0$ Max activity now (Bq/l): $7.76 \cdot 10^{-2}$

HYSPLIT-DOE

Plume activity for I-131 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-2 atmospheric deposition (Bq/m²) scaled with HYCOM mixed layer depth
Date: 26 Apr 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 42.00 days Number of particles: 21401
Max activity all time (Bq/l): $1.52 \cdot 10^1$ Max activity now (Bq/l): $1.89 \cdot 10^{-1}$

Due to 8 day half life of I-131, all concentrations from areal deposits have fallen to or below drinking water levels (0.11 Bq/l).

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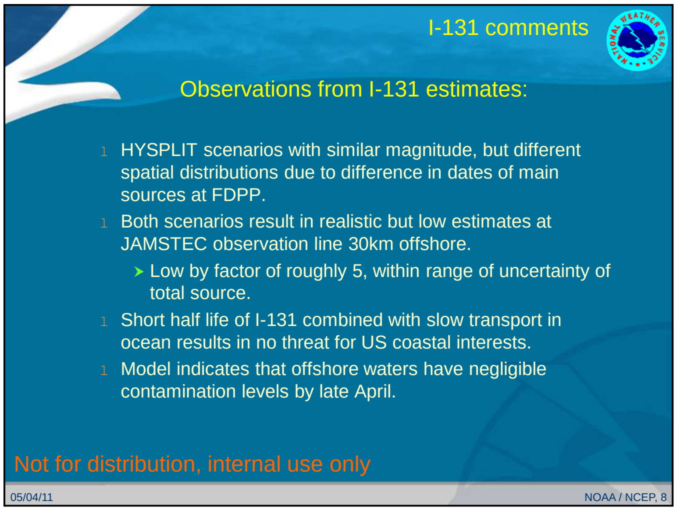
05/04/11 NOAA / NCEP, 7



I-131 comments

Observations from I-131 estimates:

- HYSPLIT scenarios with similar magnitude, but different spatial distributions due to difference in dates of main sources at FDPP.
- Both scenarios result in realistic but low estimates at JAMSTEC observation line 30km offshore.
  - Low by factor of roughly 5, within range of uncertainty of total source.
- Short half life of I-131 combined with slow transport in ocean results in no threat for US coastal interests.
- Model indicates that offshore waters have negligible contamination levels by late April.

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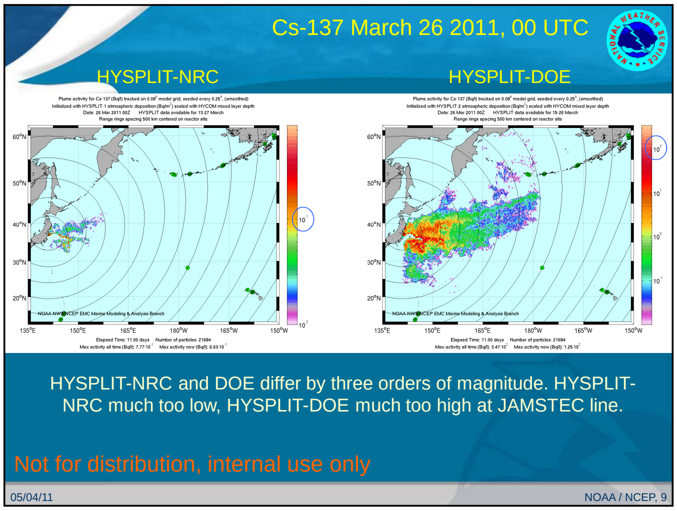
05/04/11 NOAA / NCEP, 8



Cs-137 March 26 2011, 00 UTC

HYSPLIT-NRC

HYSPLIT-DOE

HYSPLIT-NRC and DOE differ by three orders of magnitude. HYSPLIT-NRC much too low, HYSPLIT-DOE much too high at JAMSTEC line.

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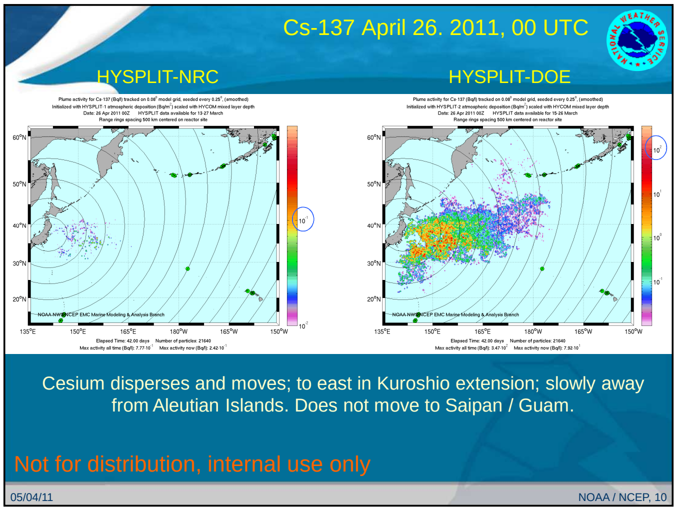
05/04/11

NOAA / NCEP, 9



Cs-137 April 26. 2011, 00 UTC

HYSPLIT-NRC

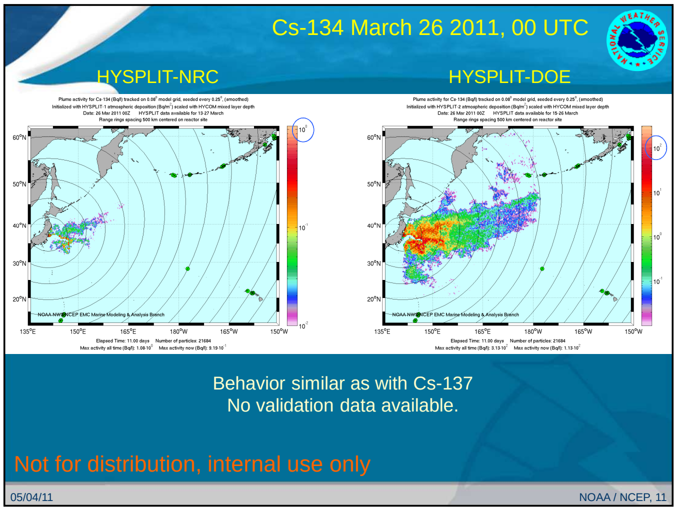
HYSPLIT-DOE

Cesium disperses and moves; to east in Kuroshio extension; slowly away from Aleutian Islands. Does not move to Saipan / Guam.

