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Atmospheric Transport of Radioactive Nuclides from Russia to Neighbouring Countries

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Abstract

On August 10 1985, during completion of reactor refueling work on a nuclear submarine at Chazhma Cove near Vladivostok, an uncontrolled chain reaction occurred. The air, ground and water were radioactively contaminated. The Vladivostok region (southern Primoriye Kray) still contains several nuclear fleet facilities where periodic refueling of operating submarines is carried out. In addition, there are about 60 decommissioned submarines that have been waiting for many years for final defueling. This causes increasing concern, as the probability of another nuclear accident is not negligible. In order to assess the consequences, the atmospheric transport analysis of radioactive nuclides released from a submarine facility in southern Primoriye Kray was evaluated using the computer code WSPEEDI. The WSPEEDI code consists of a mass consistent wind model WSYNOP for a large scale wind fields and a particle random walk model GEARN for atmospheric dispersion and dry deposition of radioactivity. A parametric study of transboundary atmospheric transport of radioactivity for a 1 Bq unit release in the vicinity of Vladivostok was carried out to determine the sensitivity of the consequences to the height of the release and its duration. Atmospheric concentrations and soil concentrations due to dry deposition over Japanese and Korean coastal areas, and corresponding internal and external doses accumulated during passage of the contaminated cloud, were calculated. The results showed that in a case of northeast winds, which are predominant in winter season, the contaminated air could reach Japan in one to three days depending on the wind velocities. The maximum concentration values over Japan occur in a release within the boundary layer (up to 1000 m). The nuclide concentration depend also on the release duration, with the highest concentrations occurring as a result of release durations of 16 to 60 min. The accumulated radiation doses depend on the concentration and the residence time over the ground. Evaluation of a severe accident was carried out using core inventory data for ^{134}Cs, ^{137}Cs, ^{90}Sr, ^{131}I, ^{133}I, ^{135}I from a NATO study of an accident near Murmansk. Use of these values reveals that doses accumulated during cloud passage, including both external irradiation due to cloud immersion and internal doses from inhalation will not exceed the 1 mSv limit in countries adjacent to Russia. Suggestions for extensions of this analysis are presented.

Acknowledgments

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Contents

Introduction

A spontaneous chain reaction in a submarine nuclear reactor occurred in August 1985, several months before the Chernobyl accident. The submarine accident and the resulting environmental damage in the area were a closely guarded secret for several years after the accident. In spite of previous accidents and the negligence of the personnel responsible for reactor maintenance, adequate precautions to limit nuclear accidents were not taken. Nine months later, Unit 4 of the Chernobyl nuclear power plant suffered a severe accident which contaminated Scandinavia and a large part of the territories of Central Europe.

Major naval ports housing nuclear powered submarines are situated near Murmansk (Murmansk Oblast), Vladivostok (Primoriye Kray), and Petropavlovsk (Kamchatka Oblast). Many retired submarines are currently waiting for decommissioning and a new nuclear accident could result in severe consequences in neighboring countries. Official data for the number of the submarines is not available, but it is considered that there are about 60 retired submarine moored in Pacific fleet bases, with a very limited staff on the board, and about 40 submarines are still in service in the Far East. Most of the submarines waiting for decommissioning have two nuclear reactors fueled with highly enriched (20-45%) uranium. The number of the nuclear reactors expected to eventually require decommissioning thus exceeds 100. Navy nuclear-powered submarine facilities for the Pacific Fleet are concentrated near Vladivostok, in Primoriye Kray. A major nuclear submarine overhaul and refueling yard is situated on the west coast of Dunai peninsula at Bolshoi Kamen, approximately 40 km from Vladivostok across Ussuriy Bay, and a small refueling yard on the east coast of the Dunai Peninsula, situated in a small inlet of Strelok Bay known as Chazhma Cove. A nuclear storage and disposal site is located in the tip of the peninsula [5].

Given that the 1985 Chazhma Cove accident occurred in southern Primoriye Kray, the research in this paper is focused on studying climate particularities and the potential for atmospheric transport from the Vladivostok area. This study estimates the potential for transboundary atmospheric transport of radioactive nuclides and the consequences to countries near to the Vladivostok area, namely, Japan and Korea.

Chazhma Cove Accident

In August 1985 a spontaneous chain reaction occurred during regular refueling operation on a nuclear submarine in Chazhma Cove. The accident occurred after the completion of refueling operations, after the reactor pressure vessel lid failed a leaktightness test. The workers decided to correct the problem without informing supervisory personnel. The lid was unfastened and lifted several centimeters, when an accidental movement of the crane holding the lid occurred. This resulted in movement of the control rods, resulting in a reactivity insertion which caused a power excursion. The power excursion resulted in a steam explosion which ejected core structural components from the vessel. The power of the reactivity accident was estimated to be 5×10^{18} fissions, and the duration of the main radionuclide release was estimated as less than one minute.

After the nuclear explosion, a fire broke out and the release of nuclear materials continued for four hours until the fire was extinguished. According to [11] the radioactive materials, iodine and activated products (^{60}Co, ^{54}Mn) blown out in the atmosphere were estimated to amount to 1.85×10^{17} Bq and the released noble gases amounted to 8×10^{16} Bq. During that day, south-east winds predominated with low cloud coverage of 10 points and periodical drizzling occurred. The radionuclide was deposited in an area of 2 km^2 in a forest in a narrow plume 3.5 km long and 200-650 m wide, in a northwest direction from the place of the explosion. The water and the bottom of the Chazhma Cove were contaminated mainly with ^{60}Co and partly with ^{137}Cs [11]. Due to the propitious wind condition and to the drizzling, contamination was not detected in Vladivostok. Most of the nuclides were deposited on the peninsula. However, ten people died in the explosion, and during the clean-up operations 290 people were overirradiated [11].

Risk of Another Submarine Accident and Long Range Contamination

Decommissioning operations include a process for unloading spent fuel. This procedure is similar to the first half of a normal refueling operation. The risk of a reactivity accident during refueling/defueling is estimated to be approximately 0.38% [6] per operation. Assuming that refueling and defueling operations are subject to equal probabilities for a reactivity accident, and that 200 defueling will need to be performed in the next 10 years, a rough estimation of 0.76 accidents can be expected for this period.

