AIR–SEA TRANSPORT, DISPERSION, AND FATE MODELING IN THE VICINITY OF THE FUKUSHIMA NUCLEAR POWER PLANT

A Special Conference Session Summary

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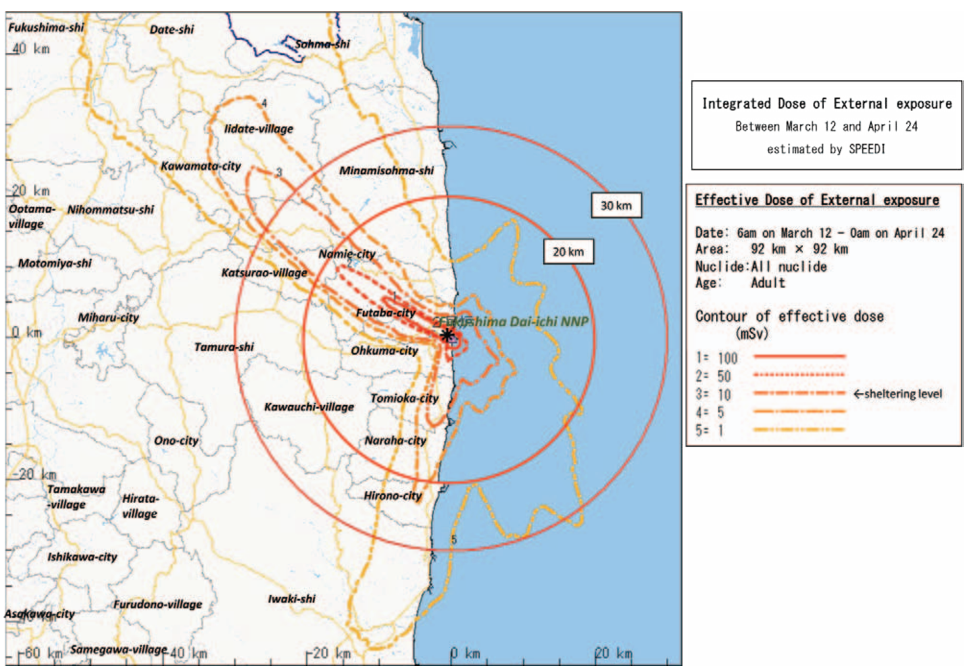
Evaluation of the operational air–sea modeling response to the 2011 radionuclide emissions crisis in Japan shows the need for accurate source information and for international coordination among parallel modeling efforts.



12 March to 24 April 2011 integrated dose (in mSv) computed by SPEEDI.

The ramifications of the Fukushima Daiichi nuclear power plant crisis continue to unfold. Scientific papers document the heterogeneous distribution (patchiness) of radioisotopes at distances over 200 km from the release site (Yasunari et al. 2011). The impact of this spatial patchiness on human health and food safety on land and in the sea is being discovered as Japan mounts a $300 million study to track the cohort of exposed children and expands the seafood and agriculture monitoring effort. Several hundred thousand people have been evacuated, and a 20-km exclusion zone has been established.

In the aftermath of the 11 March 2011 earthquake and tsunami in Japan, the Fukushima Daiichi nuclear power plant cooling systems failed. Over the subsequent days, weeks, and months, ▶

radionuclides were emitted into the atmosphere and ocean. In the initial days after the catastrophe, the focus of the operational forecast community was on the events at the reactor site, including venting, fires, and explosions that could imperil the surrounding populations. As time went on and the emissions continued at a reduced rate, the community shifted to a more focused campaign to define the source term and accumulate dosage predictions to help interpret the airborne and ground-based monitoring and mapping. Several weeks into the crisis, the controlled and uncontrolled leaks into the coastal ocean became manifest and contaminant prediction for the ocean ramped up.

