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CALCULATIONS OF THE CONCENTRATION OF RADIONUCLIDES (CS-137, SR-90, PU-239/240) IN THE PACIFIC OCEAN

By

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SYNOPSIS

To evaluate the long-term environmental effects due to discharging of low-level radioactive waste into the sea from nuclear fuel cycle facilities. It is very important to estimate the longer-term and worldwide environmental risks by steady operation of the nuclear installation. The use of the numerical model is an effective way of evaluating environmental efforts of radioactive waste. Since 1970s, numerical models have been utilized for calculating flow fields of the ocean. Although such methods enable us to understand physical characteristics of the vast expanse of the ocean, it is essential to verify how accurately the calculated results of the models can represented the actual flow fields of the ocean. We calculated the flow fields of the Pacific Ocean by means of the data assimilation system, and compared the results with the data of surface drifter observations calculated by Michida (7). We obtained a correlation factor as high as r=0.74 for the east-west zonal component of the surface layer flow. To use these flow field results, we calculated the concentration of radionuclides (Cs-137, Sr-90, Pu-239/240) in seawater originating from fallout of atmospheric nuclear tests. We found a reasonably good reproducibility of concentration of Cs-137 and Sr-90 by means of model calculations. The existence of the concentration maximum of Sr-90 in the middle and deeper layers could also be well reproduced. Although the concentration of Pu-239/240 below the depth of its concentration maximum in the middle and deeper layers was rather poorly represented, the effects of scavenging on Pu-239/240 could be effectively represented in our model. These findings provide evidence of the environmental effects relevant to radionuclides in the sea water and the high reproducibility of flow fields of the Pacific Ocean obtained by the data assimilation system.

INTRODUCTION

Direct observation is indispensable for a thorough understanding of ocean phenomena. Moored flow meters and float tracking have been used for directly measuring of the flow field of the sea. These techniques are useful for local and short-term observation, but may be inadequate, technically and economically, in a large-scale investigation comprising an immense water body such as the Pacific Ocean. Although direct observation has not been made across the whole ocean, to understand the nature of ocean currents clearly is an important factor in securing voyage safety of ships and in grasping dispersion behavior of contaminants (oil, chemicals and radioactive materials). Numerical simulation techniques using ocean circulation models have been widely employed in compensating for the shortcomings of actual observation. Bryan (3) was the first to introduce for this purpose the Primitive Equation Systems, which has influenced almost all Ocean General Circulation Models (OGCM) until now. One of the major features of the OGCM of Bryan and Cox type is the rigid-lid approximation in which any ascent or descent of sea level is excluded. We also adopted this approximation in our calculations. However, it is very difficult to obtain a satisfactory result of accurate flow analysis by means of a numerical model computation because computers cannot detect errors due to an approximation to fundamental equations and the assumption method of boundary

conditions. Therefore, we attempted to reproduce the ocean current in the Pacific by using a data assimilation method that modifies errors at each time step and then compared the observation values and the computation values.

To understand the mechanism of the ocean circulation including Kuroshio re-circulation and Subtropical Counter Current, surface drifters are deployed and tracked with ARGOS system. And Michida (7) estimated mean velocity fields for 1 degree bins calculated from the tracks of 94 drifters developed in the Western North Pacific from 1987 to 1994. We then compared these surface drifter observations calculated by Michida (7) to the results in the surface layer.

The radionuclides originating from fallout of the past atmospheric nuclear tests and nuclear power plant accidents have been examined to investigate their effects on the human body and fishery resources since 1960s and can be treated as chemical tracers, which make it possible to understand clearly the physical oceanographic process in the long term. Therefore in this study, we calculate the concentration of radionuclides (Cs-137, Sr-90, Pu-239/240) in the ocean by reference to the study of Tsumune (11). By doing this, we can evaluate the long-term environmental effect in the Pacific Ocean.

PACIFIC OCEAN CIRCULATION MODEL

MODEL DESCRIPTION

Calculation covered the entire Pacific Ocean. The calculation mesh in the horizontal direction was longitude/latitude 2°×2°(110E~70W, 60N~74S). We assumed 11 vertical layers as shown in Table 1. The coordinate system is a spherical coordinate in a horizontal direction. The following equations are used. The equation of motion (1), the hydrostatic approximation equation (2), the continuity equation (3), the equation of heat conservation (4), the salinity conservation equation (5) and finally the equation of state (6).

