Assessment in marine environment for a hypothetic nuclear accident based on the database of tidal harmonic constants

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ABSTRACT

The eleven nuclear power plants in operation, under construction and a well-planned plant in the east coast of China generally use seawater for reactor cooling. In this study, an oceanic dispersion assessment system based on a database of tidal harmonic constants is developed. This system can calculate the tidal current without a large computational cost, and it is possible to calculate real-time predictions of pollu-tant dispersions in the ocean. Calculated amplitudes and phases have maximum errors of 10% and 20%with observations, respectively. A number of hypothetical simulations were performed according to vary-ing of the release starting time and duration of pollutant for the six nuclear sites in China. The developed system requires a computational time of one hour for one month of real-time forecasting in Linux OS. Thus, it can use to evaluate rapidly the dispersion characteristics of the pollutants released into the sea from a nuclear accident.

1. Introduction

In recent years, in a context of increasing energy demand, many countries have expressed an interest in including nuclear power in their energy plans. In 2011, the Fukushima Daiichi nuclear disaster occurred in Japan, after which all nuclear plant approvals were frozen and 'full safety checks' of existing reactors were required. The current situation in the east coast of China is such that the eleven nuclear power plants at three sites are in operation (Hongyanhe, Tianwan, Qinshan), under construction (Hongshiding, Sanmen) and a well-planned plant (Haiyang). These plants are located in the Yellow sea coast and generally use seawater for reactor cooling (Fig. 1).

The marine dispersion of radionuclides from a nuclear accident has been an important issue since the Fukushima Daiichi accident in 2011 (Honda et al., 2012; Perianez et al., 2012; Tsumume et al., 2012; Min et al., 2013). Release of the radioactive materials may occur due to a major accident within a NPP or other reasons, such as spent fuel transportation or an accident involving a nuclear submarine. An emergency response system is necessary to preserve the marine environment in terms of stability and public safety. In an emergency, these systems determine the range of effects of the accident, and they can offer basic information for a protection plan.

In this study, an oceanic dispersion assessment system based on a database of tidal harmonic constants has been developed to evaluate the transport characteristics of the pollutant for a hypothetical nuclear accident located in the east coast of China. The hydrological characteristics in the Yellow Sea are mainly governed by tides, which are dominantly semidiurnal (rising twice a day). Amplitudes vary between 0.9 and 3 m along the coast of China. Tides are higher along the Korean Peninsula, typically ranging between 4 and 8 m. The speed of the tidal current is generally less than 1.6 km/h in the middle of the Yellow Sea, but it may increase to more than 5 km/h near the coast. Tidal predictions based on a database of tidal harmonic constants can calculate the tidal currents in fast without incurring a large computational cost, thus it is also possible to calculate real-time predictions of radioactivity in the ocean.

2. Tidal current forecast system

Numerical circulation models provide a useful and general view of ocean currents. A regional circulation model was firstly developed by Kirk Bryan and Michael Cox (Bryan, 1969) and it was expanded in a global scale, with a horizontal resolution of two degrees and with 12 levels in the vertical direction (Cox, 1975). After that, various numerical models have been developed to describe coastal currents, tides, and storm surges. The models extend from the beach to the continental slope and they included