We were involved in some of the initial atmospheric and oceanic modeling, and decided to organize a special session at the annual George Mason University (GMU) Conference on Atmospheric Transport and Dispersion held in July 2011. The special session was designed to examine the role of operational models for air–sea radionuclide transport and dispersion during the crisis, as applied to the local area of Japan (i.e., within a few hundred kilometers of the release). The participants at our special conference session came from the Nuclear Regulatory Commission (NRC), Defense Threat Reduction Agency (DTRA), Naval Research Laboratory (NRL), National Oceanic and Atmospheric Administration (NOAA), Japan Atomic Energy Agency (JAEA), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), University of Toulouse/National Center for Scientific Research (CNRS; France), French Institute for Radioprotection and Nuclear Safety (IRSN), and Joint Research Centre/European Commission (JRC/EC; Italy), among others.

Below we summarize the major release events in the atmosphere and ocean, provide information on the emergency response decisions, and describe air–sea modeling tools employed during the crisis as reported by conference participants. A panel discussion also took place during the special session and is covered in the final section of this paper. That panel discussion provided insights and recommendations for improving prediction and response.

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EPISODIC RELEASES AND SHIFTING WINDS. In the atmosphere, there were multiple release events in the first several weeks that delivered the bulk of the radioisotopes to regions downwind. During those several weeks venting (“feed and bleed”), explosions, and fires plagued the various reactors at the facility and distributed and deposited radionuclides via atmospheric transport and dispersion. All of the conference participants mentioned the lack of good source-emission information, including locations (horizontal position) and elevations of sources, time variations of mass release rates, and chemical and physical compositions as a particular challenge. Uncertainties in model-predicted concentrations and depositions are directly related to uncertainties in source-emission release rates. The following is a brief chronology of the major release events, based on a compilation of information presented at the conference.

In the first several days after the power loss, the operator [Tokyo Electric Power Company (TEPCO)] vented the reactors to relieve the pressure in the containment and to try to prevent explosions. During the initial period the winds were predominantly from the northwest (the prevailing direction in mid-March), directed offshore, and therefore transported the atmospheric plume over the ocean.

The winds were onshore (from the southeast) for several hours on 15 March. Source-term estimates published rapidly by JAEA researchers (Chino et al. 2011) establish that the greatest release from the Fukushima reactors occurred in the late morning/early afternoon of 15 March when explosions rocked several of the reactors and fires were ongoing at the spent fuel pool. Later that afternoon and early evening, rain deposited cesium and iodine in a plume transported by winds toward the northwest. The fallout pattern from this event was mapped at a later time, as shown in Fig. 1 (Data acquired by MEXT and DOE). Chino et al. (2011) estimate a 6-h release on 15 March [from 0900 to 1500 Japan standard time (JST)] of 10^{16} Bq h^{-1} of radioactive iodine. This event spread radioisotopes along a band through the mountains and affected areas more than 30 km away from the plant, such as the village of Iitate. It also deposited radionuclides on the mountain streams.

Another period of offshore winds ensued. Then, on 21–22 March the winds blew toward the south and southeast with a smoke seen coming out of reactors 2 and 3. Radioactive elements spread toward the outer regions of Tokyo and some deposition occurred with rainfall (Kinoshita et al. 2011).

EXPANDING EVACUATIONS. On 11 March immediately following the earthquake and tsunami, the Japanese government issued an evacuation order for a 3-km radius. On 12 March the evacuation zone expanded first to a 10-km radius, followed by a 20-km radius around the plant. The government advised sheltering in place out to a 30-km radius on 15 March. On 17 March the United States, amid fears of a worst-case catastrophic release fueled by a lack of information about the conditions at the site, advised U.S. citizens to evacuate out to 80 km. The U.S. NRC admitted the zone was conservative but that it was reasonable given the uncertainties of the situation. Other countries followed the U.S. or advised voluntary evacuation of all or part of their citizens in Japan. On 25 March Japan subsequently advised voluntary evacuation out to 30 km. On 11 April the Japanese government expanded the evacuation zone beyond circles to include hotspot regions located to the northwest of the plant, beyond the 20-km zone.