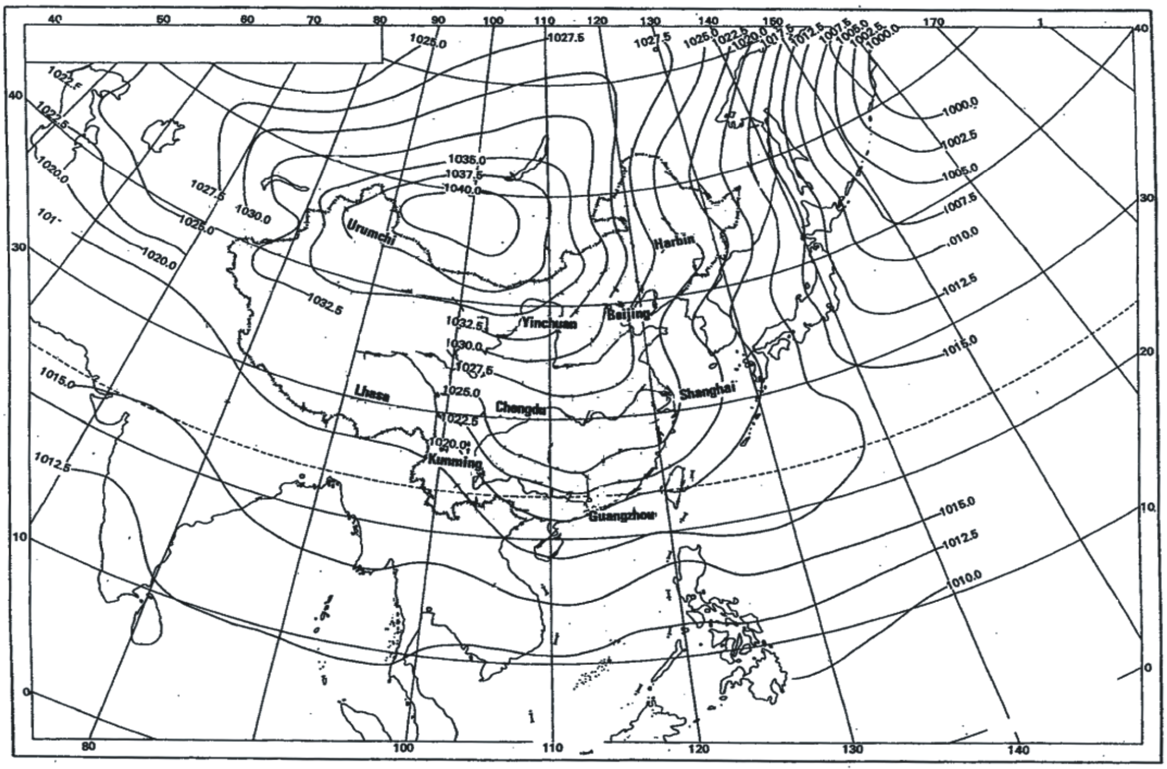

Figure 1. Mean January sea surface pressure (hPa).

General Atmospheric Circulation Patterns in East Asian Coastal Regions

Figure 1 shows the mean January sea surface pressure system. A strong cold anticyclone is usually situated in the north continental parts in winter up to altitudes of 500 hPa. It is a shallow low-level phenomenon, and is the strongest one in the Northern Hemisphere during the winter season. Two low-pressure zones are occur in winter: one is situated in the North Pacific, known as the Aleutian Low, and the other is situated near Australia and New Guinea, and is known as the Equatorial Low. The pressure field causes streaming from the Asian High to the Aleutian Low, resulting in a flow path on the Russian eastern coast from the inner continental system to the coastal regions. Northwestern winds therefore prevail in the Vladivostok region, and the air transport is towards the Japanese Islands. Southward streaming from the Asian High to the Equatorial Low can also influence the wind system, causing air masses to move to south and influence Korea. The mean (over 20 years, from 1976 to 1996) horizontal wind velocities in January at pressure 1000 hPa (Figure 2) [9], showed mean surface wind speeds at Vladivostok of more than 10 m/s.

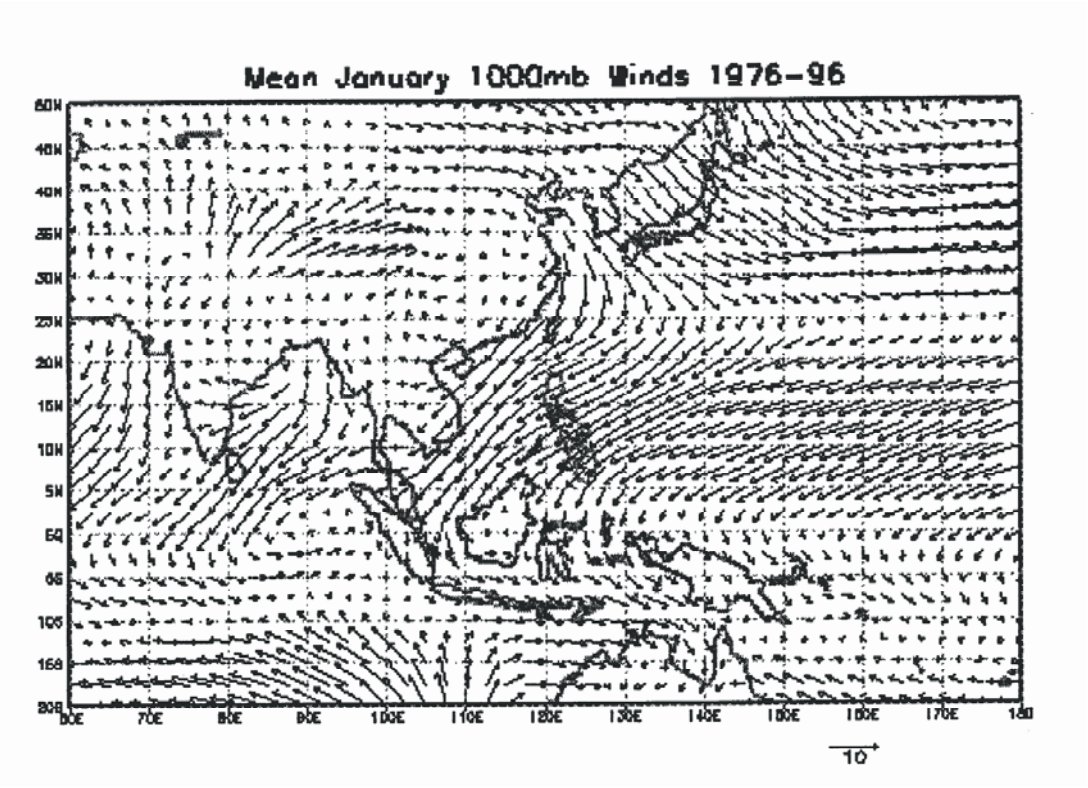

Figure 2. Mean January 1000 mB winds, 1976-1996.