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\vec{\nabla})\vec{u} + w\frac{\partial \vec{u}}{\partial z} + f\vec{k}\times\vec{u} = -\frac{1}{\rho_0}\vec{\nabla}p + A_H\vec{\nabla}^2\vec{u} + A_V\frac{\partial^2\vec{u}}{\partial z^2} \quad (1)$$

$$\frac{\partial p}{\partial z} = -\rho g \quad (2)$$

$$\vec{\nabla}\cdot\vec{u} + \frac{\partial w}{\partial z} = 0 \quad (3)$$

$$\frac{\partial \theta}{\partial t} + (\vec{u}\cdot\vec{\nabla})\theta + w\frac{\partial \theta}{\partial z} = K_H\vec{\nabla}^2\theta + K_V\frac{\partial^2\theta}{\partial z^2} + \gamma(\theta^* - \theta) \quad (4)$$

$$\frac{\partial S}{\partial t} + (\vec{u}\cdot\vec{\nabla})S + w\frac{\partial S}{\partial z} = K_H\vec{\nabla}^2 S + K_V\frac{\partial^2 S}{\partial z^2} + \gamma(S^* - S) \quad (5)$$

$$\rho = F(\theta, S, p) \quad (6)$$

$\vec{u}$ = horizontal flow velocity; $\vec{\nabla}$ = horizontal gradient operator; $\vec{\nabla}^2$ = horizontal Laplacian operator of spherical coordinate; $\vec{k}$ = unit vector of triaxial reference system; w = vertical flow velocity; p = pressure; t = time; z = vertical axis; ρ = density; θ, θ^* = calculated value of potential water temperature and observed value of potential water temperature, respectively; S, S^* = the calculated value of salinity and the observed value of salinity respectively; f = the Coriolis parameter; g = acceleration of gravity; γ = corrected term; A_H = the coefficient of horizontal eddy viscosity (1.0×10^7cm^2/s); A_V = the coefficient of vertical eddy viscosity (1.0×10^2 cm^2/s); K_H = the coefficient of horizontal eddy diffusion (1.0×10^6cm^2/s); and K_V = the coefficient of vertical eddy diffusion (1.0×10 cm^2/s), its value is set up based on the value that Wada and Nagoya (12) used for calculation.

As a method of calculation, we used the Runge-Kutta method for time terms, for the finite difference form of an advective term a first order upwind difference scheme was applied. Furthermore, we used a SMAC method for implicit discretization of pressure to satisfy the continuity equation and to simplify the Poisson equation. Though the calculation is an unsteady calculation, we calculated until its time term neared infinitely zero, and then selected 14400 sec in order to satisfy CFL condition as a calculation time interval (Δt). The characteristics of the model that we presumed to be a hydrostatic approximation in a

Table 1 Depths and Thickness of Model Levels

Level	Midpoint Depth(m)	Thickness(m)
1	10	0～20
2	35	20～50
3	75	50～100
4	150	100～200
5	300	200～400
6	600	400～800
7	1150	800～1500
8	2000	1500～2500
9	3000	2500～3500
10	4000	3500～4500
11	5000	4500～5500