Not for distribution, internal use only

05/04/11

NOAA / NCEP, 10



Cs-134 March 26 2011, 00 UTC

HYSPLIT-NRC

HYSPLIT-DOE

Plume activity for Cs-134 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-1 atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 26 Mar 2011 00Z HYSPLIT data available for 13-27 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 11.00 days Number of particles: 21684
Max activity all time (Bq/l): $1.08\cdot10^0$ Max activity now (Bq/l): $9.19\cdot10^{-1}$

Plume activity for Cs-134 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-2 atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 26 Mar 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 11.00 days Number of particles: 21684
Max activity all time (Bq/l): $3.13\cdot10^2$ Max activity now (Bq/l): $1.13\cdot10^2$

Behavior similar as with Cs-137
No validation data available.

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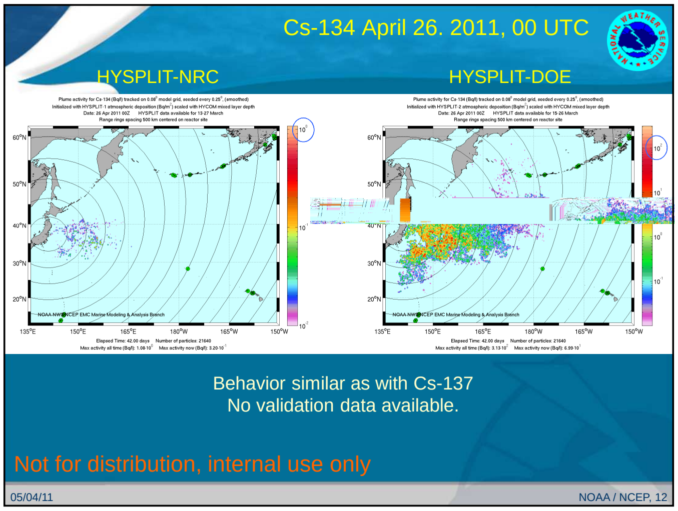


Cs-134 April 26. 2011, 00 UTC

HYSPLIT-NRC

HYSPLIT-DOE

Plume activity for Cs-134 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-1 atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 26 Apr 2011 00Z HYSPLIT data available for 13-27 March
Range rings spacing 500 km centered on reactor site

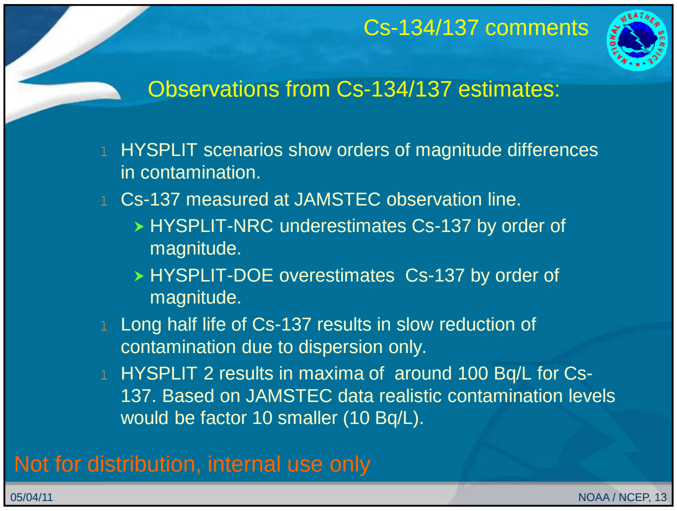
Elapsed Time: 42.00 days Number of particles: 21640
Max activity all time (Bq/l): $1.08\cdot10^0$ Max activity now (Bq/l): $3.20\cdot10^{-1}$

Plume activity for Cs-134 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-2 atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 26 Apr 2011 00Z HYSPLIT data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 42.00 days Number of particles: 21640
Max activity all time (Bq/l): $3.13\cdot10^2$ Max activity now (Bq/l): $6.99\cdot10^1$

Behavior similar as with Cs-137
No validation data available.

Not for distribution, internal use only



Cs-134/137 comments

Observations from Cs-134/137 estimates:

- HYSPLIT scenarios show orders of magnitude differences in contamination.
- Cs-137 measured at JAMSTEC observation line.
  - HYSPLIT-NRC underestimates Cs-137 by order of magnitude.
  - HYSPLIT-DOE overestimates Cs-137 by order of magnitude.
- Long half life of Cs-137 results in slow reduction of contamination due to dispersion only.
- HYSPLIT 2 results in maxima of around 100 Bq/L for Cs-137. Based on JAMSTEC data realistic contamination levels would be factor 10 smaller (10 Bq/L).

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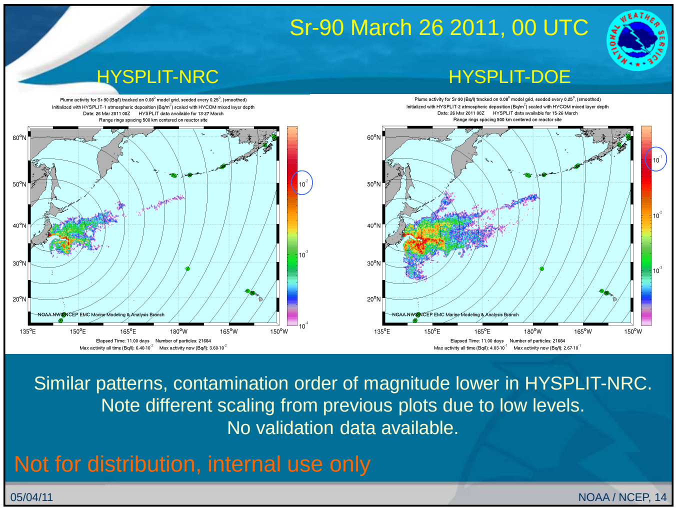

Sr-90 March 26 2011, 00 UTC

HYSPLIT-NRC HYSPLIT-DOE

Similar patterns, contamination order of magnitude lower in HYSPLIT-NRC.
Note different scaling from previous plots due to low levels.
No validation data available.