On 16 June the government designated new hotspots based on radiation surveys, in addition to the 20-km exclusion zone and the previously defined hotspots that covered specific communities. The new house-by-house hotspots exceeded the 30-km shelter-in-place zone and were often clustered near preexisting hotspots.

While circular evacuation patterns may make sense for an isolated incident, in the face of a prolonged chronic airborne threat they proved problematic. Over time the Japanese government shifted from circular zones to ones inclusive of the observed deposition created by coastal circulation patterns.

ATMOSPHERIC MODELING. After the power loss at the plant on 11 March the System for Prediction of Environmental Emergency Dose Information (SPEEDI; the Japanese government's radiological dose forecasting system) was applied but lacked adequate real-time source-emissions estimates. The SPEEDI model, employing 2-km-resolution weather

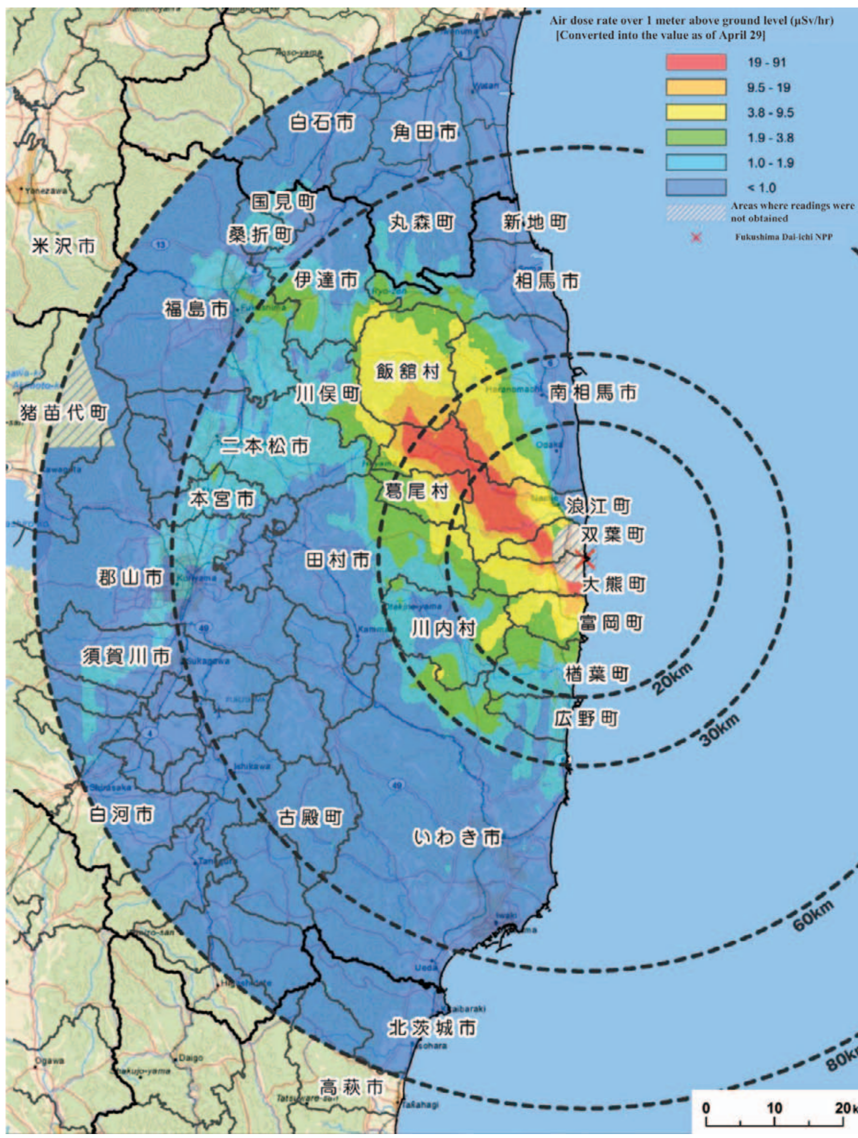

Fig. 1. Air dose rate 1 m above the ground (μSv h^{-1}) in the 80-km area surrounding the Fukushima nuclear power plant. Results are from 6–29 Apr airborne monitoring by a small airplane and two helicopters, in a total of 42 flights (Nuclear Emergency Response Headquarters 2011).