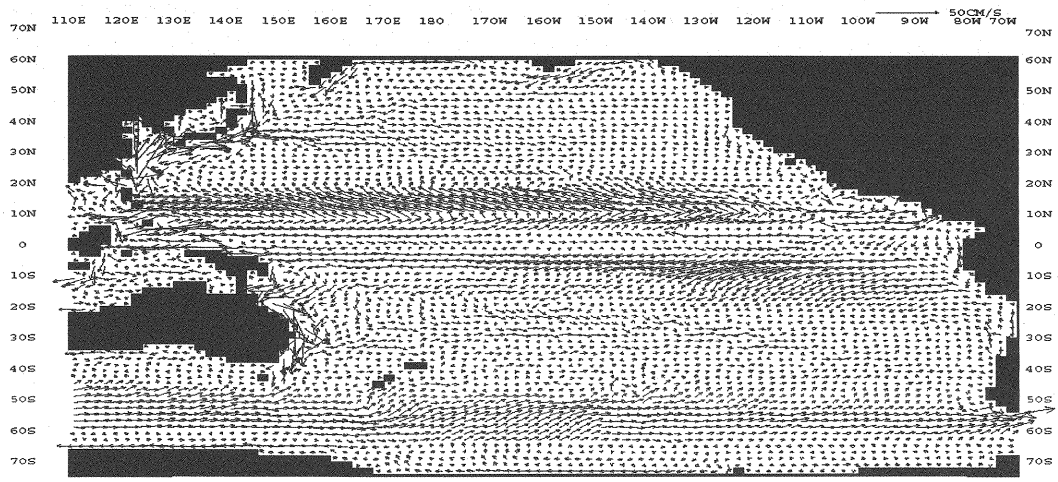

Fig. 1 The calculated horizontal current field (water depth 10m) after 30 years

vertical direction at first, but after the next time step we calculated a vertical flow velocity w from a corrected term of SMAC and presumed a rigid lid (no surface level change). Wind stress was calculated from satellite observed data sets (SSM/I: (1988 ~ 1998)) obtained by Atlas et al. (2). At the ocean boundary, we adopt the periodic condition in which a virtual open sea is established and interconnected. In addition, the setting pressure in the calculation boundary is not needed. As for water temperature/salinity data, we used data in the area between 100°E ~ 60°W, during for a period of 83 years (1906~1988), stored by JODC. As for the number of observations, BT types (XBT, MBT, DBT, AXBT) are 924392 and SD types (Hydrographic cast, STD, CTD) are 298346. For sea bottom topography, we used the General Bathymetric Chart of the Oceans (GEBCO) published by the Canadian Hydrographic Service.

We introduced a term that assimilates calculated the value and the observed value in the salinity conservation equation and heat conservation equation learned by Sarmiento and Bryan (10). In a situation such as this, observed data are assimilated continuously to a model through the assimilated term. When a calculated value deviates from an observed value, the assimilated term becomes bigger and works to return the calculated value to the observed value.

The result of flow was evaluated as steady when value defined by each calculation domain is satisfied with 10^{-6}. The equation of judgment can be expressed as follows:

$$e_x = \frac{\left\| X^{n+1} - X^n \right\|_2}{\left\| X^{n+1} \right\|_2}; \qquad \|X\|_2 = \sqrt{\sum_{ijk} X^2{}_{ijk}} \tag{7}$$

where X = the calculated velocity components, salinity and temperature.

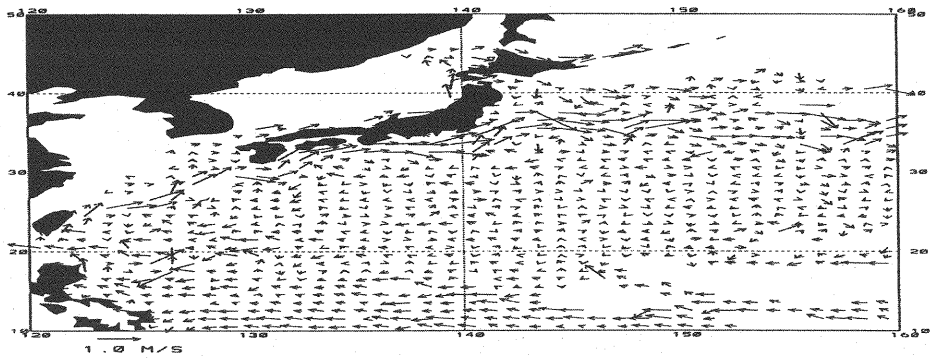

Fig. 2 Grid-averaged fields computed from drifter data of about 100 surface drifters during 1987~1994 by Michida(7)

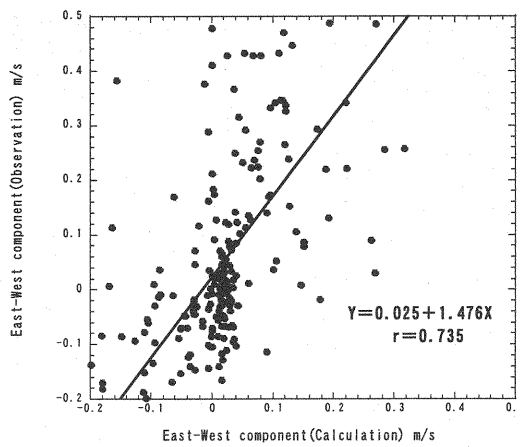

Fig. 3 Correlation between the buoy observation value and the numerical analysis result