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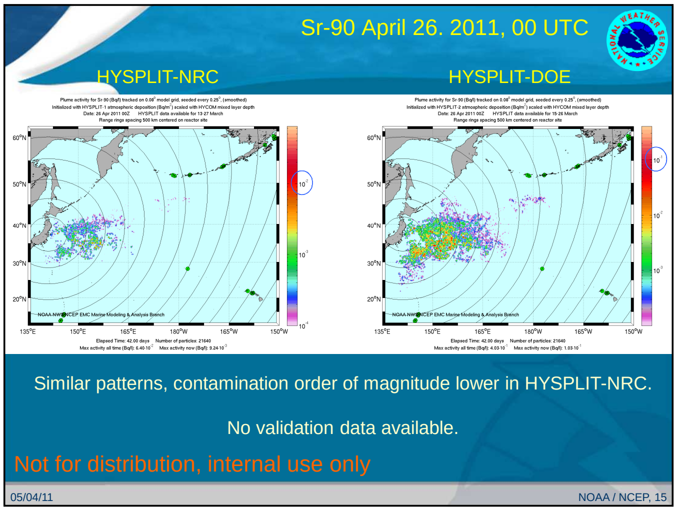


Sr-90 April 26. 2011, 00 UTC

HYSPLIT-NRC

HYSPLIT-DOE

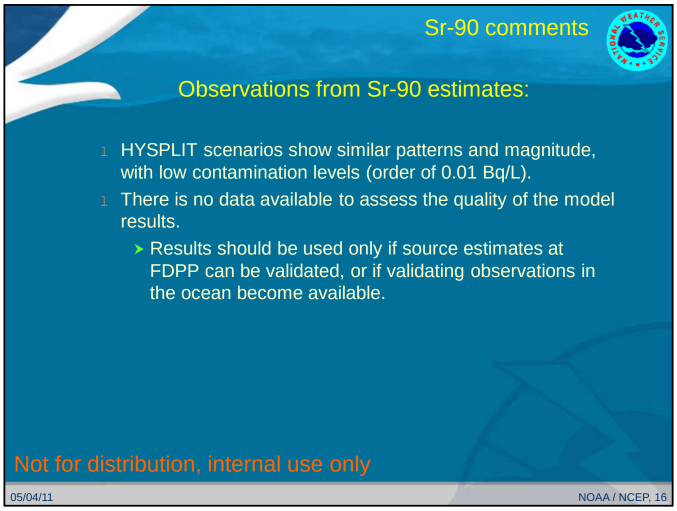
Similar patterns, contamination order of magnitude lower in HYSPLIT-NRC.

No validation data available.

Not for distribution, internal use only

05/04/11

NOAA / NCEP, 15



Sr-90 comments

Observations from Sr-90 estimates:

- HYSPLIT scenarios show similar patterns and magnitude, with low contamination levels (order of 0.01 Bq/L).
- There is no data available to assess the quality of the model results.
  - Results should be used only if source estimates at FDPP can be validated, or if validating observations in the ocean become available.

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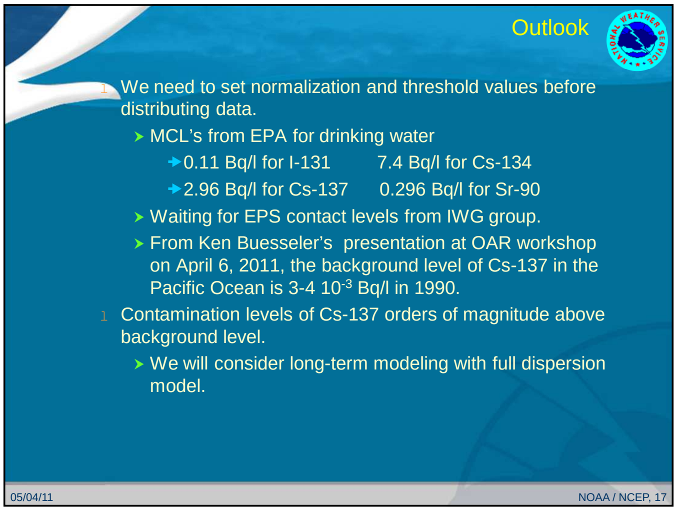
05/04/11

NOAA / NCEP, 16



Outlook

- We need to set normalization and threshold values before distributing data.
  - MCL's from EPA for drinking water
    - 0.11 Bq/l for I-131 7.4 Bq/l for Cs-134
    - 2.96 Bq/l for Cs-137 0.296 Bq/l for Sr-90
  - Waiting for EPS contact levels from IWG group.
  - From Ken Buesseler's presentation at OAR workshop on April 6, 2011, the background level of Cs-137 in the Pacific Ocean is 3-4 10^{-3} Bq/l in 1990.
- Contamination levels of Cs-137 orders of magnitude above background level.
  - We will consider long-term modeling with full dispersion model.

05/04/11

NOAA / NCEP, 17

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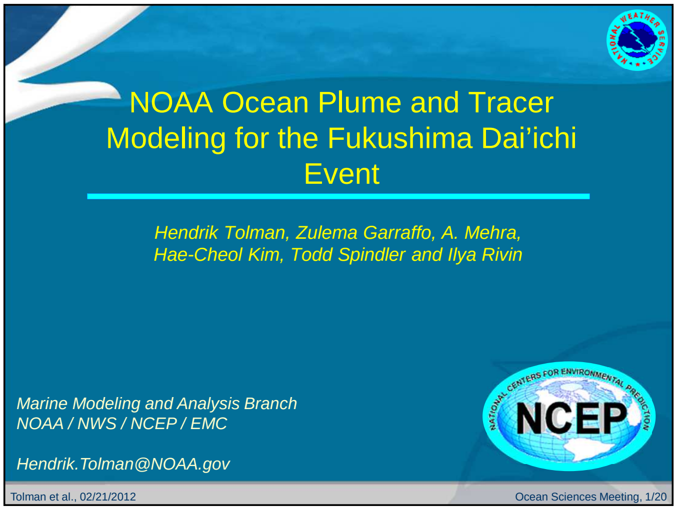
E Ocean Sciences 2012 (Salt Lake City, UT)