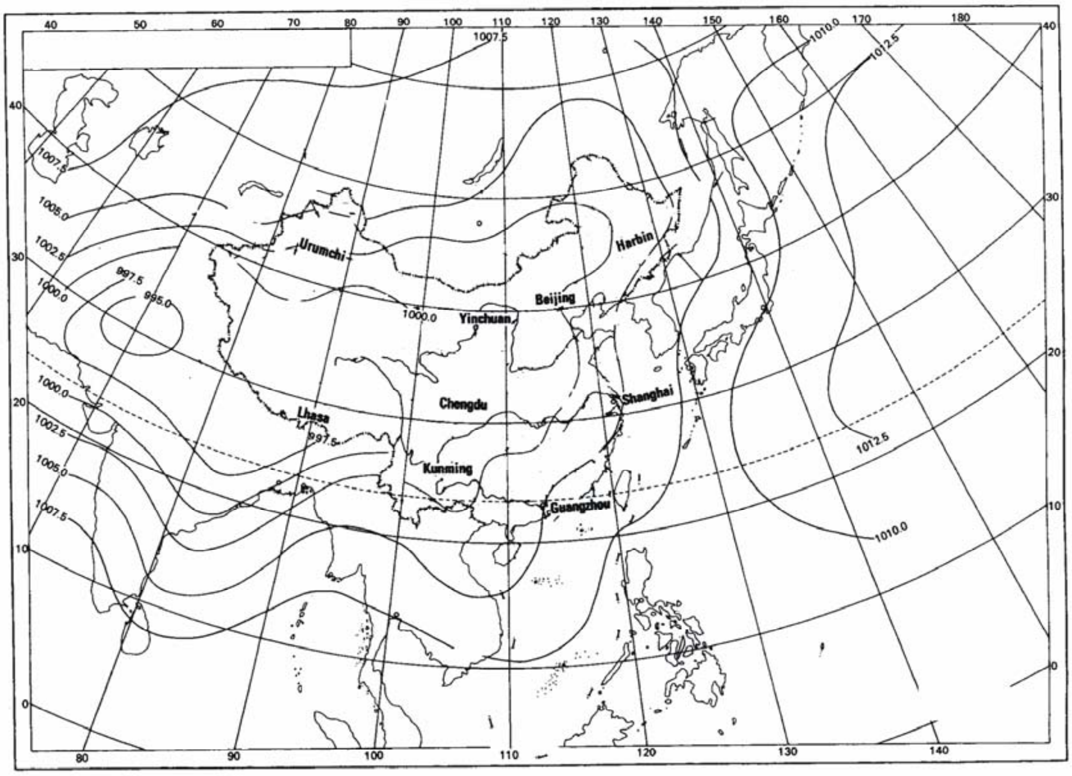

Figure 3. Mean July sea surface pressure hPa.

The pressure field in summer season (Figure 3) is dominated by the extensive low pressure system in Northern India, Pakistan and Southwest China, which is the strongest one during that time, and the Subtropical high pressure system, which is situated in the North Pacific, east of Japan. The summer surface wind is characterized by easterly winds and the transport of air masses from Vladivostok is toward the continent, where the masses travel up into Russia and can also influence China.

Monsoons, formed by the difference of the underlying surface; the cold wind, a strong and fast anticyclone with large pressure gradients (in winter); mesoscale processes as breeze effect and slope winds; and typhoons (in summer), can also contribute to the climate particularities. However, some of these processes influence the wind system only for a short time, and the others are less powerful than the synoptic formations. In this study we therefore do not account for these types of atmospheric processes.

Description of the Simulation

The simulations of the particle transport are made using the large scale model WSPEEDI. This model uses observations and measurements by the member nations of World Meteorological Organization (WMO). We investigate the possibility of radioactive contamination in Japan and Korea, where the wind flow and particle transport is toward these two countries in winter. Wind field measurement data from January 1997 is therefore used for this study as representative of weather patterns most likely to affect Japan or Korea. The distance between Vladivostok and Japan varies from 700 to 1000 km. The distance to Korea is about 400 km (Figure 1).

Wind Field Analysis for January 1997

The analysis of different meteorological conditions over the Sea of Japan, Russian far eastern coasts, and the Japanese islands show predominately north or northwest winds. During winter the temperature falls below –20 degrees and the wind values can vary from less than 5 m/s to about 20 m/s. The atmospheric transport has two typical directions: one is toward the Japanese islands and the other is toward North Korea.

Figure 4. Geographical map of the Sea of Japan, Vladivostok and Japanese Islands

The WSPEEDI calculations for the horizontal components of the wind field for different dates in January 1997 are shown in Figure 5. The three patterns shown indicate the most common weather patterns during the month. Figure 5a illustrates the pattern denoted as the Strong North Winds (SNW) case, with horizontal velocities of about 20 m/s toward Japan Islands. This condition is accepted as extreme for the long-range radionuclide transport. The pattern shown in Figure 5b exhibits wind velocities of less than 5 m/s and it is distinguished as Weak North Wind condition (WNW). Figure 5c demonstrates a more complicated situation in which the wind rotates over Korea and the Japanese island, and is termed the Cyclonic Wind (CW) case. These three wind conditions serve as a base for the analyses of the atmospheric radionuclide concentration, ground deposition and radiation doses.

In the study several different simulation conditions were analyzed in order to cover a large number of possibilities in a nuclear submarine accident. Three parameters (duration of the release, height of the release, and nuclide released) were varied. The structure of the experiment is summarized in Table 1.

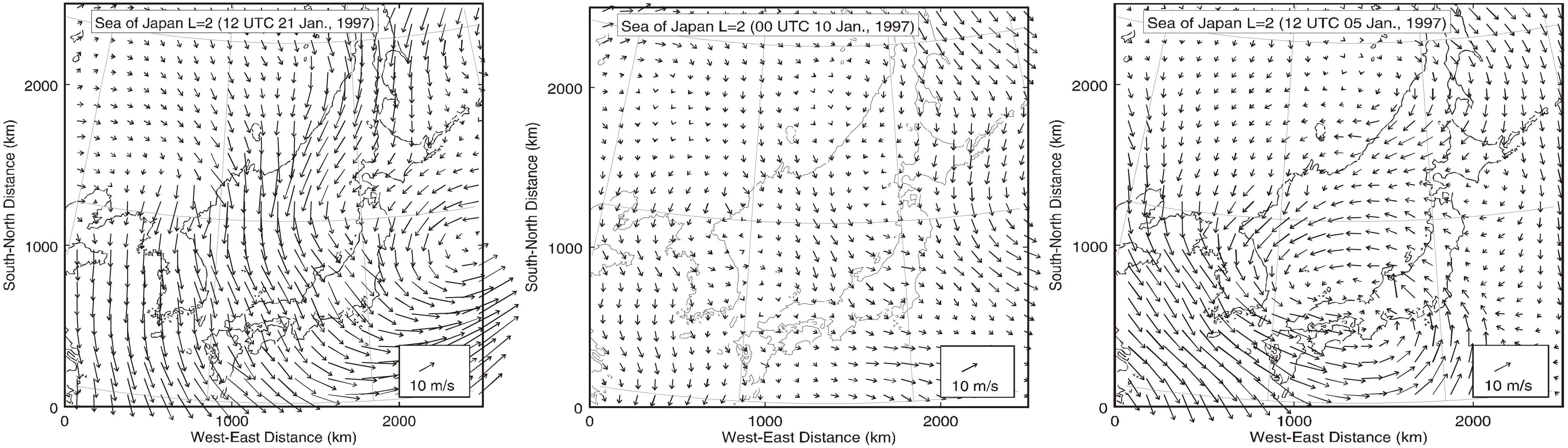

Figure 5. Wind field patterns

A) Strong North Winds (SNW)

