RESEARCH

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Operational Atmospheric Modeling System CARIS for Effective Emergency Response Associated with Hazardous Chemical Releases in Korea

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ABSTRACT / The Chemical Accidents Response Information System (CARIS) was developed at the Center for Chemical Safety Management in South Korea in order to track and predict the dispersion of hazardous chemicals in the case of an accident or terrorist attack involving chemical companies. The main objective of CARIS is to facilitate an efficient emergency response to hazardous chemical accidents by rapidly providing key information in the decision-making process. In particular, the atmospheric modeling system implemented in CARIS, which is composed of a real-time numerical weather forecasting model and an air pollution dispersion model, can be used as a tool to forecast concentrations and to provide a wide range of assessments associated with various hazardous chemicals in real time.

This article introduces the components of CARIS and describes its operational modeling system. Some examples of the operational modeling system and its use for emergency preparedness are presented and discussed. Finally, this article evaluates the current numerical weather prediction model for Korea.

Chemical manufacturing is one of the world's largest industries, accounting for approximately 13% of the world trade in manufactured goods (OECD 1997). As thousands of new chemical products enter the global market every year, episodic cases of hazardous chemical releases such as phosgene and isocyanate and the increased threat of terrorist acts involving chemical toxins compel scientists to find better ways of managing chemicals, in order to minimize risk to the environment and to human health. In doing so, one needs to assess the hazards of chemicals and to manage the risks involved scientifically.

The key decision often rests on information gathered through the transport and dispersion models, which forecast the affected areas in the event of an accidental release of chemicals to the atmosphere. During such emergencies, accurate information on the distribution of concentrations is critically important in assessing the degree of exposure, evacuation plans, and emergency response procedures. Some studies demonstrate that the emergency systems based on meteorological and air quality models for the dispersion forecast can assist the decision-making process in cases involving nuclear accidents and oil spills (Galmarini and others 2001; Saltbones and others 1998; Annika and others 2001).

Recently, the Center for Chemical Safety Management (CCSM) in Korea developed the Chemical Accidents Response Information System (CARIS) as the main mechanism to control and manage hazardous chemicals. Under the Ministry of Environment's direction, CARIS conducts a comprehensive and sophisticated atmospheric modeling system, which is an important tool in generating quick forecasts of hazardous chemical dispersions. This article describes the main components of CARIS, presents some results of dispersion models, and evaluates the operational numerical weather prediction model.

Objectives and Applications of CARIS

As a technical support tool, CARIS addresses the chemical and physical properties of released chemicals, assesses quantitatively the risks and hazards of chemicals, and manages chemicals in meeting regulatory requirements for human health. In the event of an accident or a terrorist attack, CARIS provides the emergency response teams with stepwise emergency response procedures, information regarding the location of shelters and other evacuation venues, and ex-

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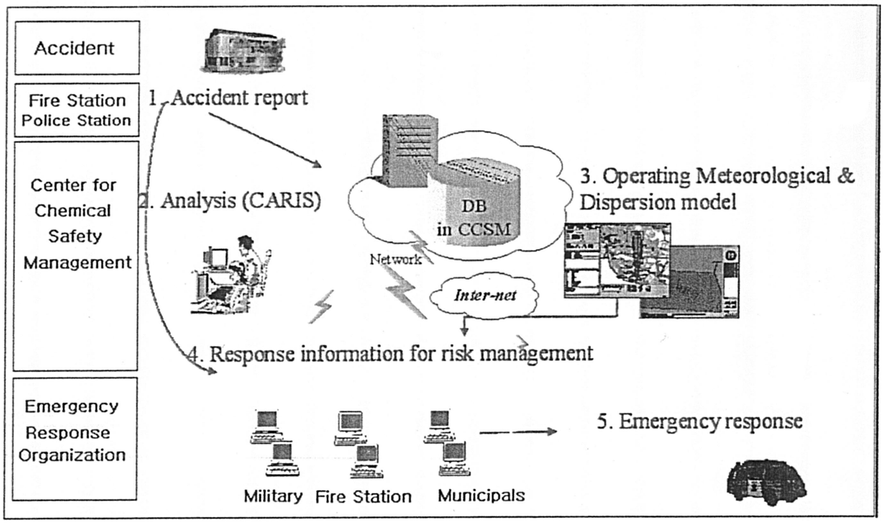

Figure 1. Sketch of CARIS as a tool for the emergency response for hazardous chemical releases.

pert advice on treating individuals exposed to chemicals.