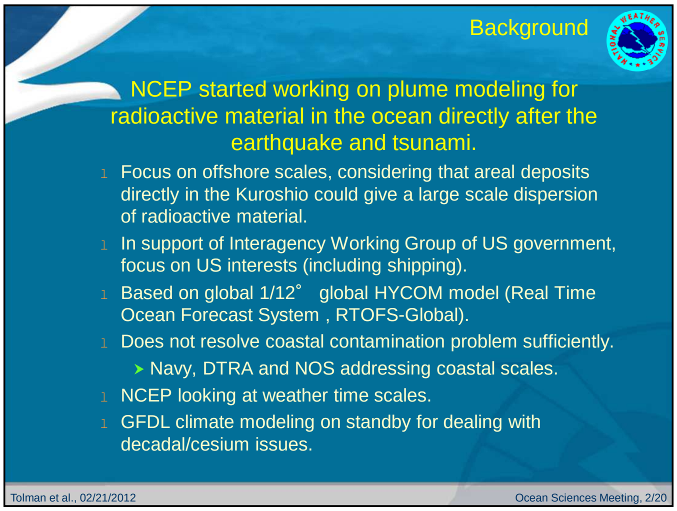


NOAA Ocean Plume and Tracer Modeling for the Fukushima Dai'ichi Event

Hendrik Tolman, Zulema Garraffo, A. Mehra,
Hae-Cheol Kim, Todd Spindler and Ilya Rivin

Marine Modeling and Analysis Branch
NOAA / NWS / NCEP / EMC

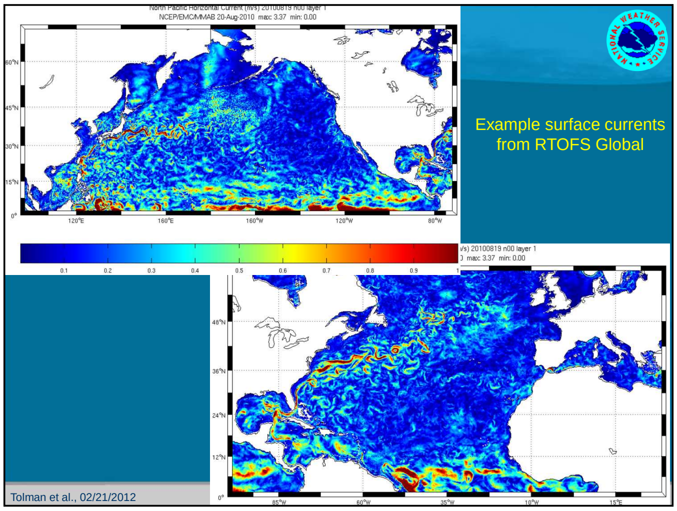
Hendrik.Tolman@NOAA.gov



Background

NCEP started working on plume modeling for radioactive material in the ocean directly after the earthquake and tsunami.

- Focus on offshore scales, considering that areal deposits directly in the Kuroshio could give a large scale dispersion of radioactive material.
- In support of Interagency Working Group of US government, focus on US interests (including shipping).
- Based on global 1/12° global HYCOM model (Real Time Ocean Forecast System , RTOFS-Global).
- Does not resolve coastal contamination problem sufficiently.
    - Navy, DTRA and NOS addressing coastal scales.
- NCEP looking at weather time scales.
- GFDL climate modeling on standby for dealing with decadal/cesium issues.



Example surface currents from RTOFS Global

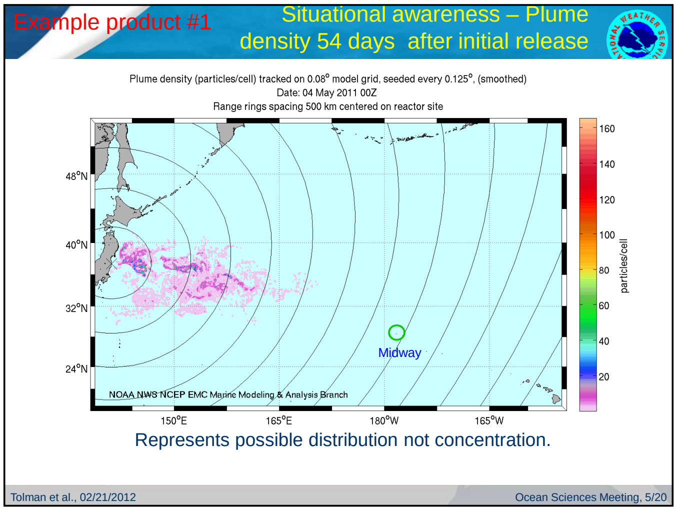
Tolman et al., 02/21/2012

Products

NOAA/NCEP products

- Virtual particle tracking:
  - Bi-weekly virtual particle density plots from particles seeded daily in 400x400km around FNPP.
  - Produced on regular schedule since April 8 2011.
  - Maintained for approximately 6 months
- Pollution estimates from particle tracking combined with atmospheric deposit of radionuclides.
  - Using atmospheric HYSPLIT deposit estimates.
  - Draft products since April 20, 2011.
  - Maintained for approximately 6 months.
- Long term monitoring of pollution of selected radionuclides using full dispersion modeling. To be implemented operationally.
  - NCEP with RTOFS-Global on basin scale (atm. deposits)
  - NOS with ROMS on coastal scale (coastal deposits)

Tolman et al., 02/21/2012 Ocean Sciences Meeting, 4/20



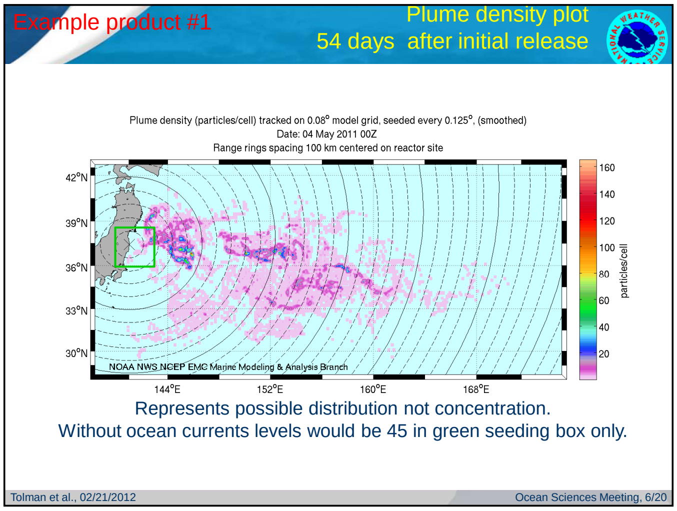
Situational awareness – Plume density 54 days after initial release

Plume density (particles/cell) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Date: 04 May 2011 00Z
Range rings spacing 500 km centered on reactor site

Represents possible distribution not concentration.