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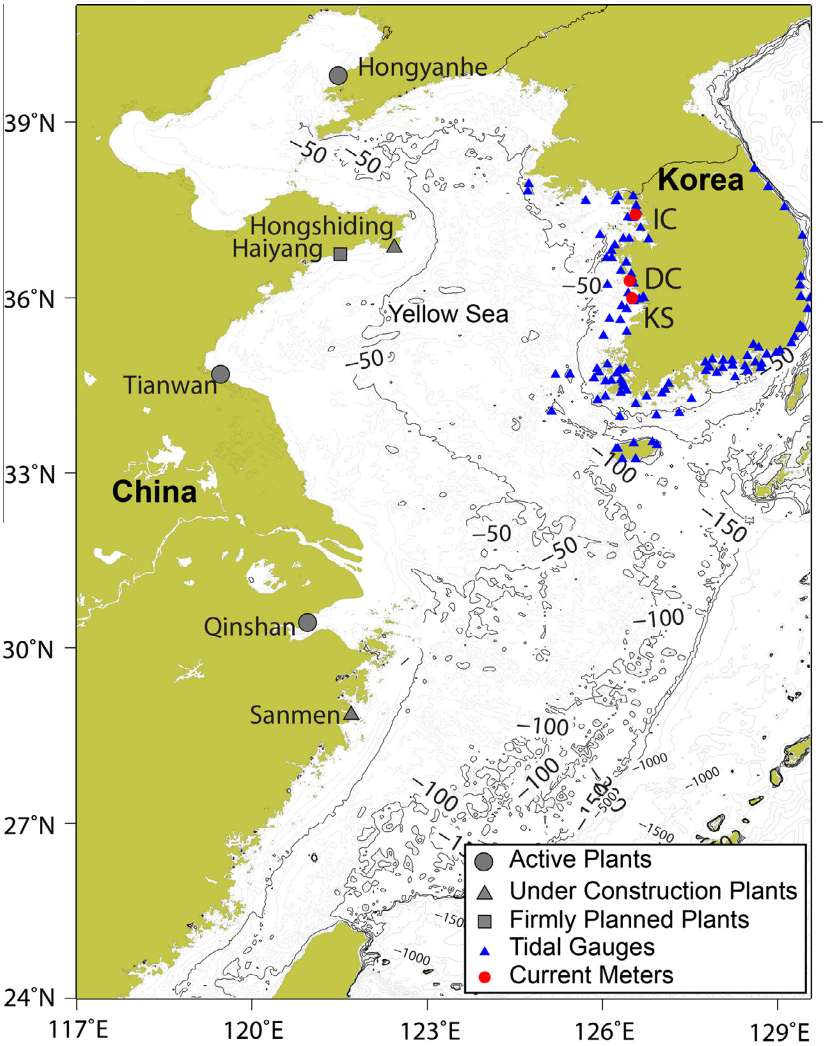


Fig. 1. Map of the Yellow Sea. The locations of six nuclear sites, three current meters and tidal gauges are indicated. Bathymetry (m) is also shown: IC:Incheon, DC:Daechun, KS:Kunsan.

a free surface, realistic coasts, bottom features, river runoff and atmospheric forcing data. The coastal models have many different goals and implementations. Thus, it is important to select of a proper circulation model to understand the characteristics of the dominant physical processes in each particular area.

Numerical studies of tidal current predictions use circulation models and focus on strong tidally driven systems. In this case, the flow may be considered to obey two-dimensional (2D) averaged dynamics vertically (Panchang et al., 1997; Dudley et al., 2000). Tides define with the periodic rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon and the Sun, and the rotation of the Earth. When periodic data is analyzed, the standard approach is to employ Fourier series with a form of analysis that uses sinusoidal functions having frequencies that are zero, one, two, etc. times the frequency of a particular fundamental cycle. These multiples are called with ‘harmonics’ of the fundamental frequency and the process is termed in harmonic analysis. Doodson (1921) introduced the Doodson Number notation to organize hundreds of harmonics constants. This approach has been the international standard since then. Real tides can be explained by a sum of harmonics in the following form.

$$z(t) = \sum_{i=1}^{N} A_i \cos(w_i t + p_i) \tag{1}$$

Here, z is the sea surface displacement or tidal current of each U and V components from the mean sea level produced by the tide and N is the number of harmonics (tidal constituents). For each constituent, A is the amplitude, w is angular frequency, p is the phase offset with regard to the astronomical state at time $t = 0$ and t is time measured in hours. The amplitude (A) and phase offset (p) denoted as tidal constants, are not uniform in space for each constituent. There are several ways to obtain them. First, a harmonic analysis of direct measurements of water levels in the region of interest is the most accurate way, but it is difficult to obtain tidal constants with spatial continuity. This method is mainly used for hydrographic surveys, and has been used in national institutions (for example, the NOAA of the USA, the POL of the UK and the KHOA of the Republic of Korea). Second, satellite observations have spatial continuity but the level of accuracy is low. The satellite data of TOPEX/Poseidon (Smith et al., 1997) and JASON-1 (Ardalan and Hashemi, 2008) can be used for this purpose. Third, numerical models can be used to calculate these harmonic constants. But numerical models and available observation data are generally applied to complement the disadvantages of each method.