FLOW ANALYSIS RESULT

Fig. 1 shows the calculated horizontal current field (water depth of 10m) after 30 years. The Northern Equatorial Current, the Kuroshio, the California Current and clockwise the North Pacific sub-tropical circulation are reproduced. In the southern hemisphere, the South Equatorial Current, the Antarctic Circumpolar Current, the East Australia Current and the counter-clockwise the South Pacific sub-tropical belt circulation are reproduced. In addition, a detailed examination of the numerical results show that the Equatorial Countercurrent, the Oyashio and the Subtropical Counter current are also well reproduced. Fujio et al. (4), (5) calculated the flow fields of the Pacific Ocean using the diagnostic model. Its circulation patterns ware similar to the ones obtained from our experiments in this research.

Fig. 2 shows an average surface ocean current field near Japan from the data of about 100 surface drifters during 1987~1994 by Michida (7) of the Maritime Safety Agency. A comparison of to these data, it is confirmed that the calculated positions of the Kuroshio, the Equatorial Counter current and the Northern Equatorial Current almost coincide. The correlation between the buoy observations and the numerical results was found to be high, r = 0.74 in the East-West component with a large flow velocity (Fig. 3). On the other hand, in the South-North component, whose flow velocity is small, the correlation is small, r = 0.25. Since the results confirmed that the East-West component of flow velocity in the subject sea area was about 7.5 times as big as that of the South-North component on average, it was concluded that the result of our calculation was very accurate.

ANALYSIS OF DISTRIBUTION OF RADIONUCLIDES CONCENTRATION

Environment assessment is very effective to ascertain the longer-term effects of the radioactive effluents from nuclear installation and nuclear power accidents, as well as atomic submarine accidents. For the purpose of analyzing the concentration of radionuclides (Cs-137, Sr-90 and Pu-239/240), we calculate the concentration values using the flow results estimated by the data assimilation method. The radionuclides concentration compiled by the Meteorological Research Institute of Japan (HAM database (1)) are compared with the calculated concentration in order to verify the reproducibility of vertical flow fields from the middle to deeper layers in particular.

DATA OF RADIONUCLIDES CONCENTRATION IN THE PACIFIC OCEAN

Natural radionuclides, including ones belonging to the uranium or thorium series and others derived by the collision of cosmic rays with elements, universally exist in all rocks, soil, building materials, foodstuffs, but their exact origins cannot be identified. Artificial radionuclides, on the other hand, have been created by atmospheric nuclear tests and by nuclear power plant accidents. Since the period of large-scale atmospheric nuclear tests, conducted during 1950s to 1960s in middle latitude of the northern hemisphere, extensive observations have been made of radioactive fallout and atmospheric, terrestrial and marine radionuclides concentration, because of environmental and human health threats. Consequently, we have plenty of data relating to the distribution and behavior of the artificial radionuclides in the oceans of the world. In our analyses, we used observation data of Cs-137, Sr-90 and Pu-239/240 in seawater that were measured at numerous points for long durations of time in the Pacific Ocean.

DETERMINATION OF FALLOUT

The amount of radioactive fallout varies widely in the latitudinal direction but less in the longitudinal direction. It is thought that amount of radioactive fallout is closely related to precipitation because over 90% of fallout reaches the surface of the earth through wet deposition. The total fallout on the oceans of the world must be determined to calculate the concentration of the radionuclides in seawater, so this was done by means of the following equation:

$$F(\lambda,\phi,t) = F_0(t)\frac{P(\lambda,\phi)}{P_0(t)}\varepsilon(\phi) \tag{8}$$

where $F(\lambda, \phi, t)$ = estimated annual fallout (Bq/m^2); λ = latitude; ϕ = longitude; $F_0(t)$ = annual fallout observed at the site of Meteorological Research Institute; $P(\lambda, \phi)$ = the average annual precipitation over the whole ocean(mm/year); $P_0(t)$ = annual precipitation observed at the site of Meteorological Research Institute; and $\varepsilon(\phi)$ = weighting coefficient for atmospheric concentration of radionuclides by latitude.