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 5/20



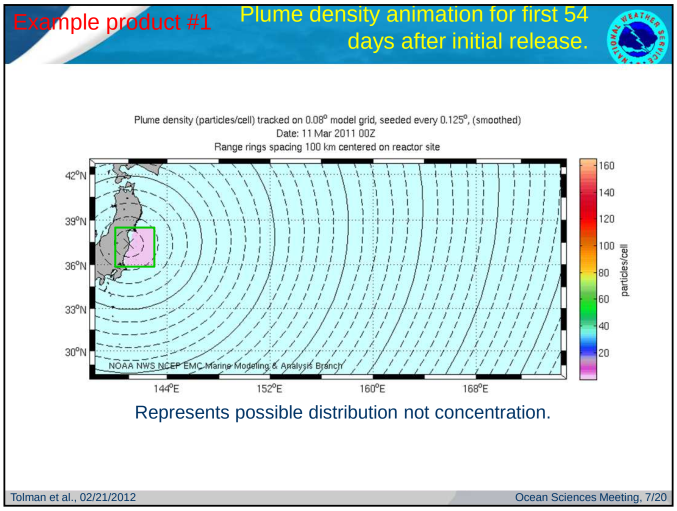
Plume density plot
54 days after initial release

Plume density (particles/cell) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Date: 04 May 2011 00Z
Range rings spacing 100 km centered on reactor site

Represents possible distribution not concentration.
Without ocean currents levels would be 45 in green seeding box only.

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 6/20

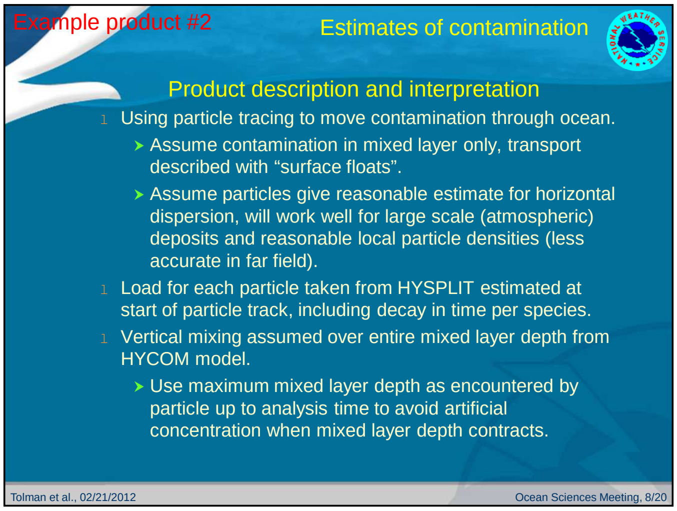


Example product #1

Plume density animation for first 54 days after initial release.

Plume density (particles/cell) tracked on 0.08° model grid, seeded every 0.125°, (smoothed)
Date: 11 Mar 2011 00Z
Range rings spacing 100 km centered on reactor site

Represents possible distribution not concentration.

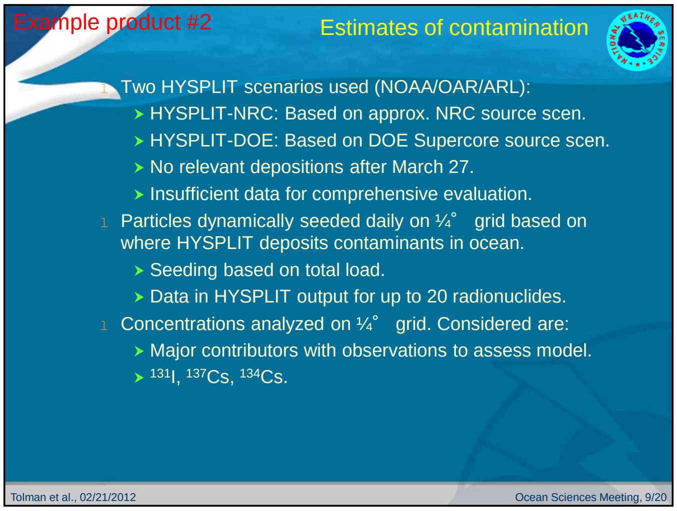


Example product #2

Estimates of contamination

Product description and interpretation

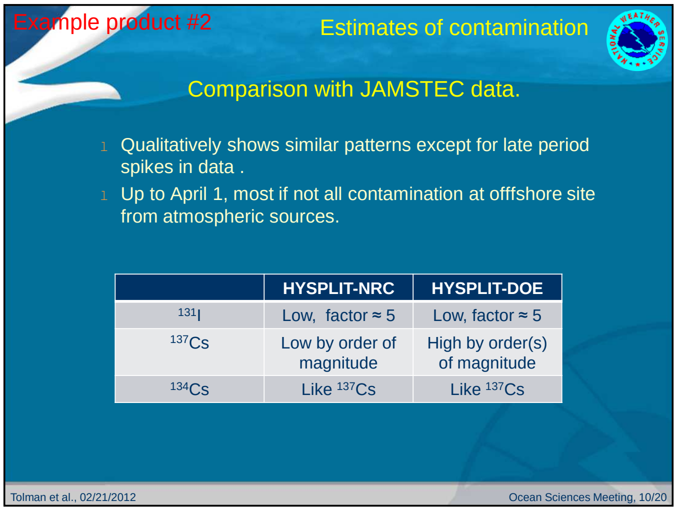
- Using particle tracing to move contamination through ocean.
  - Assume contamination in mixed layer only, transport described with "surface floats".
  - Assume particles give reasonable estimate for horizontal dispersion, will work well for large scale (atmospheric) deposits and reasonable local particle densities (less accurate in far field).
- Load for each particle taken from HYSPLIT estimated at start of particle track, including decay in time per species.
- Vertical mixing assumed over entire mixed layer depth from HYCOM model.
  - Use maximum mixed layer depth as encountered by particle up to analysis time to avoid artificial concentration when mixed layer depth contracts.



Example product #2

Estimates of contamination

- Two HYSPLIT scenarios used (NOAA/OAR/ARL):
  - HYSPLIT-NRC: Based on approx. NRC source scen.
  - HYSPLIT-DOE: Based on DOE Supercore source scen.
  - No relevant depositions after March 27.
  - Insufficient data for comprehensive evaluation.
- Particles dynamically seeded daily on ¼° grid based on where HYSPLIT deposits contaminants in ocean.
  - Seeding based on total load.
  - Data in HYSPLIT output for up to 20 radionuclides.
- Concentrations analyzed on ¼° grid. Considered are:
  - Major contributors with observations to assess model.
  - ^{131}I, ^{137}Cs, ^{134}Cs.