In this study, the five-minute interval DB of Min et al. (2011) is applied to carry out predictions of tidal currents. The DB includes harmonic constants of the sea surface displacement and tidal current of each U and V components. Details are presented by Min et al. (2011) for more information like computational domain, description and validation of the model. The tidal constant DB used in this work is basically identical by Min et al. (2011), but the new program is developed to predict tidal currents. Fig. 2 shows the amplitude and phase resulting from the DB compared with the observed data at all tidal gauges in Fig. 1. The results for the M_2, S_2, K_1 and O_1 constituents are shown where the corresponding station data are available. The solid line, at a 45-deg angle, indicates a one-to-one correspondence between the model results and the observed data. Ideally, the results for all tidal constituent should fall along this line. Dashed lines indicate a 10 percent difference between the DB results and the measured data. Most results from the DB have errors less than 10%, as seen in Fig. 2. Some under-prediction appears for phases of two diurnal constituents (K_1 and O_1). This problem is caused by the open boundary forcing used in the global model (Min et al., 2011). However, the error of the phase lag between the calculations and observations is not larger than 20%.

The DB-based predicted tidal currents over time are plotted for three stations in Fig. 3. DB-based tidal currents are in good agreement with observations for all coastal stations. In particular, observed data include the effects of wind, wind waves and other atmospheric effects; nonetheless calculations are in good agreement with them in terms of ebb and flood tide, as well as the direction and speed of tidal currents. This means that tides are predominant in the Yellow and East China Seas. Other components of the flow (density driven currents, winds, waves, etc…) are relatively small and may be neglected.

3. Marine dispersion model

After the Fukushima accident, a large amount of radioactive material was released to the ocean, as well as to the atmosphere. Therefore, it is necessary to evaluate marine dispersion for radiological emergency preparedness against a nuclear accident. From this perspective, an oceanic dispersion model named LORAS (Lagrangian Oceanic Radiological Assessment System) has been developed in Korea since 2011 (Min et al., 2013). The model was designed to calculate radionuclide concentrations in seawater, suspended matter and seabed sediments in time and space using a particle tracking method. The dispersion of reactive and non-reactive radionuclides may also be simulated in the model. Three dimensional turbulent diffusion and the pollutant interactions between water, suspended matter and bottom sediments are simulated using a stochastic method (Periáñez and Elliott, 2002). The movement of the particle is represented by the sum of the movements due to advection by the current and turbulence. The new position of a particle after a time step Δt is represented as follows.

$$X_j(t+\Delta t) = X_j(t) + v_j(t)\Delta t + v'_j(t)\Delta t \tag{2}$$

where v_j are the oceanic currents (j = 1,2,3) and v'_j are the turbulent motion (j = 1,2,3). Three dimensional turbulent mixing is computed by a random walk method.

$$v'_{1,2}(t)\Delta t = \sqrt{12K_{1,2}\Delta t}R,\ v'_3(t)\Delta t = \sqrt{2K_3\Delta t}R, \tag{3}$$

where K_j are diffusion coefficients in each corresponding direction of space and R is a random number.

A stochastic method is used to estimate the dispersion of non-conservative radionuclides and provide concentrations in water, suspended matter and bottom sediments (Periáñez and Elliott, 2002; Periáñez, 2011). The differential equations which describe transfers between the three phases are expressed the following.

$$\frac{\partial C_w}{\partial t} = -k_{1m}C_w - k_{1s}C_w, \frac{\partial C_s}{\partial t} = -k_2C_s, \frac{\partial C_b}{\partial t} = -k_2\phi C_b \tag{4}$$

where C_w, C_s and C_b are radionuclide concentrations in seawater, suspend matter and bottom sediments respectively. k_{1m} is the kinetic coefficient describing radionuclide transfer from water to suspended matter, k_{1s} describes the transfer from water to bottom sediments and k_2 is the kinetic transfer coefficient which describes radionuclide release from suspended matter or bottom sediments to water. Finally ϕ is a correction factor which takes into account that some of the sediment particle surface may be hidden by other particles. Radioactive decay is described by the following equation.