B) Weak North Winds (WNW)

C) Cyclonic Wind (CW)

Table 1. Structure of the simulations modeled using WSPEEDI

Wind condition		Strong North-west Wind	Weak North –west Wind	Cyclonic North Wind
Wind velocity		15-20 m/s	> 5 m/s	10 m/s
Level of analysis 25 m	Calculation of concentration, external and internal doses, ground deposition at fixed duration of the release 16 min and fixed unit release 1 Bq	^{131}I ^{133}I ^{135}I ^{134}Cs ^{137}Cs ^{90}Sr	^{131}I ^{133}I ^{135}I ^{134}Cs ^{137}Cs ^{90}Sr	^{131}I ^{133}I ^{135}I ^{134}Cs ^{137}Cs ^{90}Sr
Level of analysis 25 m	Variation of the height of release point at fixed duration of the release 16 min and fixed unit release 1 Bq	75 m	75 m	-
		950 m	950 m	
		2500 m (^{137}Cs)	2500 m (^{137}Cs)	
Level of analysis 25 m	Variation of the duration of the release at fixed height 75m and fixed unit release of 1 Bq	16 min	16 min	16 min
		1 hour	1 hour	1 hour
		24 hours (^{137}Cs)	24 hours (^{137}Cs)	24 hours (^{137}Cs)
Calculations for concentration at different levels		Level 1- Level 10 (corresponding to 50 , 171.05, 334.21, 539.47, 786.84, 1076.32, 1407.89, 1781.58, 2197.37, 2655.26 m)		

The calculations of a hypothetical radionuclide release are made for three representative days in January 1997. Because data on relative humidity or precipitation was not available, wet deposition was not simulated.

Brief Description of WSPEEDI

The computer code WSPEEDI (Worldwide System for Prediction of Environmental Emergency Dose Information) was developed at JAERI (Japan Atomic Energy Research Institute) [1,2,3,7]. WSPEEDI is a system for prediction of radiological impacts due to a nuclear accident. The code adjusts the wind field values in a grid system and simulates long-range transport of radionuclides. WSPEEDI consists of a mass-consistent wind model (WSYNOP) for generation of large-scale wind fields and a particle random walk model (GEARN) for simulation of atmospheric dispersion and dry and wet deposition of radioactivity. The simulations can be performed on a hemispheric scale, and the vertical dimension is the top of the troposphere (10 km). The model is formulated with reference to a terrain-following height coordinate on ten standard pressure levels and horizontal transformed map coordinates with map scale factor m. It uses a horizontal resolution of 50 km and a temporal resolution of 6 h.

WSYNOP has two procedures. The first step is calculation of the initial wind speed values (u_0, v_0, w_0) at 3-dimensional grid system by interpolation of observed wind data. The interpolation of the horizontal components is calculated by the following equation:

$$(u_0, v_0)_{i,j} = \frac{\sum_{obs=1}^{N} \frac{(u, v)_{obs}}{r^2_{obs\,.ij}}}{\sum_{obs=1}^{N} \frac{1}{r^2_{obs\,.ij}}}$$

N- number of the proximate observations

$\frac{1}{r^2_{obs}}$ - weight of the inverse square of the distance between the grid

The second step is calculation of the mass-consistent wind field (u, v, w) using variational analysis and adjust the wind field to satisfy the mass continuity. The model uses observed or predicted wind data as an input. The boundary conditions are “flow through” at horizontal boundaries, vertical velocity at the ground is zero and vertical velocity at the upper boundary is constant. The air concentration and the dose model GEARN use a Lagrangian particle dispersion model. The movement of a marked particle is a sum of displacement of the mean wind and a random displacement due to the diffusion processes:

$$\begin{aligned} x_{t+\Delta t} &= x_t + m(u_p \Delta t + \delta x) \\ y_{t+\Delta t} &= y_t + m(v_p \Delta t + \delta y) \\ z_{t+\Delta t} &= x_t + m(w_p \Delta t + \delta z) \end{aligned}$$

where

(u_p, v_p, w_p) - advection wind at particle position

$\delta x, \delta y, \delta z$ - diffusion terms

The horizontal diffusion coefficient is calculated using simple distribution function with Gifford's standard deviation. The horizontal diffusion terms are defined through horizontal diffusion coefficient and a uniform random number. The vertical diffusion term is defined through vertical diffusion coefficients which depends on the stratification. The atmospheric boundary layer is up to 900 m and it corresponds to slightly unstable layer. The layer over 1000 m is assumed to be stable and the transition layer is a linear function between the boundary and the stable layer.

Dry deposition is calculated by assuming different deposition velocities depending on the type of nuclide and the condition of the surface. The deposition velocity for Cs-137 is 0.001 m/s, and for I-131 (aerosol) is 0.003 m/s. Wet deposition can be calculated by using a washout coefficient which is a function of rainfall intensity. The washout coefficient for Cs-137 is $5.0 \times 10^{-5} J^{0.8}$, where J [mm h^{-1}] is rainfall intensity. The total surface deposition is a sum of wet and dry deposition.

The accumulated external gamma dose is calculated from time-integrated air dose rate. Finally the accumulated 70 years internal dose accepted due to inhalation during the period of contaminated air passage can be defined.

Input and Output Data, Units

The model accounts for the complex source, terrain condition and non-uniform and non-steady state of the atmosphere. Input for WSYNOP and GEARN models are as follows:

- The GPV (Grid Point Value) data for WSYNOP, which is provided by JAERI and is accessed automatically by the program
- Geographical data, covering 2500 km x 2500 km, centered at Vladivostok with latitude of 43.1 degrees North and longitude 131.9 degrees East (these coordinates are used for fixing the release point)
- Table of yields of iodine and xenon isotopes with reactor type (BWR or PWR), fuel burn-up and cooling time
- Physical data of 60 fission products, fertile material and activated nuclides (nuclide names, decay constants, conversion factors of dose from nuclide concentration)
- Starting date and time of calculation and duration of calculation for wind field system
- Starting date and time of release, duration of analysis, step of calculation, duration of the particle release, release height, reactor type, fuel burn-up, time of reactor shut down

The output of the model is as follows:

- wind field data in vertical mesh boundary and date and time to which it corresponds, serving as input for GEARN
- radioactive concentration in atmosphere
- radioactive deposition on ground surface
- external dose data
- internal dose data

Units for input and output:

INPUT				
Latitude, longitude of release point	Release height	Release duration, step	Release rates	Fuel burn up
Deg	m	days, hours, s	1 Bq/h	MWd/t

OUTPUT				
Wind velocity	Radionuclide Concentration	Ground Deposition	External Dose	Internal dose
m/s	Bq/m^3	Bq/m^2	MSv	mSv

The plot program dhccw reads calculation results of WSYNOP and GEARN and produces graphical output.