Although radioactive fallout is closely related to precipitation, there is not an exact proportional relation because of the nuclear tests were conducted in the northern hemisphere, while few nuclear tests were carried out in the tropical regions where rainfall is abundant. For these reasons, we corrected the latitudinal distribution of precipitation by calculating $\varepsilon(\phi)$ based on the distribution of total fallout of Sr-90 for each latitude, as reported by Monetti (8).

COMPARISON WITH THE TOTAL GLOBAL FALLOUT

Yearly fallout determined by equation (8), however, does not necessarily assure that it accurately represents fallout in our targeted area when compared with the total global fallout estimated by Playford et al. (9). We employed a correction factor so that the yearly fallout in the Pacific Ocean may be 50% of the globally integrated value of yearly fallout estimated by Playford et al. (9), because the Pacific Ocean occupies about 50 % of the surface of ocean on the earth. The correction factor is presented as

$$F^*(\lambda,\phi,t) = F(\lambda,\phi,t)\gamma(t) \tag{9}$$

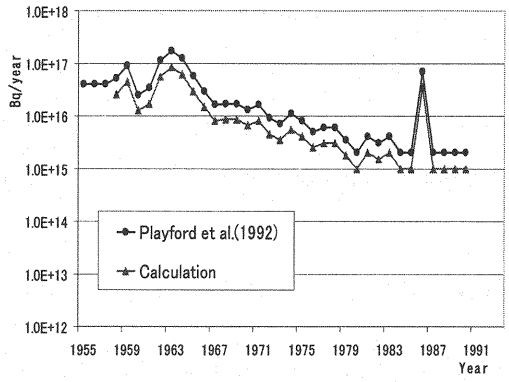

Fig. 4 Total Global Fallout of Cs-137 estimated by Playford et al. (9) and values used in the calculation

Table 2 List of the coefficients used in concentration analysis

Summary of Coefficient Used		Coefficient Value	
u,v,w : rate of the advection (m/s)		obtained by the data assimilation system	
K_H : horizontal diffusion coefficient (m^2/s)		1.0×10^{2} m^2/s	
K_V : vertical diffusion coefficient (m^2/s)		1.0×10^{-3} m^2/s	
half-life of radionuclides ($=1/\lambda n$)		Cs-137	30 (year)
		Sr-90	28.8 (year)
		Pu-239	24100 (year)
		Pu-240	6540 (year)
K_d : distribution coefficient of radionuclides (m^3/g)		Cs-137	2.0×10^{-3} (m^3/g)
		Sr-90	2.0×10^{-4} (m^3/g)
		Pu-239, 240	1.0×10^{-1} (m^3/g)
$\rho_s(z)$: concentration of suspended matter (g/m^3)		surface concentration : $\rho_s(0)=0.25$ (g/m^3) (assumed to be uniform in the whole sea)	
		distribution in deeper layers (d:depth) : $\rho_s(d) = \rho_s(0) \times 10^{-0.0005d}$	
Ws : settling rate of suspended matter (m/s)	large particles (over 50 μm)	component ratio $a_1=0.04$, $W_1=100$ (m/day) $Ws = 1.16 \times 10^{-3}$ (m/s)	
	small particles (less than 50 μm)	component ratio $a_2=0.96$, $W_2=100$ (m/year) $Ws = 3.17 \times 10^{-6}$ (m/s)	
	average particles	component ratio $W_s=a_1 \times W_1+a_2 \times W_2$ $Ws = 4.93 \times 10^{-5}$ (m/s)	

where $F^*(\lambda, \phi, t)$ = the total estimated annual fallout (Bq/m^2) after the correction; and $\gamma(t)$ = the correction factor determined from the estimated fallout of Playford et al. (9).

Yearly fallout calculated with equation (9) are shown in Fig. 4, and tally well with the estimation by Playford et al. (9).