Moreover, CARIS is able to direct and guide the emergency responders by identifying exposed zones and forecasting the dispersion of contaminants. The operational modeling system, consisting of weather forecasting and dispersion models, can predict effectively the trajectory of chemical movements and assess the duration of chemical passage. When hazardous chemicals are released from the storage tanks, the critical emergency response decision can be made effectively and supported by using the CARIS modeling system. Figure 1 illustrates the necessary emergency response units and information required for the response.

CARIS can also be used to establish roadblocks in the areas through which the emergency response units must pass and to provide various pieces of information such as notifying residents about evacuating to a shelter where they will be safe from potential harm.

System Components

CARIS consists of several components, as depicted in Figure 2. Numerical Weather Prediction (NWP) system, Dispersion and Air Quality Modeling (DAQM) system, Chemical/Physical Property Database (CPPD), Scenario Database (SD), and GIS Display Module (GDM).

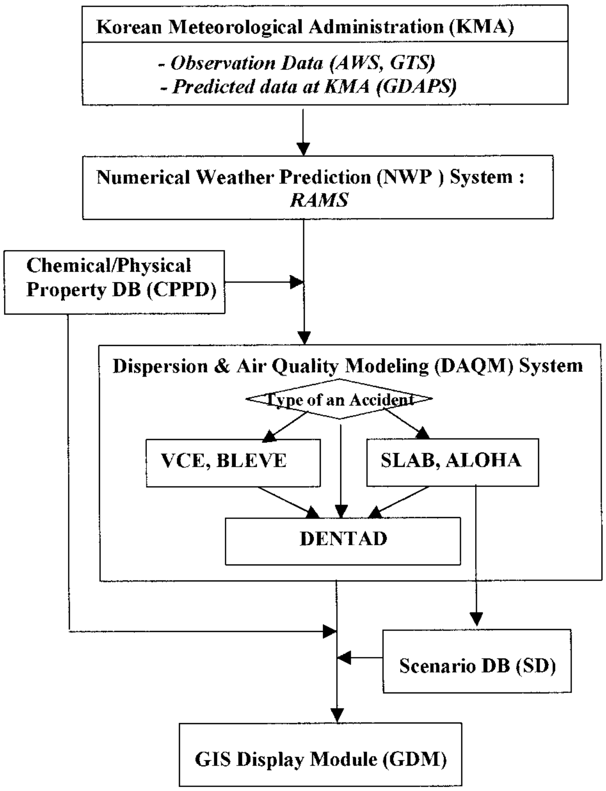

Figure 2. Schematic diagram of the main components and the data flow in the emergency response system CARIS.

Numerical Weather Prediction System

The methodologies for generating the three-dimensional meteorological variables are generally divided into two categories: prognostic approach and diagnostic objective analysis methodology. Air pollution predictions for environmental impact assessments usually use observationally based meteorological inputs driven by the diagnostic approach. However, in the event of the accidental release of a hazardous chemical, the predicting capability (i.e., for periods from approximately 1 to

24 hr) of the time-varying spatial/temporal distribution patterns and locations of vapor cloud via the prognostic model is a key role in CARIS for the effective emergency response.

The employed prognostic numerical weather prediction model is the parallel processing version (version 4.3) of the prognostic CSU-RAMS (Regional Atmospheric Modeling System) (Pielke and others 1992) developed at Colorado State University. RAMS is a multipurpose numerical prediction model designed to simulate atmospheric circulations spanning in a scale from the hemisphere down to Large Eddy Simulations (LES) of the planetary boundary layer (Walko and others 1995). In CARIS, RAMS is run in a nonhydrostatic mode, and it utilizes a multiple-nested grid system applied to the Eastern Asian area, including Korea (Figure 3), based on 1-km grid spacing topography and land use. The nests cover a range of horizontal scales from regional to local (i.e., urban) to be used for the air quality forecasting in Korea. The Arakawa-C grid system (Messinger and Arakawa 1976) is used to reduce the finite difference error, resulting in a staggering of the thermodynamic and momentum variables. The vertical grid consists of 26 layers, with a spacing of 50 m at the surface, resulting in the lowest above the ground layer at 25 m. This grid is telescoping to allow more detail in the boundary layer and expands in spacing to ~ 1 km at a model top of the 20,000 m above the ground level. Additionally, the turbulence parameterization of Mellor and Yamada (1982) is employed for diffusion in the vertical direction.