model fields as input, was run assuming a hypothetical source term and produced forecasts shortly after the crisis began. However, the quality of the simulations of concentrations and doses was not well known given the lack of an accurate source term. Onishi and Fackler (2011) note that three government agencies—the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), and the two nuclear regulators, the Nuclear and Industrial Safety Agency (NISA) and Nuclear Safety Commission (NSC)—exchanged their results, but there was no clear line of responsibility for the concentration and dose estimates. This had a negative impact on the evacuation decisions. For example, Namie, a community located within 20 km of the plant, was evacuated in the early hours of 12 March to a city that itself was being predicted by SPEEDI to be receiving elevated radiation loads (Hayashi 2011a). The mayor was not informed of the danger. SPEEDI also predicted deposition to the northwest of the plant on 15 March when the winds blew in that direction for a few hours and rain showers occurred, but the information was not disseminated to local officials who could have used it to guide evacuation strategies (Hayashi 2011b; Onishi and Fackler 2011).

At the end of April Japan's NSC commenced a full-scale public release of SPEEDI forecasts, both retrospectively and going forward. The Japanese government report stated, "Although the results generated by SPEEDI are now being disclosed, disclosure should have been conducted from the initial stage" (Nuclear Emergency Response Headquarters 2011).

Other non-Japanese governmental and international agencies also responded to the crisis using various modeling tools. The United States has a well-practiced national federal environmental modeling protocol for domestic emergency response where the Department of Homeland Security's Interagency Modeling and Atmospheric Assessment Center (IMAAC) would conduct and coordinate plume modeling for incidents of national significance. However, because the event took place in Japan, an IMAAC response was not activated. Nevertheless, several U.S. agencies carried out separate modeling of the Fukushima nuclear power plant release, including the Departments of Defense, Commerce, and Energy (DOE). In the immediate aftermath of the earthquake and tsunami, the response was humanitarian in nature and the Department of State provided critical coordination. As the magnitude of the Fukushima nuclear power plant accident became manifest, and more technical support from the U.S. NRC and Departments of Energy and Defense was needed, the character of the U.S. response shifted.

For the incident the U.S. NRC used a Lagrangian trajectory Gaussian puff model [the Radiological Assessment System for Consequence Analysis (RASCAL)], designed to simulate impacts from distances of 100 m or less to mesoscale distances (several hundred kilometers). At the special conference session, Lou Brandon of the U.S. NRC described the simulation timeline. Beginning on 12 March the NRC ran various scenarios initially assuming source-emission terms based on 10% and 100% core damage. They compared their results with the limited on-site monitoring data that became available after 14 March and provided their source-term estimates to the U.S. DOE's National Atmospheric Release Advisory Center (NARAC). The NARAC model is primarily intended to estimate radiological concentrations and doses in the United States, but was configured for Japan as a special effort. At the time of the conference session (July 2011), NARAC did not have permission to discuss or release plume forecasts used during the incident to inform U.S. evacuation policy and decision making. During the same time period as the NRC/NARAC response, the U.S. Defense Threat Reduction Agency (DTRA) provided U.S. Forces Japan (USFJ) with predictions of radiation doses using the Hazard Prediction and Assessment Capability (HPAC), a Lagrangian Gaussian puff model.

France's nuclear agency, the IRSN, predicted radiological consequences of the accident using their operational C3X system and using the Météo-France Applications of Research to Operations at MEsoscale (AROME) weather model forecasts at 2.5-km resolution. In the special session, Olivier Isnard of IRSN gave an account of his time in Tokyo, providing direct support to the French ambassador in that country's decision making in the crisis. Their effort consisted of significant outreach to the French public to summarize the forecast results on a daily basis and respond to public questions and concerns.