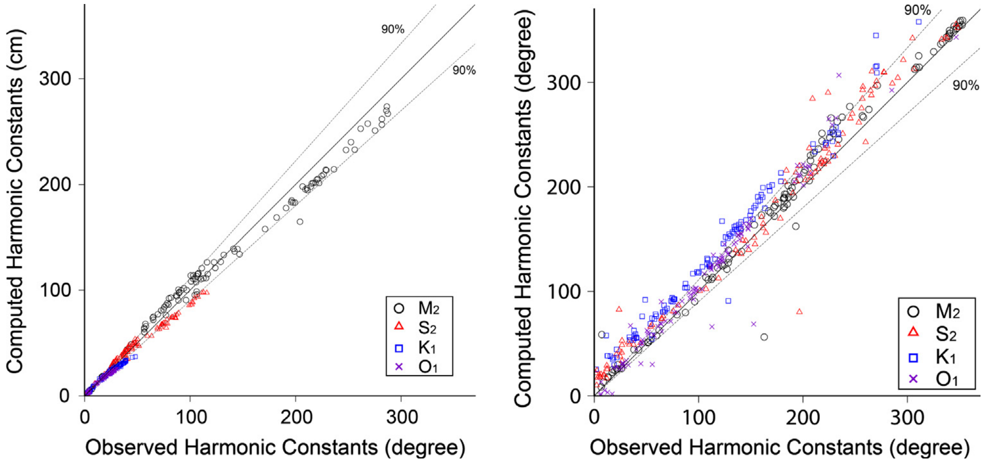
$$c(t+\Delta t)_{decay} = c(t)[1-\exp(-\lambda\Delta t)] \tag{5}$$

where $c(t)$ is the concentration and λ is the radioactive decay rate.

Radionuclide concentrations in seawater (C_w), suspended matter (C_s) and seabed sediments (C_b) are calculated in the domain of interest by counting the number of particles as follows.

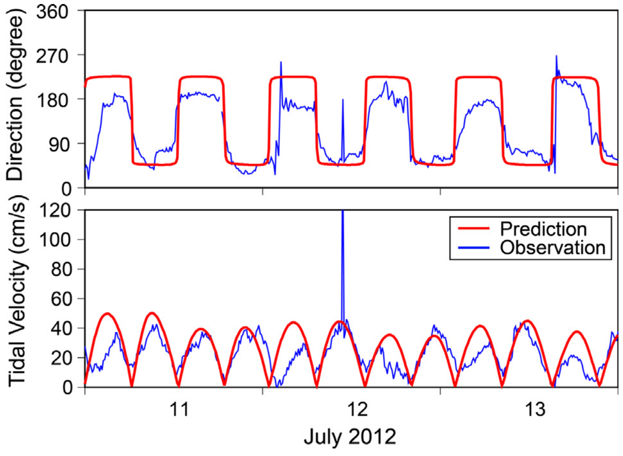
$$C_w = \frac{I.N_w}{\Delta x\Delta y\Delta z}, C_s = \frac{I.N_s}{m.\Delta x\Delta y\Delta z}, C_b = \frac{I.N_b}{\Delta x\Delta y.H.\rho_b} \tag{6}$$

Here $I = Q/NP$, where Q is the source term and NP is the number of particles used in the simulation. $\Delta x\Delta y\Delta z$ is the volume of the each cell, m is suspended matter concentration, H is the mixing depth in the bottom sediment and ρ_b is sediment bulk density. Finally N_w, N_s, and N_b are the number of particles in each phase.