Dispersion and Air Quality Modeling System

The Dispersion and Air Quality Modeling (DAQM) system consists of discrete dispersion modules. Based on the atmospheric dispersion modeling algorithms, the individual dispersion module can simulate various types of hazardous chemical release. In order of increasing complexity, the DAQM consists of (1) a source model for the explosion algorithms, such as VCE (Vapor Cloud Explosion) (AIChE/CCPS 1994) and BLEVE (Boiling Liquid Extending Vapor Explosion) (AIChE/CCPS 1994), (2) a Gaussian-type steady-state plume model, SLAB (Atmospheric Dispersion Model for Denser-Than-Air Gas) (Ermak 1990), and ALOHA (Areal Locations of Hazardous Atmospheres) (NOAA/HMRAD and EPA/CEPPO 1992) for dense gas modeling, (3) a three-dimensional transient modeling algorithm for long-term strategic planning, which can be applied in a coastal area, a mountainous region, and other complex terrain.

By choosing the appropriate modules, the user creates a site-specific dispersion module. The source model of explosion algorithms can produce thermal radiation and blast overpressure impact zones. A full range of release types can be modeled: gas, liquid, and two-phase release; instantaneous, continuous and transient release; and ground-level and elevated release. Using one-point meteorological information, including wind direction and atmospheric class, SLAB and ALOHA can quickly generate information on contamination distributions.

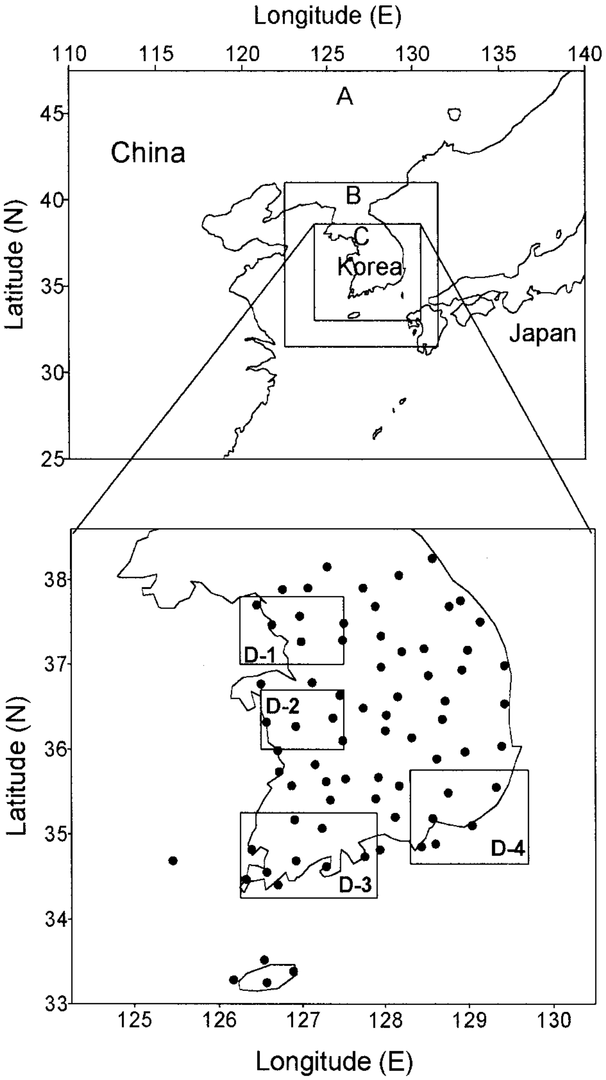

Figure 3. Domain of the three nested grids in the operational meteorological model (RAMS) in CARIS for weather prediction. A: Coarse grid (30-km grid spacing); B: nest 1 (10-km grid spacing); C: nest 2 (3-km grid spacing); D: nest 3 (1-km grid spacing). D1–D4 cover 80 × 50 km^2, 65 × 50 km^2, 100 × 65 km^2, 90 × 70 km^2, respectively, which are designed to cover the areas of densely located chemical companies in Korea. Solid circles denote 76 meteorological monitoring stations operated by the Korea Meteorological Administration.

However, it is obvious that the Gaussian-type models cannot account for variable structures within the plume or vapor cloud. If the cloud is influenced by a nearby terrain feature or a building, a three-dimensional non-steady-state dispersion model, which accounts for varying gradients and flux divergences within the plum, is imperative in predicting the time-varying deposition of hazardous chemicals. For this reason, we employed the Lagrangian Particle Dispersion Model (LPDM) called DENTAD (DENse gas Tracer And Deposition model), which uses meteorology generated by RAMS. Figure 4 shows an example of output from the RAMS–DENTAD run stream.