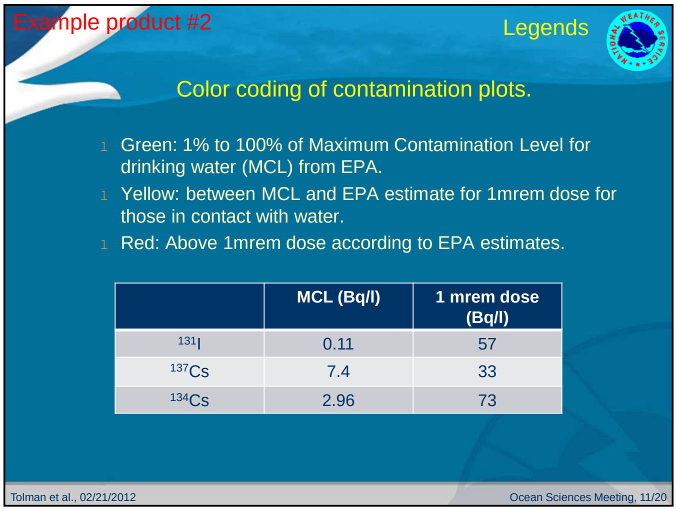
Example product #2

Estimates of contamination

Comparison with JAMSTEC data.

- Qualitatively shows similar patterns except for late period spikes in data .
- Up to April 1, most if not all contamination at offfshore site from atmospheric sources.

	HYSPLIT-NRC	HYSPLIT-DOE
^{131}I	Low, factor ≈ 5	Low, factor ≈ 5
^{137}Cs	Low by order of magnitude	High by order(s) of magnitude
^{134}Cs	Like ^{137}Cs	Like ^{137}Cs



Example product #2

Legends

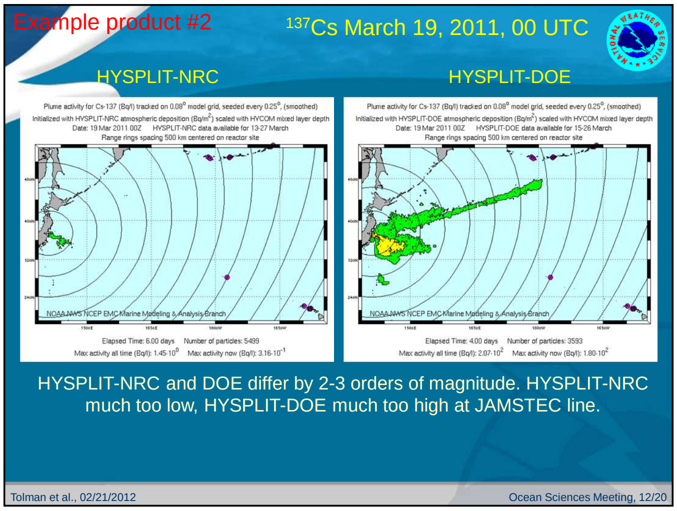
Color coding of contamination plots.

- Green: 1% to 100% of Maximum Contamination Level for drinking water (MCL) from EPA.
- Yellow: between MCL and EPA estimate for 1mrem dose for those in contact with water.
- Red: Above 1mrem dose according to EPA estimates.

	MCL (Bq/l)	**1 mrem dose (Bq/l)**
^{131}I	0.11	57
^{137}Cs	7.4	33
^{134}Cs	2.96	73

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 11/20



Example product #2

^{137}Cs March 19, 2011, 00 UTC

HYSPLIT-NRC

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-NRC atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 19 Mar 2011 00Z HYSPLIT-NRC data available for 13-27 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 6.00 days Number of particles: 5499
Max activity all time (Bq/l): $1.45 \cdot 10^{0}$ Max activity now (Bq/l): $3.16 \cdot 10^{-1}$

HYSPLIT-DOE

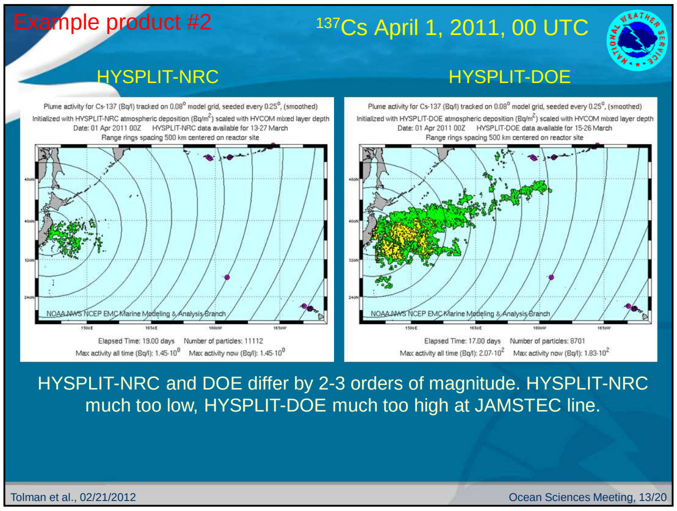
Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-DOE atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 19 Mar 2011 00Z HYSPLIT-DOE data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 4.00 days Number of particles: 3593
Max activity all time (Bq/l): $2.07 \cdot 10^{2}$ Max activity now (Bq/l): $1.80 \cdot 10^{2}$

HYSPLIT-NRC and DOE differ by 2-3 orders of magnitude. HYSPLIT-NRC much too low, HYSPLIT-DOE much too high at JAMSTEC line.