MODEL FOR OCEAN RADIONUCLIDES CONCENTRATION

Radionuclides introduced into seawater are diluted by advection and diffusion in the sea. During these processes, they not only disintegrate with their specific decay constants, but also are adsorbed to suspended particles that settle down toward the bottom and are removed from the water column. This process is known as scavenging. By considering these phenomena, the basic equation for nuclide concentration in seawater is expressed below. The flow fields used in calculations are the same as those that are obtained by the data assimilation system.

$$\frac{\partial C}{\partial t} + L(C) = R(K_H, K_V, C) - \lambda_n C + K_d \rho_s(z) w_s \frac{\partial C}{\partial z} + F^*(\lambda, \phi, t) \qquad (10)$$

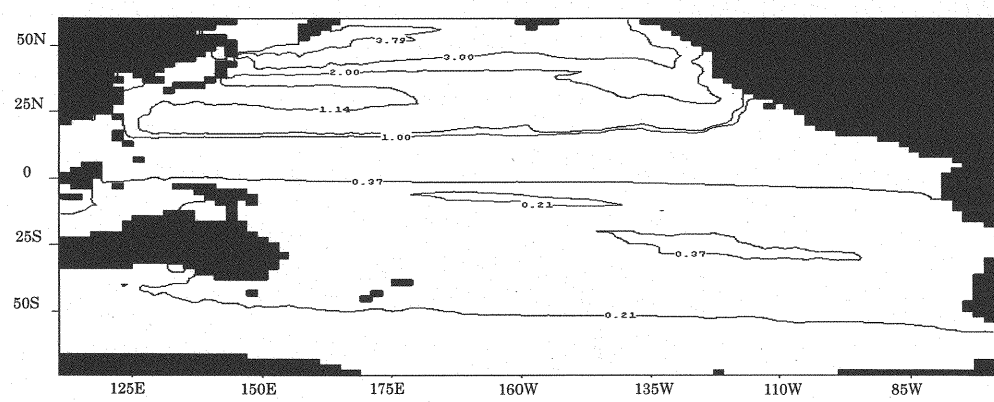

Fig. 5 Horizontal distribution of Cs-137 concentration at the surface layer in 1990

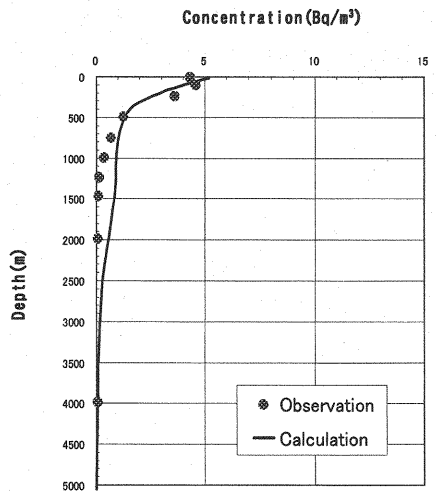

Fig. 6 Vertical Profile of Cs-137 concentration in 1986 (lat.146° E,long.30° N)

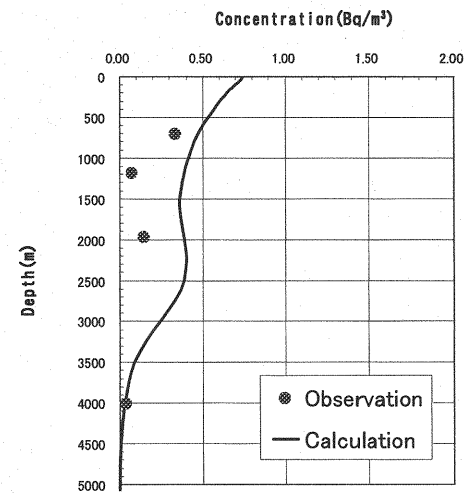

Fig. 7 Vertical Profile of Sr-90 concentration in 1979 (lat. 137° E and long. 62° N)

Where C = radionuclide concentration (Bq/m^3); $L(C)$ = advection term; $R(K_H, K_V, C)$ = diffusion term; λ_n = the decay constant of radionuclides = (1/half-life)(1/s); K_d = distribution coefficient of radionuclides (m^3/g); $\rho_s(z)$ = the concentration of suspended matter in seawater (g/m^3); $w_s(>0)$ = settling rate of suspended matter (m/s). The values K_H and K_V which were used are the same as those used in the data assimilation system, and the value of $F^*(\lambda, \phi, t)$ is the one obtained by equation (9), divided by the depth of mixing layer, 20m.

The advection term of equation (10) is given by the equation below, flow components of the spherical coordinate being (u, v, w).

$$L(C) = \frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(uC) + \frac{\partial}{\partial\phi}(v\cos\phi C)\right] + \frac{\partial}{\partial z}(wC) \qquad (11)$$

Where a = diameter of the earth.