Chemical/Physical Property Database and Scenario Database

The CARIS database module consists of two parts: the Chemical/Physical Property Database (CPPD) and the Scenario Database (SD). CPPD stores the chemical and physical properties of hazardous chemicals and contains information about the impact levels of concerns, potential hazards on human health, and guidelines for safe treatments. It also includes detailed information on hazardous chemicals produced or used in Korea. Based on the degree of chemical risks and the amounts used in chemical companies, Table 1 lists the 38 most hazardous chemicals identified by each facility for special control and management. For each chemical company, pertinent information exists, including the location of companies, the chemical names of hazardous material, the units of storage, and a brief description of how these chemicals are stored. Also, the database provides contact information in the case of an emergency, including local fire and police stations, military authorities, municipal offices, and other emergency medical services.

In the case of an emergency, rapid and secure communication is crucial in ensuring a prompt and coordinated response. In demonstrating the utility of SD, over 150 preset scenarios for each facility are currently incorporated based on the SLAB and ALOHA models, covering two types of typical accidental release (orifice leak and line release) and 144 types of the worst-case instantaneous release (catastrophic rupture). The worst-case scenario involves the classifications of atmospheric stability categories (i.e., Pasquill 1961; Turner 1964), which depend mainly on meteorological conditions: wind speed (six types), wind directions (eight types), and stability classes (three types). Thus, instantaneous wind speed, wind direction, and stability class at the time of an accident are assessed promptly, in order to provide an escape route for residents and to clear a passageway through which the emergency re-

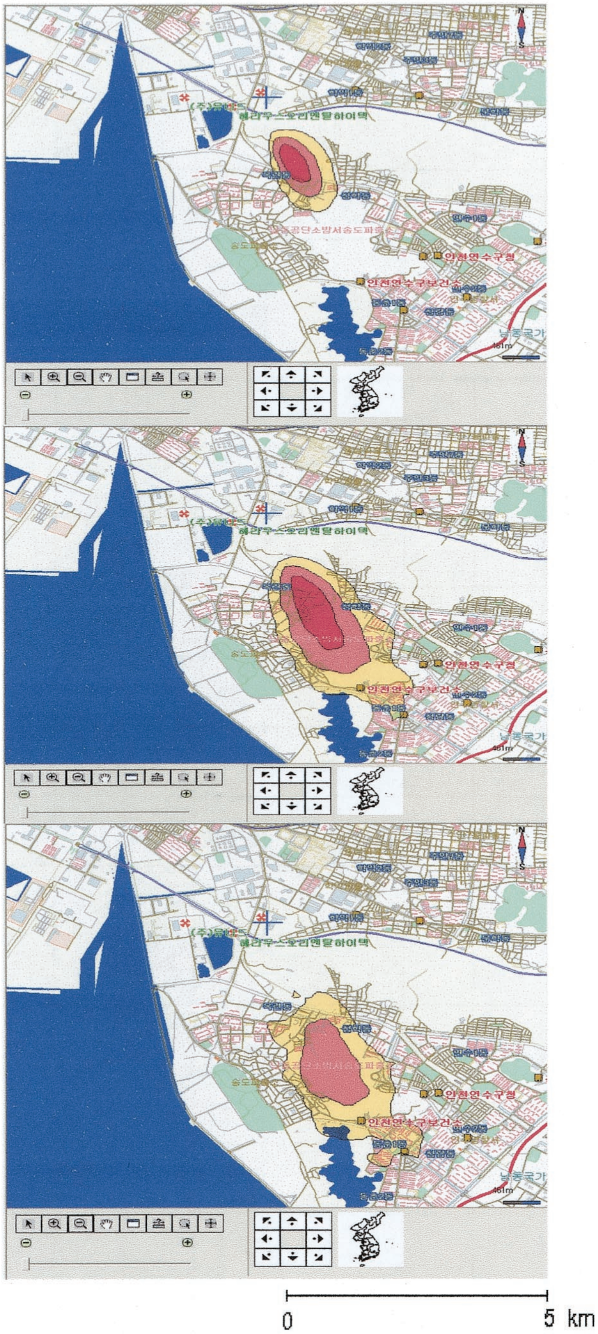

Figure 4. Sample outputs of the coupled RAMS–DENTAD run stream in CARIS. The outputs are displayed in 30-min intervals after the instantaneous release of gaseous ammonia. The plus sign indicates the source location (source strength is 12,000 kg/year) and Emergency Response Planning Guidelines (ERPG). The contaminated ERPG levels are yellow (between ERPG-1 and ERPG-2 levels), pink (between ERPG-2 and ERPG-3 levels), and red (ERPG-3 level or higher).