Analysis of the Results

Atmospheric Nuclide Concentration and Dry Surface Deposition

Nuclide concentrations were compared for the following input conditions: duration of the release -16 min, height of the release - 75 m, quantity of the released nuclide – a unit of 1 Bq. The code calculates the concentration every 6 hours after a hypothetical unit release of 1 Bq from a submarine facility located in southern Primoriye Kray (Figure 6).
Figure 6.

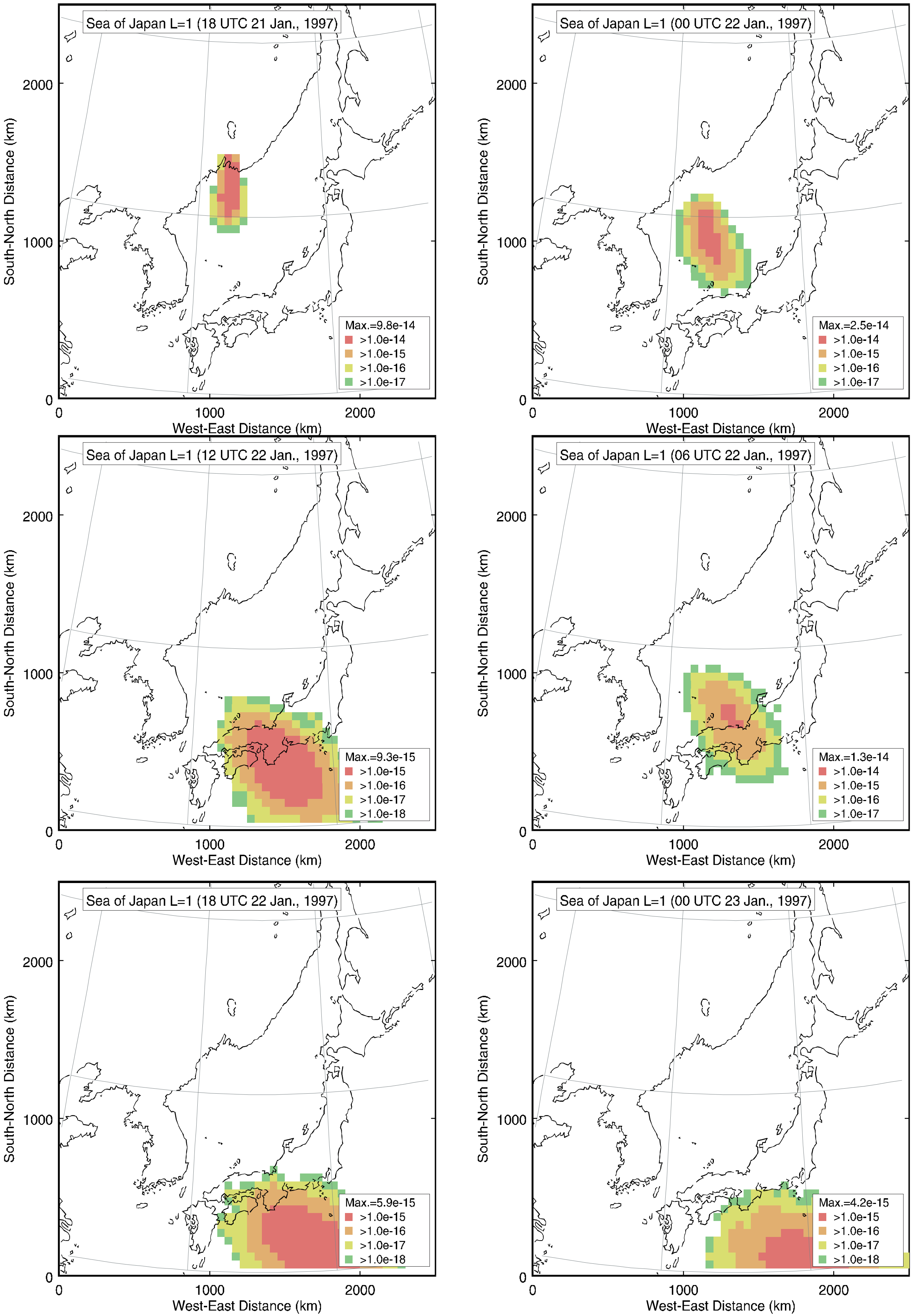

Figure 6. Concentration of ^{137}Cs every 6 hours after the release, release duration 16 min height if the release 75 m

A) SNW
B) WNW
C) CW

In the SNW (Figure 6a) case, the contaminated cloud reaches Japan in 12 hours, with the maximum concentrations over central Japan occurring 24 hours after the release. The maximum atmospheric concentration for ^{137}Cs is 9.3x10^{-15} Bq/m^3 per Bq released. The maximum atmospheric concentration values for other modeled nuclides 24 hours after the release are listed in Table 2. The contaminated air masses cover the central part of Japan and quickly pass over the populated territory. The residence timeover Japan is about 12 hours. Under the WNW condition (Figure 6b), the contaminated cloud reaches Japan in 36 hours and the maximum value for ^{137}Cs is about 3 times less than in the SNW case (2.8x10^{-15} Bq/m^3 per Bq released). However, the contaminated cloud is much larger, covering almost the whole territory of the Japanese main island, and the residence time is over three days. The third (CW) case (Figure 6c) results in air masses that move over Korea and rotate over the southern portion of the Japanese islands. Korea is affected mainly in the coastal regions. The maximum concentration occurs 30 hours after the release, over the sea, and the maximum values are comparable to those in the SNW (Table 2). The residence time is longer due to the closed rotation system which does not permit outflow of the air masses. The observed lower values of iodine nuclides (Table 2) are due to the shorter half-lives (^{133}I – 20.8 h, ^{135}I – 6.61 h).