The private sector had an acute need for plume forecasts and guidance to aid in decisions related to business operations in the region as well as shipping and supply chain impacts. Many international businesses struggled with an appropriate response and often hired consultants to assemble and interpret forecasts from disparate sources to help guide their response strategies. This perspective was represented at the special session where we heard from a consultant for a major international company with operations in the Fukushima area, as well as scientists contacted by major shipping lines.

RADIOLOGICAL EMISSIONS TO THE SEA. As in the atmospheric releases, there were significant uncertainties in oceanic radiological source terms. In the ocean, the timing and method of distribution of radioactive contamination from Fukushima Daiichi changed significantly in the days after the accident. In the few weeks immediately following the earthquake and tsunami the ocean received airborne deposition from winds directed offshore. During this period, 80% of the total radioisotope mass is estimated to have blown out over the ocean (Stohl et al. 2011). In early April, inadvertent discharge of contaminated water from leaking containment facilities was identified. In the absence of sufficient storage, the plant also began intentionally discharging contaminated water that had been used to cool the reactors. These radioisotopes were transported in currents along the coast and some were deposited to the sediments. The majority of the contaminant load discharged directly to the ocean occurred between 21 March and 8 April, resulting in the "greatest single contamination by artificial radionuclides of the sea ever seen" (Institute for Radioprotection and Nuclear Safety 2011). Fortunately, dilution and mixing in the ocean served to reduce concentrations, particularly in the far field (Buesseler et al. 2011).

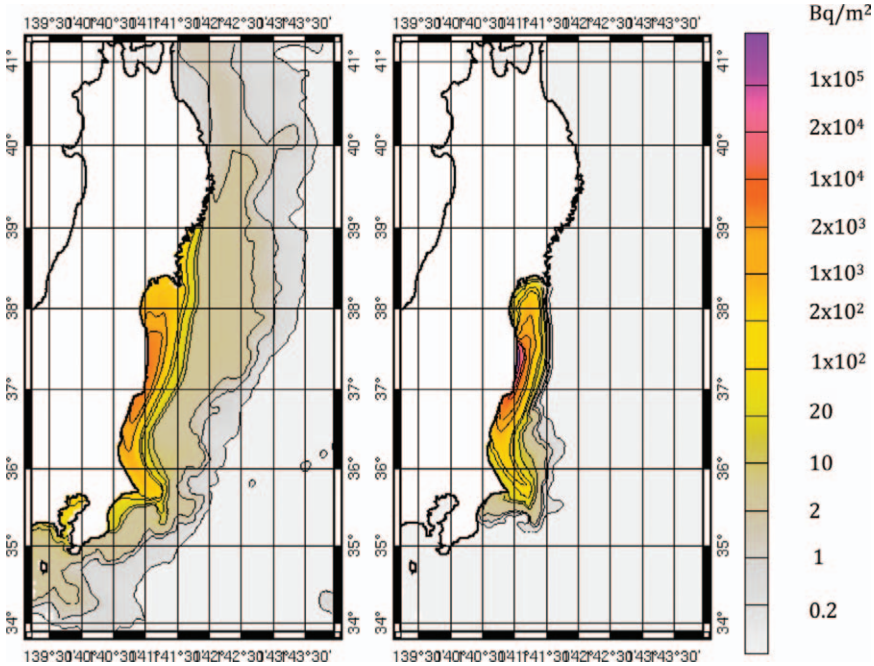

Fig. 2. The University of Toulouse/CNRS's SYMPHONIE model estimation of cumulative deposition of cesium-137 on the ocean sediment at the end of June (left) from atmospheric deposition and (right) from direct release into the ocean. Model assumptions include K_D = 4,000 l kg^{-1} (International Atomic Energy Agency 2004), a concentration of suspended matter of 5 mg l^{-1} and a sedimentation velocity of ~1 m day^{-1} (very fine suspended matter). [Courtesy of Claude Estournel, University of Toulouse/CNRS.]

COASTAL OCEAN AND RIVER MODELING.