Table 1. The preselected 38 specific hazardous chemicals of major concern in Korea

1. Acrolein
2. Amiton
3. Ammonia
4. Ammonium bifluoride
5. Arsenic trichloride
6. Bromine
7. Chlorine
8. Chloropicrin
9. Cyanogens chloride
10. Ethylene oxide
11. Hydrochloric acid
12. Hydrogen cyanide
13. Hydrogen fluoride
14. Hydrogen selenide
15. Mechlorethamine
16. Methyl bromide
17. Methyl chloride
18. Methyl ethyl ketone
19. Methyl isocyanate
20. Mustard
21. Paraqaut
22. Phosgene
23. Phosphine
24. Phosphorus oxychloride
25. Phosphorus pentachloride
26. Phosphorus pentasulfide
27. Phosphorus trichloride
28. Potassium cyanide
29. Potassium fluoride
30. Sarine
31. Sodium cyanide
32. Sodium fluoride
33. Sulfur monochloride
34. Sulfuric acid
35. Thionyl chloride
36. Toluene
37. 2-Chloroethanol
38. 2-Chloroethydiethyl ammonium chloride

sponse units can pass. SD contains critical information that can be used to assess the degree of chemical hazard, provide emergency alerts, and guide emergency response teams on how to deal with specific chemicals based on preset scenarios for each facility. All of this information can be readily accessed, supporting emergency response teams with expert advice and immediate assistance.

GIS Display Module

When the results of the CARIS modeling system (see Figure 5) are produced and transmitted, communities are informed immediately of the direction in which hazardous chemicals travel and the projected time of vapor cloud arrival. The distribution of concentrations is displayed using the Emergency Response Planning Guidelines (ERPG), and the possible health effects of each ERPG levels are described on the GDM. Seamlessly integrating the extensive chemical database and the modeling outputs, the user-friendly GDM projects critical information, such as the meteorological data and the impact zones. All users of CARIS can view the information on remote monitors.

As shown in Figure 5, GIS-Map (Kim and others 2000) is incorporated into the GDM. The GDM provides several display capabilities, including panning, rotating, and zooming. The impact zones can be displayed on grids or on customized site-specific maps, allowing CARIS operators to see the snapshots and footprints of the vapor cloud movement and to plan a course of action in the event of an emergency. As well, the use of the CPPD and the scenario reports can help with the assessment of the released chemicals' toxicity.

Users of CARIS and CCSM

CARIS is housed at CCSM and is connected to a network of approximately 200 emergency response units. They include fire and police stations, military installations, municipal government offices, and other emergency management agencies and centers. CARIS Software for Clients (CSFC), the software installed in the remote monitor for all users to communicate with CARIS, enables all users to exchange information instantaneously. For instance, one-point meteorological data (e.g., 24-hr NWP data at 10 m above the ground level) is designed to be transmitted to CSFC automatically, allowing all users to run SLAB or ALOHA on a real-time basis. These meteorological variables, such as wind speed and direction, air temperature, humidity, and solar radiation, are updated twice a day.

Upon notification of a hazardous chemical release, CARIS identifies the location of the facility and develops a coordinated plan to alert emergency response teams by pulling together information about the facility and the preprogrammed scenarios (Figure 6). The data from CPPD and SD are transmitted immediately over the network. Next, the CCSM technical staff runs DENTAD, generating a three-dimensional distribution of hazardous chemical concentrations. Once the simulation is complete, more detailed information on the extent, time of arrival, and duration of the vapor clouds is sent to CSFC for the local emergency response units. The computing time of DENTAD for short-term prediction (i.e., 24-hr simulation) takes less than 1 min for a one-point source. The total response time from when CCSM is notified about the chemical release to when