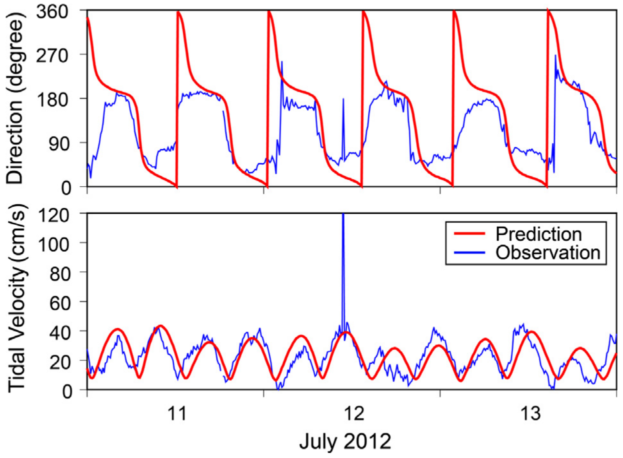


(a) Amplitude (b) Phase

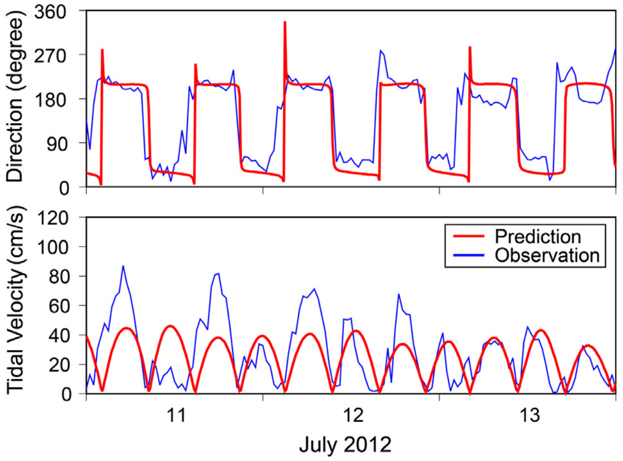
Fig. 2. DB calculated versus measured harmonic constituents at all stations of Fig. 1.



(a) Kunsan



(b) Daechun



(c) Incheon

Fig. 3. Tidal current times series of DB (red) versus observations (blue) for the three stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Numerical experiments and results

The oceanic dispersion model based on the Lagrangian particle-tracking method described above has been developed and tested for the Fukushima Daiichi nuclear disaster (Min et al., 2013). When it needs to evaluate the distribution of radionuclides leaked in the ocean, full calculations using an oceanic circulation model are very inefficient because of a large computational time and input data. Therefore, a compact harmonic prediction system consisting of a database of tidal constituents has been developed and is presently used to demonstrate how real-time predictions are generated. The coupled LORAS and tidal prediction system extracts harmonic constants from the five-minutes DB based on the location of radionuclides, which are represented by discrete particles. Sixty-two harmonic constants for the tidal current were extracted. These values are used to predict real-time tidal currents based on Eq. (1). Each particle moves by these real-time tidal currents, resulting in a new location at the end of each computational time step.

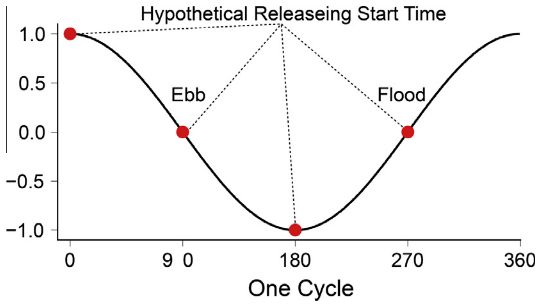
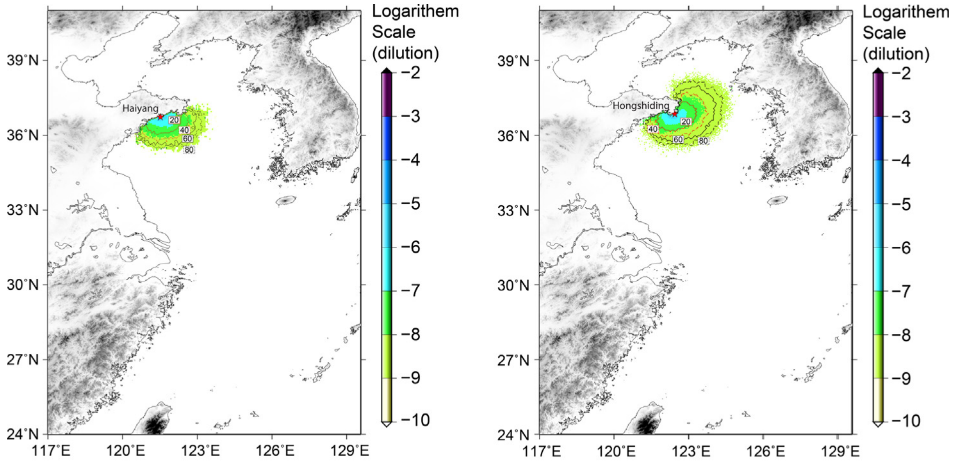


Fig. 4. Hypothetical pollutant release instants along a tidal cycle.