Table 2. Maximum concentration 25 m over the ground

Max Radionuclide Concentration in Air (Bq/m^3)	25 m over Japan Islands		25 m over Korea
	Strong North Winds 24 h after release	Weak North Winds 72 h after release	Cyclonic North Winds 30 h after release
^{137}Cs	9.3 10^{-15}	2.8 10^{-15}	7.5 10^{-15}
^{134}Cs	9.3 10^{-15}	2.8 10^{-15}	7.5 10^{-15}
^{131}I	7.2 10^{-15}	1.2 10^{-15}	5.1 10^{-15}
^{133}I	4.3 10^{-15}	1.8 10^{-16}	2.6 10^{-15}
^{135}I	1.2 10^{-15}	1.6 10^{-18}	4.8 10^{-16}
^{90}Sr	9.3 10^{-15}	2.8 10^{-15}	7.5 10^{-15}

Ground deposition for the three wind conditions is shown in Figure 7. The largest affected territory is produced under the WNW case, with deposition occurring over the whole territory of Japan. In the other two cases, deposition occurs mainly in central Japan (SNW) and in Korea and South Japan (CW). The maximum values range between 10^{-12} –10^{-13} Bq/m^2 per Bq released.

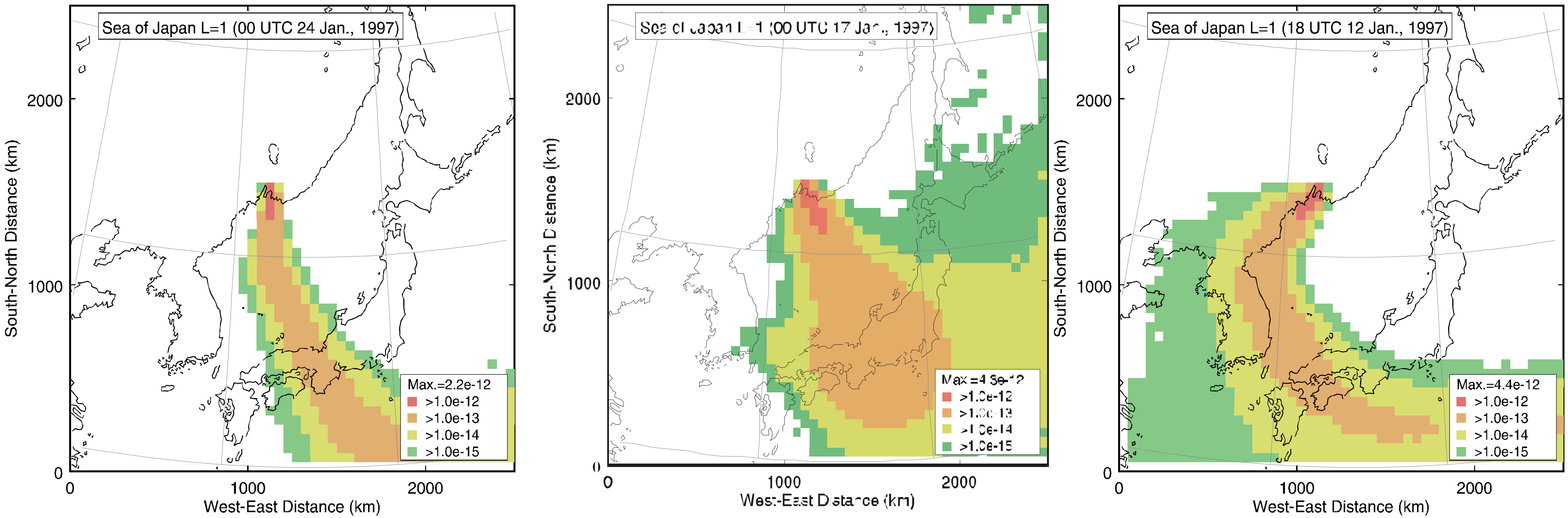

Figure 7. Dry surface deposition of ^{137}Cs

- **A) SNW**
- **B) WNW**
- **C) CW**

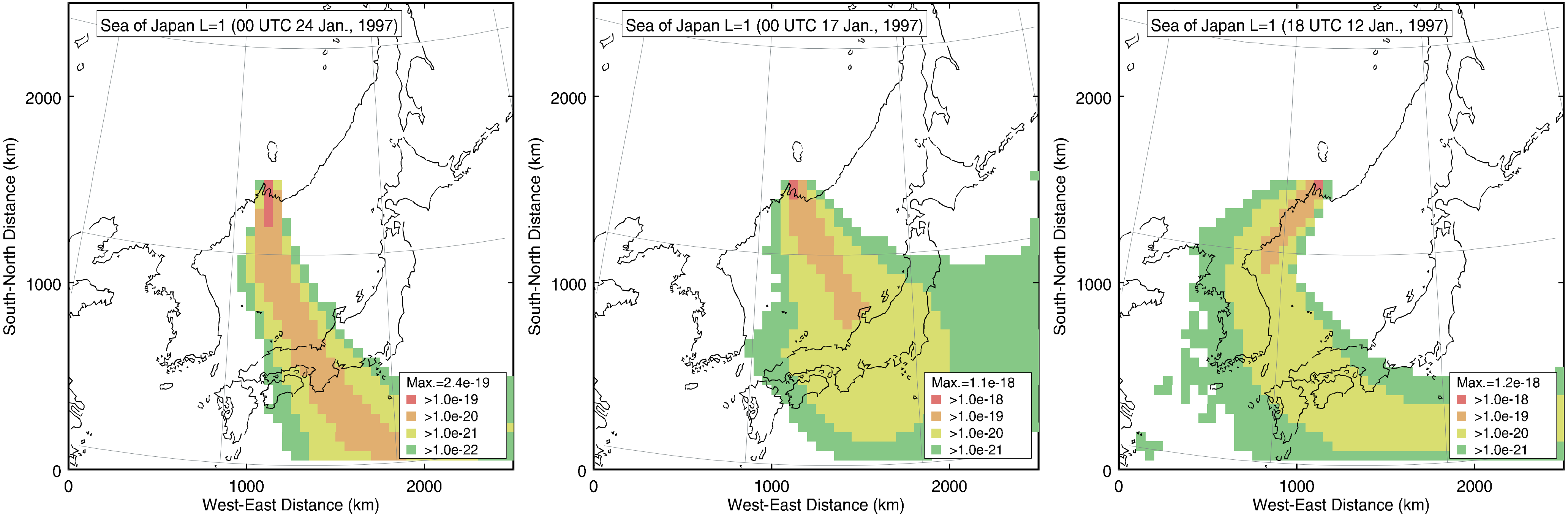

Figure 8. External doses of ^{137}Cs.