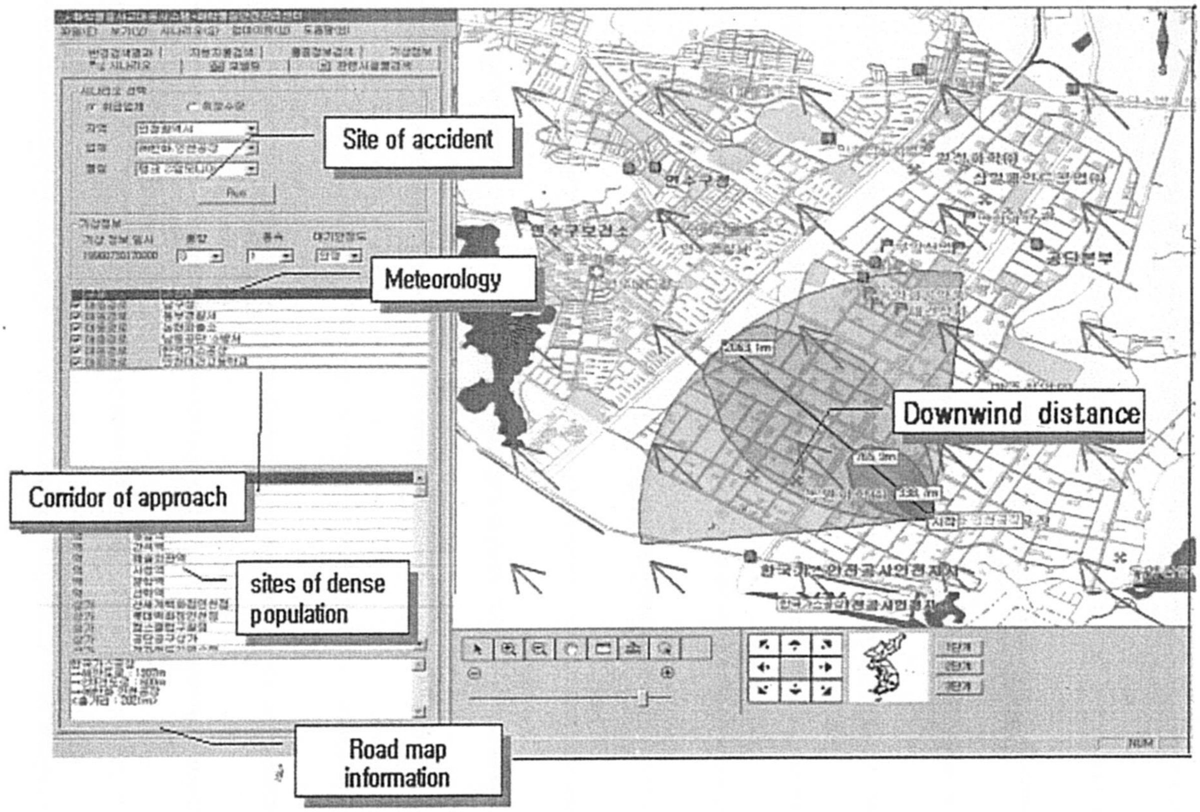

Figure 5. Sample output showing ALOHA dispersion results and RAMS meteorology (winds) in the GIS display module. ERPG-1, ERPG-2, and ERPG-3 levels are used for contour lines.

the information is sent to CSFC takes approximately 3–5 min in real time, depending on the treatment of input data before running the DENTAD.

At its core, CARIS depends on the timely transmission of reliable information to emergency response teams. Seamless cooperation among these independent organizations is crucial for dealing with emergency situations. Toward this end, the Ministry of Environment established a task force and developed a CARIS-based multifaceted program to train key personnel and to foster better communication. When South Korea hosted the 2002 World Cup soccer event, for instance, we conducted drills and trained emergency response teams based on CARIS-generated information about the potential threat of chemical releases in and around the stadiums.

Operational Considerations

Episodic releases of hazardous and toxic chemicals to the atmosphere are characterized by being of relatively short duration, with a release rate that typically varies rapidly with time (Koutsenko and Ross 1998). Such a release is usually accidental and may potentially have severe localized consequences, which may result in acute and prolonged health effects. Modeling the impact of such releases is, at times, beyond the capabilities of simple Gaussian type of the dispersion model. Additionally, the presence of complex terrain causes spatial and temporal variations in the wind and turbulence fields.

We recognize that the transient puff or particle dispersion model takes into account the complex surroundings, time-varying meteorological, and topographical features. For this reason, the three-dimensional RAMS–DENTAD run stream is employed as an operational model in simulating the hazardous chemical movements for the short range (i.e., less than 10 km) as well as for a longer distance affecting transport and deposition.

However, the operational weather prediction system requires tremendous computational power; thus, until recently, the numerical weather prediction model has been run operationally on a CRAY-class supercomputer as a prototype real-time mesoscale forecast model. With the rapid development of recent computing technol-