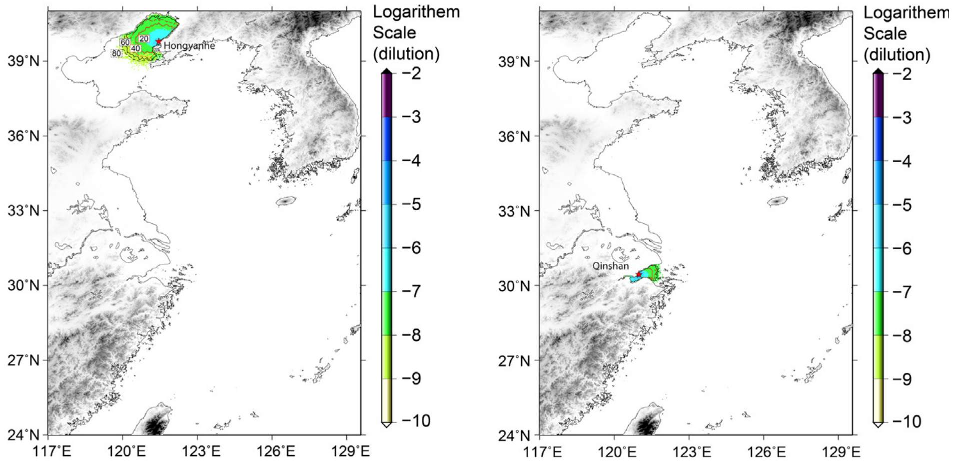
It assumed that a contamination source, releasing a hypothetical pollutant, was located in the coast near each nuclear power plant. The magnitude of the release is arbitrary, since dilution over the sea is calculated. The tidal signal roughly approximates a half-day cycle. Thus, we can assume the release starting time to be at every three-hour interval (Fig. 4). These hypothetical release situations include flood and ebb tidal currents, as well as slack water conditions. Also, the following release durations were considered with the 10, 20, 30 and 40 tidal cycles. Thus, we have 16 hypothetical pollutant release cases for each NPP. A perfectly conservative and long-lived radionuclide was considered for the experiments. Interactions with sediments reduce the radionuclide mobility, thus wider dispersion occurs if radionuclides remain dissolved and the radioactive impact along the Yellow Sea coasts would be higher. Therefore, radionuclide decay and interactions with solid phases are neglected.

Fig. 5 shows the calculated dispersion patterns released into the Yellow Sea from each NPP in China. These hypothetical events imply several assumptions, but selected physical parameters and values are the same in the previous work (Min et al., 2013). The results are valid for a range of conservative radionuclides. The number of particles used in each simulation is 2,000,000. Dilution over the sea is calculated for each experiment, considering 1 dilution at each release point. Simulation results in Fig. 5 are presented with the largest radionuclide distribution (i.e., largest radionuclide patch) within the water column and the leading edge of the averaged concentration of less than 10 m from the sea surface, defined as a 10^{-9} dilution (concentration here would be 10^{-9} times the concentration in the release point). A total of 16 distributions have been obtained, corresponding to four release starting time and four release duration for each NPP. In general, the leading edges of the pollutants spread for 20 arc minutes on every 20 days. Hongshiding, the nuclear power plant closest to the Republic of Korea, is about three arc degrees away. Therefore, released pollutants can theoretically reach the coast of the Korean Peninsula after some 180 days.