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 12/20



Example product #2

^{137}Cs April 1, 2011, 00 UTC

HYSPLIT-NRC

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-NRC atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 01 Apr 2011 00Z HYSPLIT-NRC data available for 13-27 March
Range rings spacing 500 km centered on reactor site

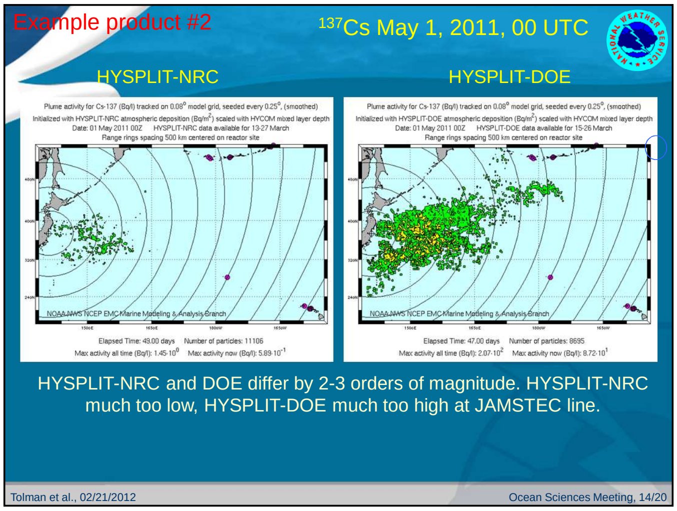
Elapsed Time: 19.00 days Number of particles: 11112
Max activity all time (Bq/l): $1.45 \cdot 10^0$ Max activity now (Bq/l): $1.45 \cdot 10^0$

HYSPLIT-DOE

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-DOE atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 01 Apr 2011 00Z HYSPLIT-DOE data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 17.00 days Number of particles: 8701
Max activity all time (Bq/l): $2.07 \cdot 10^2$ Max activity now (Bq/l): $1.83 \cdot 10^2$

HYSPLIT-NRC and DOE differ by 2-3 orders of magnitude. HYSPLIT-NRC much too low, HYSPLIT-DOE much too high at JAMSTEC line.



Example product #2

^{137}Cs May 1, 2011, 00 UTC

HYSPLIT-NRC

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-NRC atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 01 May 2011 00Z HYSPLIT-NRC data available for 13-27 March
Range rings spacing 500 km centered on reactor site

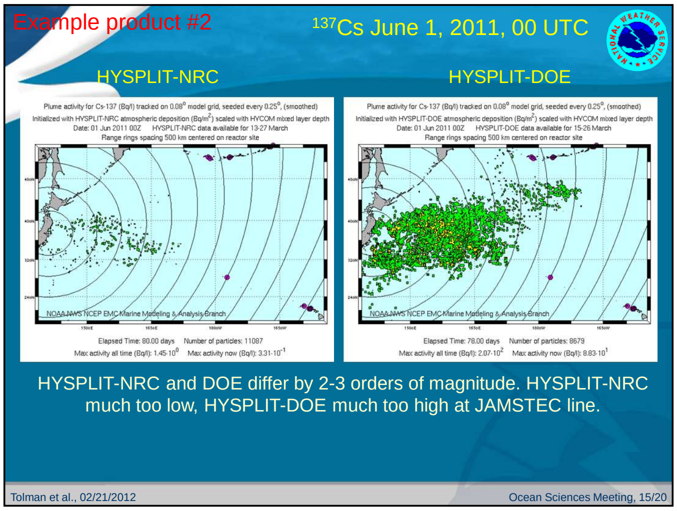
Elapsed Time: 49.00 days Number of particles: 11106
Max activity all time (Bq/l): $1.45 \cdot 10^0$ Max activity now (Bq/l): $5.89 \cdot 10^{-1}$

HYSPLIT-DOE

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-DOE atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 01 May 2011 00Z HYSPLIT-DOE data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 47.00 days Number of particles: 8695
Max activity all time (Bq/l): $2.07 \cdot 10^2$ Max activity now (Bq/l): $8.72 \cdot 10^1$

HYSPLIT-NRC and DOE differ by 2-3 orders of magnitude. HYSPLIT-NRC much too low, HYSPLIT-DOE much too high at JAMSTEC line.



Example product #2

^{137}Cs June 1, 2011, 00 UTC

HYSPLIT-NRC

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-NRC atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 01 Jun 2011 00Z HYSPLIT-NRC data available for 13-27 March
Range rings spacing 500 km centered on reactor site

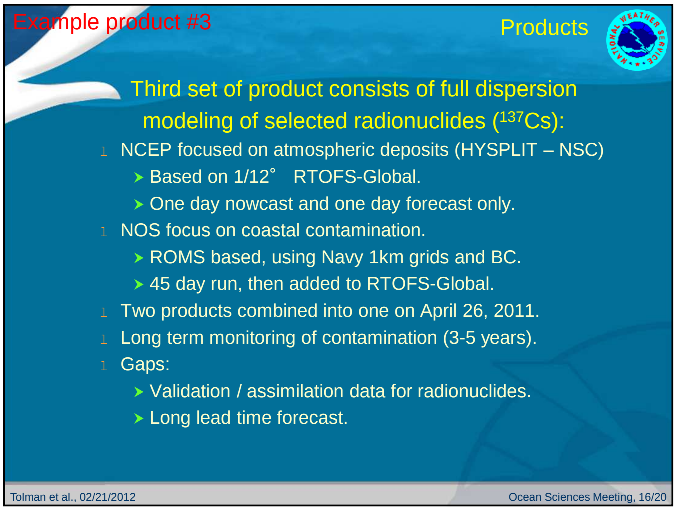
Elapsed Time: 80.00 days Number of particles: 11087
Max activity all time (Bq/l): $1.45 \cdot 10^0$ Max activity now (Bq/l): $3.31 \cdot 10^{-1}$

HYSPLIT-DOE

Plume activity for Cs-137 (Bq/l) tracked on 0.08° model grid, seeded every 0.25°, (smoothed)
Initialized with HYSPLIT-DOE atmospheric deposition (Bq/m^2) scaled with HYCOM mixed layer depth
Date: 01 Jun 2011 00Z HYSPLIT-DOE data available for 15-26 March
Range rings spacing 500 km centered on reactor site

Elapsed Time: 78.00 days Number of particles: 8679
Max activity all time (Bq/l): $2.07 \cdot 10^2$ Max activity now (Bq/l): $8.83 \cdot 10^1$

HYSPLIT-NRC and DOE differ by 2-3 orders of magnitude. HYSPLIT-NRC much too low, HYSPLIT-DOE much too high at JAMSTEC line.