A) SNW
B) WNW
C) CW

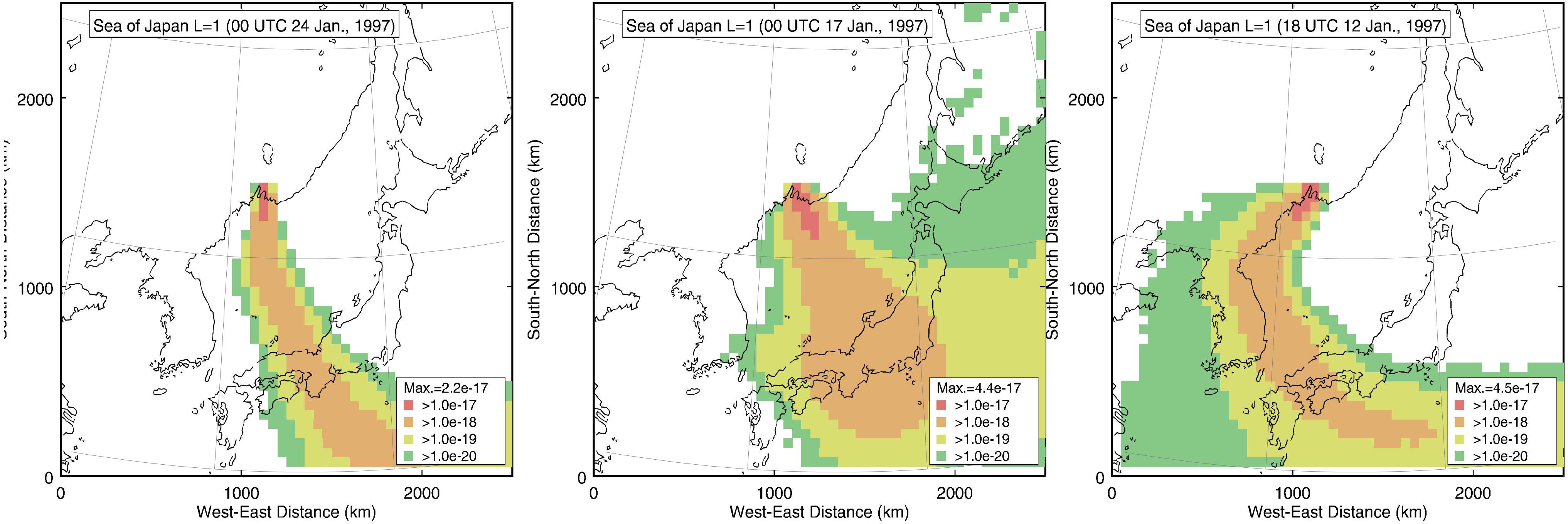

Figure 9. Internal doses of ^{137}Cs

A) SNW
B) WNW
C) CW

External and Internal Dose

The model calculates the 70 year accumulated dose due to inhalation and external gamma irradiation during cloud passage (Figures 8 and 9). Calculations were made for each of the selected nuclides after the contaminated cloud had passed completely over the examined region. The doses were calculated respectively up to 60 hours, 7 days and 7 days for the SNW, WNW and CW cases (Table 3).

Table 3 Calculated external and internal doses [mSv]

Nuclide	Strong North Winds (SNW) 60 hours (2.5 days) after release		Weak North Winds (WNW) 168 hours (7 days) after release		Cyclonic Winds (CW) 168 hours (7 days) after release			
	Japan		Japan		Korea		Japan	
	Ext. dose	Int. dose	Ext. dose	Int. dose	Ext. dose	Int. dose	Ext. dose	Int. dose
I-131	$>10^{-20}$	$>10^{-18}$	$>10^{-20}$	$>10^{-18}$	$>10^{-20}$	$>10^{-19}$	$>10^{-20}$	$>10^{-19}$
I-133	$>10^{-20}$	$>10^{-19}$	$>10^{-20}$	$>10^{-20}$	$>10^{-20}$	$>10^{-20}$	$>10^{-21}$	$>10^{-20}$
I-135	$>10^{-20}$	$>10^{-20}$	$>10^{-22}$	$>10^{-22}$	$>10^{-21}$	$>10^{-21}$	$>10^{-21}$	$>10^{-21}$
Cs-137	$>10^{-20}$	$>10^{-18}$	$>10^{-20}$	$>10^{-18}$	$>10^{-20}$	$>10^{-18}$	$>10^{-20}$	$>10^{-18}$
Cs-134	$>10^{-20}$	$>10^{-18}$	$>10^{-19}$	$>10^{-18}$	$>10^{-19}$	$>10^{-18}$	$>10^{-20}$	$>10^{-19}$
Sr-90	-	$>10^{-17}$	-	$>10^{-17}$	-	$>10^{-18}$	-	$>10^{-18}$

Assuming 1 Bq release quantity for ^{137}Cs and ^{134}Cs, the external doses for the three wind conditions are similar. All result in external irradiation doses of the order of 10^{-20} mSv per Bq released. The external dose depends on the concentration and the residence timeover the ground.

The estimations showed that the concentration is three times higher in the SNW than for the other two cases, and the residence time is about one day. In the case of WNW the concentration is three times smaller; however, the residence time is more than 3 days. The longer residence time offsets the smaller atmospheric concentration values in the WNW. For the short lived nuclides as ^{133}I and ^{135}I the doses in WNW are negligible. The external gamma dose of ^{90}Sr is zero because ^{90}Sr is not a significant gamma-emitter. A similar dependence can be observed in the internal doses. The values for ^{131}I, ^{134}Cs, ^{137}Cs are about 10^{-18} mSv per Bq released for the the SNW and WNW cases, in conformity with the dependence of dose on both the concentration and the residence time. The short-lived nuclides should not be considered in WNW condition. The maximum internal doses are observed for ^{90}Sr, which is a strong beta-emitter.

In the CW condition the contaminated cloud reaches Korea and Japan 30 hours after the release, with wind velocities comparable to those of the SNW case. As a consequence, it follows that the values for internal and external doses are also comparable. In the CW case the contaminated cloud moves between Korean coast and Japan and affects both countries almost equally (Table 3).

Variation of Atmospheric Concentration with the Release Duration

The main radionuclide release during the Chahzma Cove accident occurred in a period of less than one minute. The subsequent fire resulted in the release of another, smaller fraction to the atmosphere for four hours. Simulations including different duration of the release at the submarine facilities in southern Primoriye Kray were carried out to estimate the effect of short and long release times. The code resolution permits a minimum release duration of 2 min (120 sec). Calculations for ^{137}Cs nuclide concentrations for the three meteorological conditions involving 16 min, 1 hour and 24 hours release duration. The simulations for 16 min and 1 hour release do not influence upon the form of the contaminated air masses and max values of the concentration. The wind field is interpolated for every 6 hours and almost the same meteorological circumstances affects nuclide dispersion. The simulations for 24 hours continuous release of 1 unit bequerel showed that the concentrations are smaller but the residence timeover the Islands is longer. In the case of WNW the contaminated air masses stay over Japan more than 4 days. It results in higher values for external and internal doses and ground deposition.