Three-dimensional oceanic transport models were employed to predict contaminant circulation patterns off the coast of Japan by a variety of agencies and organizations. These models revealed that the winds were a dominant driver of local transport and diffusion, along with smaller-scale coastal processes.

Yukio Masumoto described JAMSTEC researchers' efforts in running the Japan Coastal Ocean Predictability Experiment—Tides (JCOPET) model with 3-km resolution, data assimilation, tides, rivers, hourly Japan Meteorological Agency weather model forcing, and tracer transport (with advection, diffusion, and half-life decay). The depth of the contaminated plume in the ocean was ~100–150 m, with offshore and southward excursions throughout April.

On 14 March the University of Toulouse and CNRS were tasked by the International Atomic Energy Agency (IAEA) with conducting embedded tracer coastal ocean simulations. As described by Claude Estournel at the GMU special session, the team provided model results on their website starting 24 March. Their SYMPHONIE model has 600-m resolution inshore out to 5-km resolution offshore, is nested within a global model, includes tidal forcing, and utilizes the European Centre for Medium-Range Forecasts (ECMWF) 3-hourly forcing at 0.25° resolution. An effort was made to match radiological source terms to in situ observations, which included an estimate of deposition from the atmosphere. The fallout (deposition) extended farther along the coast in the north–south direction, but the direct release into the ocean dominated close to the plant (Fig. 2). In the first month after the accident the plume was strongly confined to the coast either by weak winds or by southward winds driving shoreward Ekman transport.

NOAA and the U.S. Navy also provided operational support and experimental products. For example, at the GMU special session, Emanuel Coelho described how NRL Stennis Space Center produced 48-h forecasts of 2-km-nested ocean ensembles with particle trajectories to generate risk assessments going back to 1 March. These products were available on the web starting 25 March. The Navy Coastal Ocean Model (NCOM) was run at 1- and 3-km resolution and was also redistributed by NOAA. Moreover, NOAA ran the Hybrid Coordinate Ocean Model (HYCOM) and Regional Ocean Modeling System (ROMS) with a focus on the basin wide impacts. They provided preliminary HYCOM particle tracing results within the Pacific basin starting on 8 April. Presenters noted a large spread in ocean model predictions. Differing initial and boundary conditions and atmospheric forcing account for some of these discrepancies.

Given the solubility of cesium-137, a concern was the possible contamination of the drinking water for the ships supporting U.S. naval operations off the coast of Japan. Under DTRA support, Applied Science Associates (ASA) used their coastal model System for Hazard Assessment of Released Chemicals (SHARC), a three-dimensional Lagrangian transport model with time-dependent release and radioactive decay, to ingest HPAC ground deposition output data and assist in defining areas of potential impact offshore. Like the University of Toulouse/CNRS effort, analytical results from an evolving set of offshore monitoring stations were used in an effort to validate source terms. In addition, Science Applications International Corporation (SAIC) applied the Geospatial Streamflow Model (GEOSFM) and Incident Command Tool for Drinking Water Protection (ICWater) to model the transport and dispersion of radionuclides in coastal Japanese rivers, using source terms calculated from rainfall events and soil concentrations of isotopes at the river source.

IMPROVING ATMOSPHERIC AND OCEANIC FORECASTING IN THE COASTAL ZONE. The experiences shared by the participants in the GMU special session raised several key points. For example, no single model could account for all of the environmental processes important in the transport, dispersion, and fate of radionuclides in a nuclear power plant crisis such as that at Fukushima Daiichi. In general, and in the case of Fukushima Daiichi in particular, the primary deficiencies in the atmospheric models are related to the source-term uncertainties and to the treatment of chemical and physical behaviors of radioactive species.[1] The sources of error in the ocean models were also largely the result of uncertainties in the source term (including the neglect of sediment resuspension induced by waves and currents), but there were also uncertainties in wind-driven currents and in radioactive species transformations in an aqueous environment. The nuclear power plant is located near where the northward-flowing Kuroshio boundary current is prone to flow instability, eddies, and meanders. Consequently, it was particularly difficult to forecast the trajectory of a radiological release into the ocean in this complex environment.