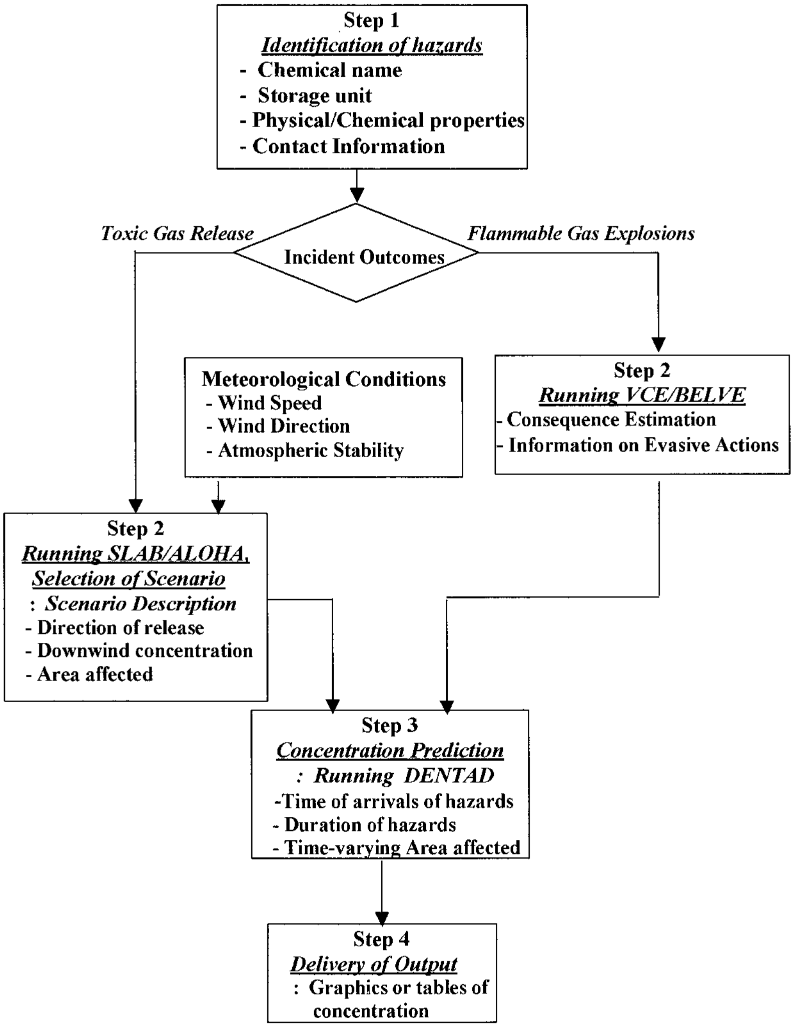

Figure 6. Illustration of generalized conceptual process of CARIS.

ogy, however, these runs can be done on relatively inexpensive personal computers (PCs). Although modestly priced, high-performance PCs have computational capabilities comparable to those of CRAY-class supercomputers (Lee and others 1997).

The parallel processing version of RAMS was implemented on the parallel architecture PC clusters with universal adoption of the LINUX operating system. In CARIS, the operational meteorological modeling is designed to be fully automated. We programmed RAMS to run automatically twice a day (starting at 0000UTC and 1200UTC), generating 48-hr predictions. The meteorological wind fields are updated after every run.

Initially, we import the global prediction and analysis data, known as the Global Data Assimilation System (GDAPS), from the Korean Meteorological Administration (KMA). The hourly-averaged observation data, gathered from on-site meteorological stations [e.g., Automatic Weather System (AWS) and Global Telecommunication Station (GTS)] are then assimilated with the initial GDAPS data. The entire procedure is done automatically: receiving data for initial conditions, running the meteorological models, updating the meteorological fields, and preparing the meteorological data for the dispersion model.

The First Evaluation of the NWP Component in CARIS

The quality of dispersion simulations is highly dependent on the meteorological input data. Accordingly, the qualification and interpretation of NWP uncertainty is an important issue in the traditional meteorology and air quality communities. There are many sources of weather prediction uncertainties in the meteorological variables when applying operational

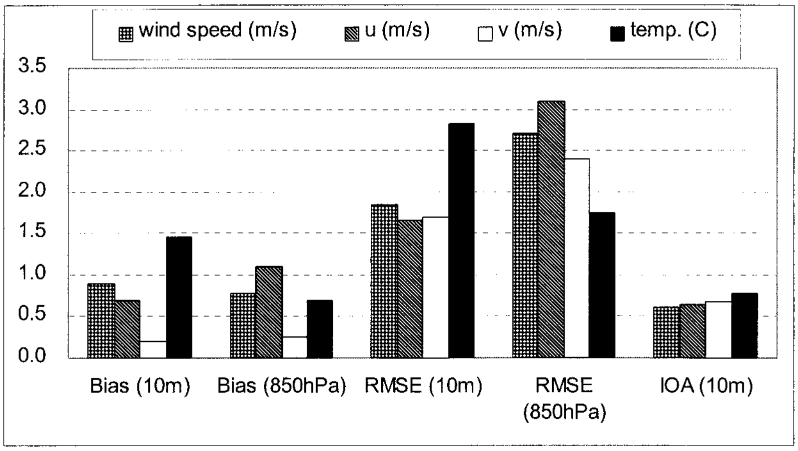

Figure 7. Statistics for the simulation on 19–23 August 2002 averaged over the meteorological monitoring stations in Korea for wind speed; the west–east component (u) of the wind speed; the south–north component of the wind speed (v), and temperature.

modeling. Brooks and others (1995) addressed various sets of uncertainties in the fundamental NWP and pointed out that the main uncertainties are involved in the specification of initial conditions and the role of model error.