In order to calculate the concentration of radionuclides, we utilized observation data covering 36 years from 1958 to 1993, for which data of Cs-137, Sr-90 and Pu-239/240 concentration are sufficiently available

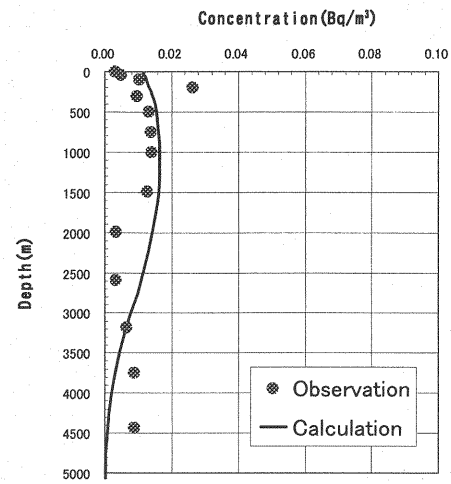

Fig. 8 Vertical profile of Pu-239/240 concentration in 1985 (lat. 177° W and long.44° N)

in the database of the Meteorological Research Institute.

We adopted the yearly fallout determined by equation (9) as the boundary condition at sea surface, and supposed a uniform concentration of radionuclides in seawater of the mixing layer at a depth of 20m. We also assumed that radionuclides concentration of all cells of the targeted sea area were 0 (Bq/m3) at the initial state, and that radionuclides came exclusively from fallout on the surface layer of the ocean. Radionuclides that reached the sea bottom were supposed to thought to have been lost from the water column. The included area, meshes and sea bottom topography are the same as those used in calculation of the ocean circulation model. The coefficients used in the concentration analysis, which were included in published IAEA reports (6), are shown in Table 2.

RESULT OF CONCENTRATION ANALYSIS

Results of the concentration analysis were verified for years almost up to the final year of calculation (1990), because measurement accuracy of radionuclides concentration might have been insufficient in earlier years from 1960s to the beginnings of 1970s, and because the reproducibility could have possibly been low in the earlier periods of our calculations, starting in 1958. We selected, from the HAM database, data from continuous observations conducted by the same research group in the Pacific Ocean, to avoid variations in accuracy of observation data due to the fact that different observational apparatuses and procedures are sometimes used.

Fig. 5 shows the horizontal distribution of Cs-137 concentration at the surface layer in 1990, after 33 years integration. In during these periods, atmospheric nuclear tests had been carried out since 1980s, and the Chernobyl power plant accident occurred in 1986. The maximum concentration sea areas are placed in west North Pacific. In spite of the fact that fallout existed in the whole sea area, the elevation of concentration is very small in the southern hemisphere. This trend continued during the calculation period and is reflected in the calculation results of 1990. We assume that concentration of Cs-137 is dominated by Subtropical Gyre and Subarctic Gyre. Fig. 6 shows the vertical profile of Cs-137 concentration in the sea area of lat. 146°E and long. 30°N in 1986. Although the calculation somewhat overestimated the observed values, the reproducibility of concentration as a whole is reasonably good. Fig. 7 shows the vertical profile of Sr-90 concentration in the sea area of lat. 137°E and long. 62°N in 1979. In this case, the calculation also produced some overestimation of the observed values. It should be noted, however, that the observed increase in concentration at depth of 2000m is well represented by the calculation. Fig. 8 shows the vertical profile of Pu-239/240 concentration in the sea area of lat. 177°W and long.44°N in 1985. In the upper layers above 1500m, the calculation reproduced reasonably well the distribution pattern, although a slight degree of overestimation occurred in such cases as Cs-137 and Sr-90. However, the reproducibility was not good in the layers below 2000m.

Pu-239/240 is more susceptible to the scavenging effect than Cs-137 and Sr-90, since it tends to be adsorbed onto suspended particles in seawater far more easily (over 200 times) than the other radionuclides. This causes a formation of concentration maximum in the middle layer of the ocean. Our calculation was able to reproduce accurately the scavenging phenomenon, but failed to simulate the abrupt change in concentration in deeper layers. The Roughness of the mesh size in the vertical direction in our model may have been one of the reasons as well as possible errors contained in observation data. It is possible that the actual concentration of Pu-239/240 in seawater is too small to be represented in calculation.