The complexity of atmospheric and oceanic coastal processes acting on multiple scales was not represented by any model applied operationally in the crisis. More accurate prediction requires physical coupling of the oceanic and atmospheric models, along with a consistent treatment of the source term to account for fallout and fate (including resuspension). To enhance forecast skill, Haruyasu Nagai of JAEA described the latest version of Japan's SPEEDI—the SPEEDI Multi-Model Package, a coupled ocean–atmosphere system under development at ~1-km resolution.

A coupled air–sea ensemble capability employed in hindcast mode was presented by Teddy Holt from the U.S. NRL Monterey. He demonstrated the coastal variability in the Fukushima nuclear power plant area using 28 ensemble members drawn from the 5-km-resolution Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) with an atmospheric passive tracer. Ensemble members with slightly different initial or boundary conditions lead to variations in outcomes that can indicate uncertainty in weather conditions. In the simulations, a dominant sea breeze before the frontal passage on 15 March (the day of the greatest radionuclide release) brought a temperature drop and large spread in boundary layer wind direction and air temperature predictions among the ensemble members (Fig. 3). There was also a large ensemble spread on 15–16 March in the ECMWF products for the Japan region. These events can strongly influence transport and dispersion pathways in coastal Japan (Holt et al. 2009).

[1] A 22–23 February 2012 workshop at the U.S. National Center for Atmospheric Research on "Fukushima Airborne Radiation Source Term Estimation" is the subject of a separate workshop summary in this issue (Bieringer et al. 2013).

SUMMARY OF PANEL DISCUSSION. The special GMU conference session ended with a panel discussion on experiences and insights from the Fukushima nuclear power plant incident. A general conclusion from most participants in Japan and elsewhere was that, in the first month or two after the accident, individual agencies and laboratories mostly carried out their activities independently, and there was little data sharing. Some decision makers on the ground were unaware of some of the experimental modeling efforts that they felt could have added value to the decision-making process.

Anticipating that crises will increasingly cross national boundaries with their impacts and that compounding disasters are often not easily categorized, the coordinated and rapid sharing of information among agencies and governments is critical in order for it to be of value to decision makers. It is paramount that agreements and protocols be established and continuously rehearsed before an incident occurs. Sufficient resources must also be devoted to support the agreements and ensure that data exchanges are in compatible formats. Several participants pointed out that, in a crisis, it becomes virtually impossible to respond to outside requests that require additional time and explanation.

Stefano Galmarini (JRC/EC in Ispra, Italy) described the development and implementation