Several statistical uncertainty analysis techniques have been developed (Krzyszofowicz 1998; Fox 1981, Klung and others 1992; Mosca and others 1997), and various sets of statistical indexes were used for determining model uncertainties. We employed a set of statistical indexes (Karppinen and others 2000) to estimate how well the observed and the model-calculated meteorological variables fit.

The statistical indexes root mean square error [RMSE = $\sqrt{1/N}\Sigma(P_i - O_i)^2$, bias [BIAS = $(1/N)\ \Sigma(P_i - O_i)$, and index of agreement [IOA = $1 - \Sigma(P_i - O_i)^2/\Sigma(|P_i - O_i| + |O_i - O_i|)^2$] are chosen and applied in this study to evaluate the three-dimensional wind and temperature data predicted from the operational model RAMS compared with the observations from the meteorological monitoring sites over Korea on 19–23 August 2002. In this equation, N is the number of pairs of observations and predictions, P_i is the prediction, $\bar{O}_i$ is the observation, and$_i$ is the observed mean [$= (1/N)\Sigma_1^N O_i$]. The hourly averaged meteorological data obtained from 76 meteorological monitoring stations in Korea operated at KMA are used. The locations of meteorological monitoring sites are depicted in Figure 3.

Model predictions at 10-m above the ground level were calculated from the first grid level (25 m above the ground level) based on the atmospheric stability functions and logarithmic wind profiles and were extracted at the grid point nearest to the meteorological monitoring site on Grid C (3-km grid spacing). Figure 7 shows the averaged statistics of model performance for the wind and temperature fields predicted by RAMS on 19–23 August 2002. In the predicted wind and temperature fields, the statistical analysis shows overall overprediction; for example, the BIAS, RMSE, and IOA of wind speed (WS) at 10 m above the ground are 0.9 m/s, 1.85 m/s, and 0.61, respectively. The west–east (u) and south–north (v) components of the wind speed have been overpredicted, respectively, at 10 m above the ground as well as at the 850-hPa level. For the temperature fields, the BIAS, RMSE, and IOA at 10 m above the ground are 1.45°C, 2.82°C, and 0.78, respectively, showing a slight level of overpredictions relative to the observation.

The overprediction of temperature fields may lead to overmixing during the day, causing some of the overprediction of wind speed as a result of the momentum being mixedfrom the surface aloft in the model (Hurley and others 2001). The discrepancies of the wind and temperature fields between measurement and simulation may be attributed partly to the oversimplified surface flux processes because the soil moisture contents are currently set to constant over the land, whereas the topography, soil, and vegetation classification is resolved at the 1-km grid spacing. Some improvement probably could be gained if the subgrid scale nature of moisture was taken into account.

However, the IOA values of the wind fields (0.65) and temperature fields (0.78) show a good agreement. These IOA values are greater than the "good" value criteria of IOA (>0.5) implied by other studies (Hurley and others 2001), suggesting potential in predicting the urban- and local-scale wind fields generated from the current operational initial and boundary conditions.

Summary and Future Plan

The emergency response system CARIS provides critically important information to emergency response teams in order to deal effectively with dangerous chemical releases. Using a cluster-PC parallel architecture, the operational atmospheric modeling system implemented in CARIS consits of RAMS and DENTAD. CARIS is currently desidned to provide quick and accurate information about the chemical and physical properties of over 1000 hazardous chemicals. It also has the capability of simulating atmospheric transport, dispersion, and deposition for 38 specific gaseous chemicals.

In this article, we introduced the vital components of CARIS and explored an integrated operational modeling system. The results of the prognostic meteorological model RAMS show that the wind speeds and temperature fields have been generally over predicted, but yield no significant biases and high IOA (>0.5) suggesting that the CARIS modeling system is a reliable emergency response system for providing the meteorological input data in predicting the spatial/temporal concentration distributions of hazardous chemicals.

Each year, we will continue to review, update and add information to the database, ensuring that the emergency response plan is up to date. Moreover, continuous efforts will be made to enhance and refine the modeling technology, so that we can improve predicting dispersion and deposition of the model for the real-time ground-level or elevated releases of hazardous chemicals. The second evaluation of RAMS is being implemented over complex areas in Korea. The comprehensive wet and dry deposition modules will be built into DENTAD, and we are also planning to conduct tracer experiments as a way of evaluating and improving the dispersion modeling system. These tests will provide an opportunity for a comprehensive evaluation of DENTAD, particularly in the mountainous areas.

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