Variation of Atmospheric Concentration with Changes in the Release Height

According to [10] the thermal rise of a plume, assuming horizontal wind speed of about 10 m/s in a case of neutral stratification of the temperature, can range from 45 m to 4.6 km. The code simulates a point release, and calculations were made for 75 m, 950 m and for 2500 m corresponding to the Chazhma accident in a slightly unstable layer, a release in neutral layer, and a release in stable layer. The max concentration at level 25 m over the ground for the both SNW and WNW can be observed in a case of 75 m release height (Table 4).

Table 4: Max concentration of Cs-137 at different heights of the point release.

Height of the release	Strong North Winds (24 hours after the release) [x10^{-15} Bq/m^3]	Weak North Winds (36 hours after the release) [x10^{-15} Bq/m^3]
75 m	9.3	9.0
950 m	7.6	8.0
2500 m	1.6	2.0

Vertical Distribution of Atmospheric Concentration

Plots of atmospheric concentration of ^{137}Cs at different height levels were evaluated. The simulations were done for 75 m release point and 16 min duration, and show the stratification of the plume at the time when the maximum values occur over the territory of Japan. The concentration decreases continuously over the height of 1000 m, and the maximum concentration is shifted toward the wind direction in the levels above 2000 m. In the boundary layer, the concentration varies and the maximum values are observed near the ground.

Consequence Analysis for a Severe Reactor Accident

The results obtained were applied to a hypothetical severe reactor accident. NATO's [8] calculated quantities of the radioactive fission product inventory remaining 5 years after submarine shutdown, assuming 8x10^{19} fissions, is as follows:
^{137}Cs - 3.5x10^{17} Bq
^{134}Cs 3.5x10^{16} Bq
^{90}Sr - 7.0x10^{16}
The estimated quantities of iodine nuclides [6] produced in an accident involving a freshly fueled reactor core, such as that involved in the Chazhma Cove accident, are as follows:
^{131}I - 2.9x10^{13} Bq
^{133}I - 6.2x10^{14} Bq
^{135}I - 1.84x10^{15} Bq.

Application of the dispersion model described above, using these release quantities, results in a value of 3,200 Bq/m^3 for the maximum ^{137}Cs atmospheric concentration under the SNW case. The external cloud irradiation dose and internal inhalation dose are on the order of 0.001 mSv and 0.1 mSv, respectively. These results indicate that the doses in Japan resulting from an accident on a nuclear submarine in Russia would be below the public limits.

Concluding Discussion

The WSPEEDI code developed in JAERI was used for assessment of the consequences for the neighboring to Russia countries after a hypothetical nuclear submarine accident at the submarine facilities in southern Primoriye Kray. Meteorological conditions during the winter are usually described with predominant strong northwest winds, which are favorable for the northeast transport of cold air masses.

The nuclide concentration, radiological doses and surface deposition were calculated for the three most common winter wind conditions over the Sea of Japan – Strong North Winds, Weak North Winds and Cyclonic Winds. The calculations showed differences in atmospheric concentrations over Japan due to the differences in the wind velocities as the max values were observed in the short transport of 12 hours. However, because the accumulated radiation doses are a function of the time-integrated atmospheric concentration, most nuclides display similar values in all of the three meteorological conditions due to the offset between atmospheric concentration and residence time of the contaminated cloud over the populated area. In addition, a parametric analysis of selected input parameters was carried out to identify critical variables. It was found that input of the point release in an unstable atmosphere (up to the boundary layer), or under long duration of the release (24 h), was the limiting case. We conclude that in a hypothetical nuclear accident at one of the submarine facilities in southern Primoriye Kray, the most severe consequences will occur in meteorological conditions similar to these that we characterize as weak north winds, particularly if the release occurs over a long period and into an unstable boundary layer.

Finally, we evaluated the impact of a hypothetical severe reactor accident. Using the estimated quantities of the different nuclides from the NATO report on a hypothetical submarine accident at Murmansk and applying the quantitative values to our results, we found out that the internal and external doses for Japan and Korea do not exceed the commonly accepted 1 mSv annual dose limit for members of the public. However, our calculations and analysis do not evaluate doses due to long-term exposure to contaminated soil, and do not include wet deposition, which can result in increases in soil contamination and in the accumulated radiation dose. The effect of long-term exposure to contaminated soils, particularly under the effects of wet deposition, are suggested as topics for further study.

References

1. Hirohiko Ishakawa, development of Worldwide Version of system for Prediction of Environmental Emergency Dose Information, WSPEEDI (III), J of Nuclear Science and Technology, vol. 31, No. 9, pp. 969 – 978, Sept. 1994
2. Hirohiko Ishikawa, Evaluation of the Effect of Horizontal Diffusion on the Long-range Atmospheric Transport Simulation with Chernobyl data, J of Applied Meteorology, vol. 34, No 7, July 1995
3. Hiromi Yamazawa, Akiko Furuno, Masamichi Chino, Evaluation of a Long-range Lagrangian Dispersion Model with ETEX, Atmosph. Environment, vol. 32, No 24 pp. 4343–4349,1998
4. Jiacheng Zhang, Zhiguang Liu, Climate of China
5. Joshua Handler, Preliminary Report on: Greenpeace Visit to Vladivostok and Areas around the Chazhma Cove and Bolshoi Kamen Submarine Repair and Refueling Facilities, Nuclear Free Seas Campaign, Greenpeace, Washington
6. Makoto Takano, Vanya Romanova, Hiromi Yamazawa, Yuri Sivintsev, Keith Compton, Vladimir Novikov, Frank Parker, Reactivity Accident of Nuclear Submarine at Vladivostok, applied in the Appendix
7. Misamichi Chino, Hirohiko Ishikawa, Hiromi Yamazawa, Haruyasan Nagai and Shigern Morinchi, WSPEEDY (Worldwide Version of SPEEDI) A Computer Code System for Prediction of Radiological Impacts on Japanese due to Nuclear Accident in Foreign Countries
8. NATO/CCMS Pilot Study: “Cross-Border Environmental Problems Emanating from Defence Related Installations and Activities”, Phase II: 1995-1998, Final Report, Vol. 4: “Environmental Risk Assessment for Two Defence Related Problems”, Report No. 227, North Atlantic Treaty Organization, I–73 – I–75, Mar. (1998)
9. NCEP/NCAR Reananalysis, Mean January 1000 mb Winds 1976–96, www.uea.ac.uk
10. Scorer Richard, Dynamics of meteorology and climate, WILEY-Praxis Series in Atmospheric Physics
11. Yu. V. Sivintes, V. L. Vysotskii, V. A. Danilyan, Radiological Consequences of Radiation Accident in a Nuclear-powered Submarine in Chazhma Cove, Atomic Energy, vol 76, No. 2, 19