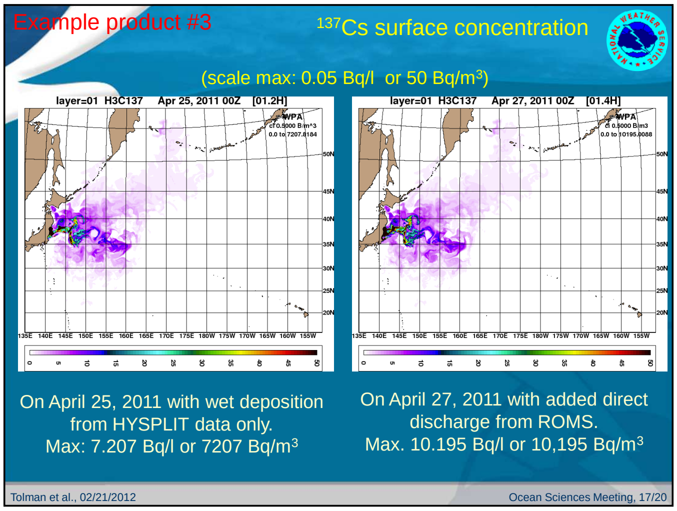


Example product #3

Products

Third set of product consists of full dispersion modeling of selected radionuclides (^{137}Cs):

- NCEP focused on atmospheric deposits (HYSPLIT – NSC)
  - Based on 1/12° RTOFS-Global.
  - One day nowcast and one day forecast only.
- NOS focus on coastal contamination.
  - ROMS based, using Navy 1km grids and BC.
  - 45 day run, then added to RTOFS-Global.
- Two products combined into one on April 26, 2011.
- Long term monitoring of contamination (3-5 years).
- Gaps:
  - Validation / assimilation data for radionuclides.
  - Long lead time forecast.



Example product #3

^{137}Cs surface concentration

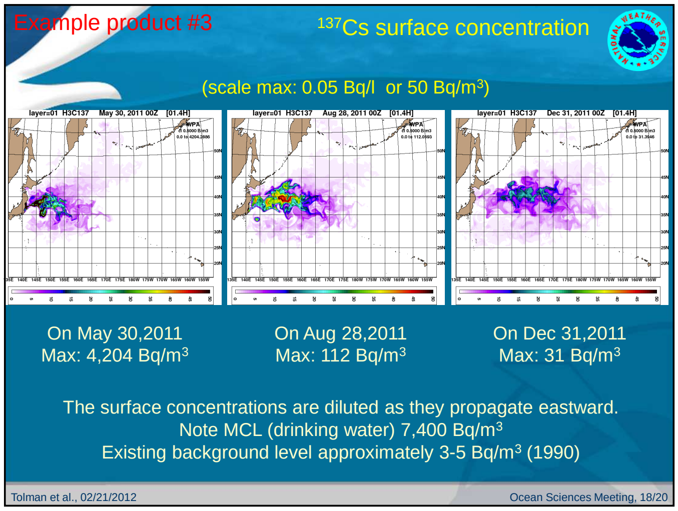
(scale max: 0.05 Bq/l or 50 Bq/m^3)

On April 25, 2011 with wet deposition from HYSPLIT data only.
Max: 7.207 Bq/l or 7207 Bq/m^3

On April 27, 2011 with added direct discharge from ROMS.
Max. 10.195 Bq/l or 10,195 Bq/m^3

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 17/20



Example product #3

^{137}Cs surface concentration

(scale max: 0.05 Bq/l or 50 Bq/m^3)

On May 30,2011
Max: 4,204 Bq/m^3

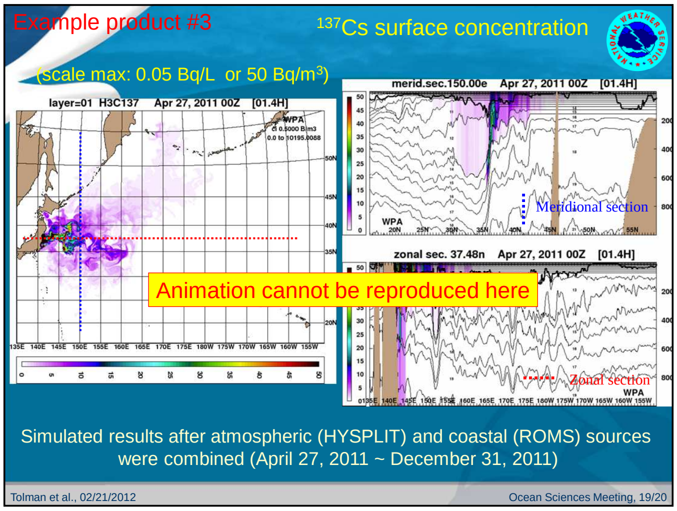
On Aug 28,2011
Max: 112 Bq/m^3

On Dec 31,2011
Max: 31 Bq/m^3

The surface concentrations are diluted as they propagate eastward.
Note MCL (drinking water) 7,400 Bq/m^3
Existing background level approximately 3-5 Bq/m^3 (1990)

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 18/20



Example product #3

^{137}Cs surface concentration

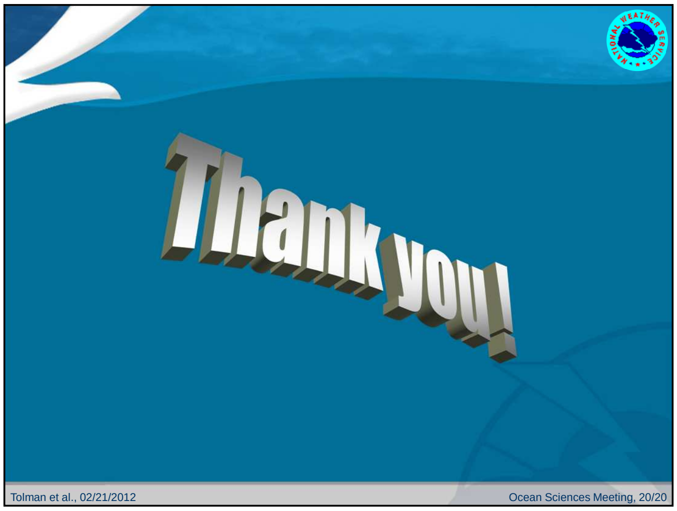
(scale max: 0.05 Bq/L or 50 Bq/m^3)

Animation cannot be reproduced here

Simulated results after atmospheric (HYSPLIT) and coastal (ROMS) sources were combined (April 27, 2011 ~ December 31, 2011)

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 19/20



Thank you!

Tolman et al., 02/21/2012

Ocean Sciences Meeting, 20/20