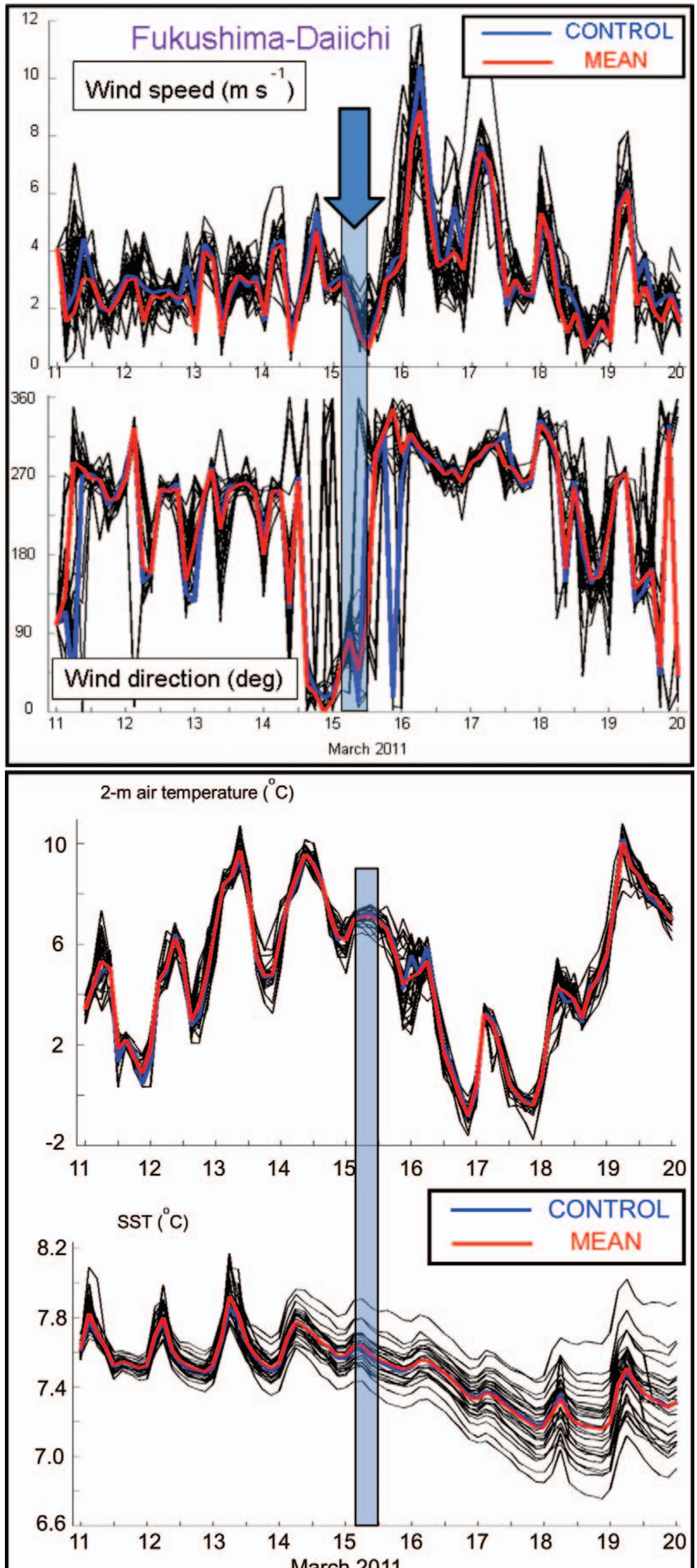

FIG. 3. Ensemble coupled model (COAMPS) predictions showing 28 ensemble members (black), the unperturbed control (blue), and the ensemble mean (red) for (top) Fukushima Daiichi 10-m wind speed and direction and (bottom) 2-m air temperature and SST at a point 15 km offshore of Fukushima Daiichi. The period of highest emissions during the accident is shown (gray shaded vertical box). [Courtesy of Teddy Holt, NRL-Monterey.]

of an ensemble system (Galmarini et al. 2004) that, if activated, could have been useful during the crisis. Ensemble forecasting aggregates the forecasts from multiple models to create (after appropriate postprocessing) a product that, in many cases, is superior to the constituent members. Dr. Galmarini demonstrated the method's ability to produce realistic contaminant maps for the 1986 Chernobyl disaster and the European Trace Experiment (ETEX). An international ensemble dispersion prediction system operating in real time would allow countries to share their detailed dispersion forecasts and provide input to decision making by mapping model spread and providing a quantitative measure of uncertainty.

A major conclusion of the panel discussions was that lack of information on the source terms hampers consistency, communication, and decision making among agencies and governments. Reports from the field suggest that an optimal course of action should be navigated between two decision-making extremes: over reaction fueled by worst-case scenarios and confusion/inaction driven by source-term uncertainty. The Fukushima Daiichi incident illustrated this dichotomy, with different countries recommending different evacuation zones based on the available information, including model predictions. More than one participant with direct experience noticed how initial worst-case scenarios formed a cognitive anchor for decision makers that was difficult to abandon when new and more refined measurement and modeling information became available. An example of the second extreme is poor evacuation planning early on due to the Japanese government's apprehension in utilizing SPEEDI model predictions without accurate source terms.

Finally, these model results must extend beyond a single realm. Hence, important linkages should be developed in advance of the next crisis to produce tools for more effective emergency response both on land and at sea.

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