In spite of these problems, the results of our calculation reproducing the radionuclides concentration in the ocean were quite good, which shows that flow fields of middle layers of the Pacific Ocean were satisfactorily reproduced by our model.

DISCUSSION AND CONCLUSION

Pacific Ocean flow fields were reproduced by using the data assimilation system (Fig. 1). Surface flow fields are generally known to be dominated by wind stress. But on the other hand, flows of the middle and deeper layers are mainly determined by thermohaline circulation that is controlled by temperature and salinity distributions in the ocean, rather than by the wind stress. In our model, the assimilation term was added to the conservation term of potential temperature and the salinity conservation equations. The assimilation term enabled us to find fewer differences between observed and calculated salinity data, and consequently, to effectively represent the thermohaline circulation within the ocean. The following conclusions can be drawn from this study:

(1) For the surface flow fields, a comparison was made with the current distribution reported by Michida (7) based on the track of floating buoys (Fig. 2), and a high correlation coefficient of r=0.74 was found for the East-West component with an especially high velocity (Fig. 3). The accuracy of the calculation is thought to be due to the fact that we estimated the wind stress by utilizing the satellite observation data of SSM/I. Since the flow field of the surface layer is strongly influenced by wind, determining the wind stress will be an important factor in OGCM calculations in the future.

(2) Calculated distributions of artificial radionuclides which are shown in Fig. 6, Fig. 7 and Fig. 8 also agree well with observed ones. This study supports that evidence of the high accuracy of reproducing flow fields, and showes that the effects of scavenging and physical decay of radionuclides are effectively represented in our model to reproduce the concentration of these nuclides.

The findings of this study provide strong evidence of the high reproducibility of the Pacific Ocean flow fields by means of the data assimilations system. Furthermore, we were able to analyze the concentration of radionuclides for evaluating the long-term environmental effect.

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APPENDIX -NOTATION

The following symbols are used in this paper:

a	= diameter of the earth;
A_H	= coefficient of horizontal eddy viscosity (1.0×10^7cm^2/s);
A_v	= coefficient of vertical eddy viscosity (1.0×10^2 cm^2/s);
C	= radionuclide concentration (Bq/m^3);
f	= Coriolis parameter;
$F_0(t)$	= annual fallout observed at the site of Meteorological Research Institute;
$F(\lambda,\phi,t)$	= estimated annual fallout (Bq/m^2);
$F^*(\lambda,\phi,t)$	= total estimated annual fallout (Bq/m^2) after the correction;
G	= acceleration of gravity;
$\vec{k}$	= unit vector of triaxial reference system;
K_d	= distribution coefficient of radionuclides (m^3/g);
K_H	= coefficient of horizontal eddy diffusion (1.0×10^6cm^2/s);
K_V	= coefficient of vertical eddy diffusion (1.0×10 cm^2/s);
$L(C)$	= advection term;
p	= pressure;
$P(\lambda,\phi)$	= average annual precipitation on the whole ocean (mm/year);
$P_0(t)$	= precipitation on the whole ocean (mm/year);
$R(K_H,K_V,C)$	= diffusion term;
S, S^*	= calculated value of salinity and observed value of salinity respectively;
t	= time;
$\vec{u}$	= horizontal flow velocity;
X	= the calculated velocity components, salinity and temperature
w	= vertical flow velocity;
$w_s(>0)$	= settling rate of suspended matter (m/s);
z	= vertical axis;
γ	= corrected term;
$\gamma(t)$	= correction factor determined from the estimated fallout of Playford. et al. (9);
$\varepsilon(\phi)$	= weighting coefficient for atmospheric concentration of radionuclide by latitude;
θ, θ^*	= calculated value of potential water temperature and observed value of potential water temperature, respectively;
λ	= latitude;
λ_n	= decay constant of radionuclide = (1/half-life)(1/s);
ρ	= density;
$\rho_s(z)$	= concentration of suspended matter in seawater (g/m^3);
ϕ	= longitude;
$\vec{\nabla}$	= horizontal gradient operator; and
$\vec{\nabla}^2$	= horizontal Laplacian operator of spherical coordinate.

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