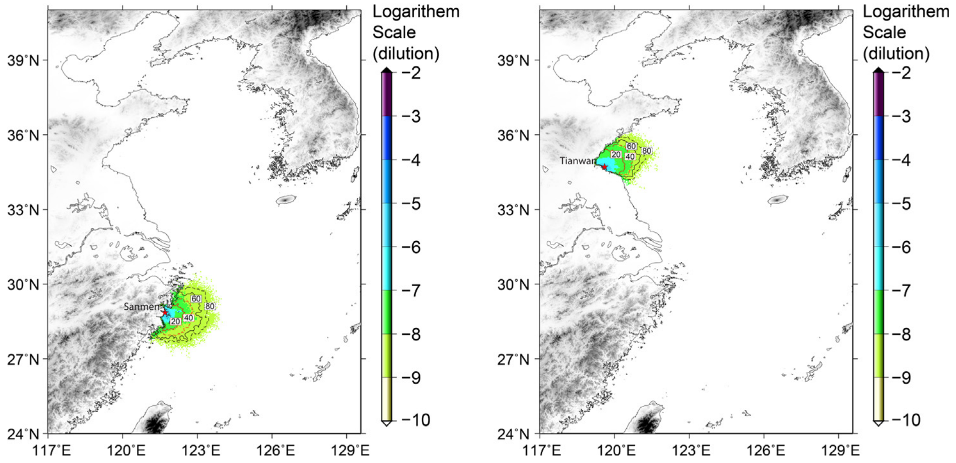
Any effect of an accident occurring from Qinshan and Hongyanhe NPPs is unlikely in the Korean Peninsula due to their geographic locations. In contrast, accidents from Haiyang, Hongshiding and Tianwan NPPs may easily affect Korean ocean environment. A



(a) Haiyang (b) Hongshiding



(c) Hongyanhe (d) Qinshan

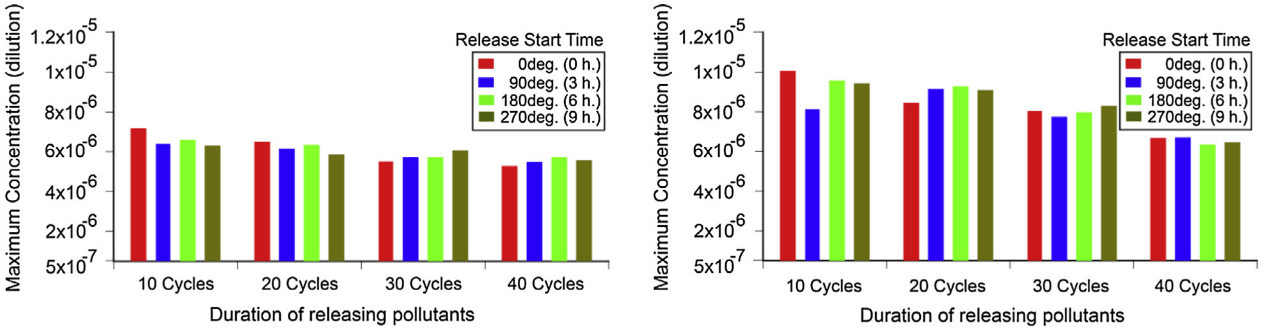


(e) Sanmen (f) Tianwan

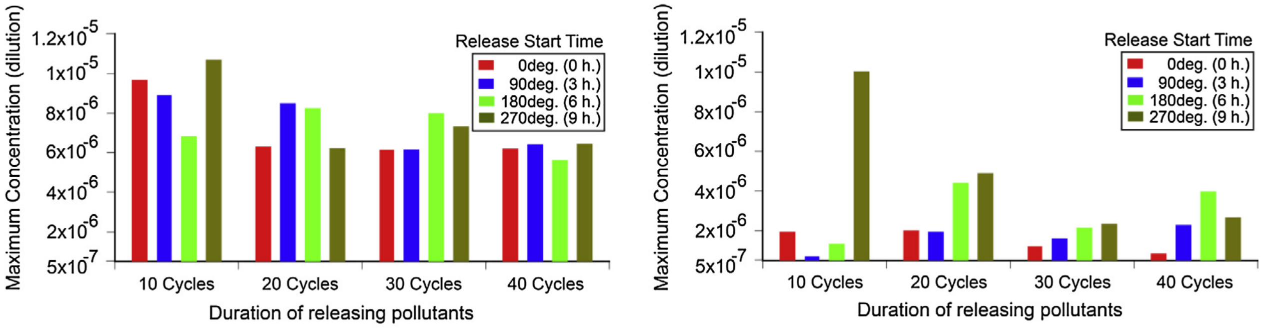
Fig. 5. Calculated maximum pollutant distribution for each NPP. The leading edge is defined by the 10^{-9} dilution contour.

nuclear accident will have a significant economic and sociologic impact, since marine resources produced in the Yellow Sea have a very large proportion of the food of Korea and around the country.

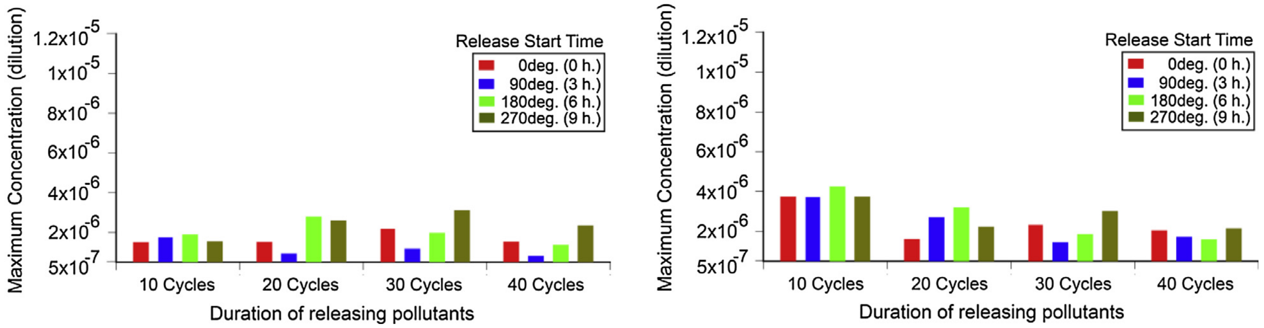
Emergency response systems are relevant to support decision making after an accident. An evaluation of model result sensitivity to the accident characteristics should be carried out. The Monte Carlo method is generally considered to be the most suitable approach to carry out a quantitative analysis of model sensitivity and propagation of uncertainties pertaining to radionuclide transport codes. The sensitivity analysis in this study was only applied to evaluate the model response according to the variations in the starting time and duration of the pollutant release. Therefore, we used a simple sensitivity analysis involving a direct comparison of the 16 simulations which were made for each NPP. Fig. 6 shows the variations in maximum concentrations at 20 km offshore from



(a) Haiyang (b) Hongshiding



(c) Hongyanhe (d) Qinshan



(e) Sanmen (f) Tianwan

Fig. 6. Concentration sensitivity to changes in 16 hypothetical simulation cases.

each power plant. Concentrations for Haiyang, Hongshiding, Tianwan and Hongyanhe decrease as the release duration increases, since the release rate is determined by the same total emission volume but divided by a longer time period. This pattern is not evident for Qinshan and Sanmen, because currents around them are strongly influenced by rivers and islands. The release starting time can also be seen as a relevant factor, except for Haiyang. In this case tidal currents are very uniform, leading to a rather isotropic dispersion in space, as shown in Fig. 5. In other regions, results are more sensitive to the release starting time than to the release duration.

5. Conclusions

The reliability of predictions is a crucial performance criterion for numerical models. The database of harmonic constants can be improved by modifying its physical parameters, numerical scheme and details of its mesh system. In this paper, the forecast efficiency and current forecasts from an independent model system were evaluated. The introduced DB-based tidal current forecast system is highly reliable. Amplitudes and phases from the comparisons of calculation and observation are obtained with errors less than 10% and 20%, respectively. The calculated results for the tidal current forecasts showed generally good agreements with observations. The 16 hypothetical simulations were performed depending on the release starting time and duration of the pollutant emission for each of the six NNPs of China. Contamination from Hongshiding NPP after a hypothetical accident is expected to reach the coast of the Korea Peninsula after 180 days. Pollutant dispersion patterns are very sensitive to the location of the NPP, as well as to the release starting time and duration. Thus, accurate forecasts of real-time tidal currents are required for emergency response systems which would support decision-making after an accident. The developed system requires one hour of computational time for one month of real-time forecasts in Linux OS. Thus, it is relatively easy to implement it into an emergency response system.

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