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An optimization strategy in wind-driven circulation with uncertain forcing problem off the southeastern coastal waters of Korea

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한국 남동해역 취송순환문제에서 바람응력에 대한 최적화 연구

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Abstract

We demonstrated the importance of initial estimates of model parameters and the utility of an optimization approach of the uncertain forcing of wind-driven circulation off the southeastern coastal waters of Korea. The wind stress represents the upper boundary condition in this model and enters in the model equation as a forcing term in the numerical formalism. The wind field contributes to maintain the almost time-independent distribution of the upper layer thickness feature in a north-south direction and negative wind stress curl to maintain the formation of warm eddy off the southeastern coastal waters of Korea. Elucidated is the variational characteristics of the East Korean Warm Current due to the variations of the zonally averaged wind stress (southward transport) from the seasonal variations of the meridional transport by the Ekman transport.

요 약

한국 남동해역 취송순환에서의 부정확한 외력의 바람응력 문제에 대한 최적화 방법의 유용성에 관하여 검토하였다. 바람응력은 모델 및 수치적 정식화 과정에서 상층 경계조건 및 외력항으로 고려되었다. 그리고 바람응력 평가에 대한 최적화 방법의 적용성 및 모델변수의 초기값 추정치의 중요성을 검토하였다. 최적화 연구로부터 동해 남부해역의 취송순환에 관한 동한난류의 수송량 변화 및 동해 난수층의 형성과 분포특성을 바람응력, 바람응력 회전성 및 상층두께의 변동으로부터 파악할 수 있음을 확인하였다.

Keywords : Optimization approach, Wind-driven circulation, Uncertain forcing, Wind stress, Wind stress curl, Upper layer thickness, Ekman transport

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1. Introduction

The East Sea of Korea is a marginal sea surrounded by the Japanese Islands and the Asian continent. In general, the upper layer of the East Sea of Korea is known to be divided into two regions; the warm water region in the southern part and the cold water region in the northern part. The complicated oceanic conditions result from the interaction of these two water masses.

Historical wind data (Japan Meteorological Agency, [1977]) depict a clear seasonal variation in wind stress over the East Sea of Korea and the northern Pacific. Moreover, a seasonal variation in wind stress might have a significant influence on the branching of the Tsushima Current and the current system of the East Sea of Korea (Sekine, [1986]). Since the temporal change of the wind stress over the East Sea of Korea is large, a large variation in wind-driven circulation is seen in his numerical experiment. The wind stress over the East Sea of Korea may be significantly influenced by the local effects such as mountains stretching in a north-south direction. Na [1988] suggested that wind field in the East Sea of Korea is favorable to some extent for the "saddle-like" feature of the warm core.

The purpose of this study is to examine the utility of an optimization strategy in wind-driven circulation with the uncertain forcing problem off the southeastern coastal waters of Korea.

2. Data and Methods

Wind data were obtained from the reports by NFRDI (National Fisheries Research and Development Institute) and JMA (Japan Meteorological Agency) ([Fig. 1] ; [Table 1]).

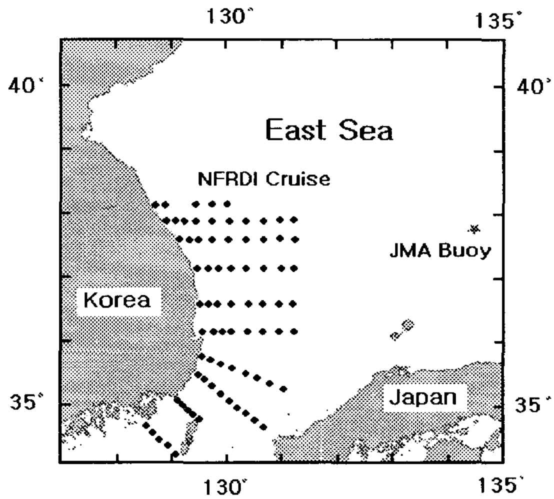

Fig. 1 Schematic representation of observation stations

Annual mean and monthly mean wind stress fields over the East Sea of Korea are obtained using the data reports during the 20 years

Table 1 List of data used in this study

Data ID	Institution	Observation Period	Observation Interval	Measured Depth	Measured Item
Ship Data	NFRDI	1972~1992	2 Months	Standard	WBT, SWT, SSW
Buoy Data	JMA	1972~1992	3 Hours		WBT, SWT, SSW
Model Data	University		Monthly		
Na(1992)	HanYang	1985~1987	Mean	SSW	SSW
Kang(1994)	Seoul	1985~1987	Mean	SSW	SSW

WBT : Wet Bulb Temperature, SWT : Sea Water Temperature, SSW : Sea Surface Wind from 1972 to 1992. We calculated the wind stress from the individual ship reports which were measured at about ten meters height using the following bulk formula [Fig. 2].

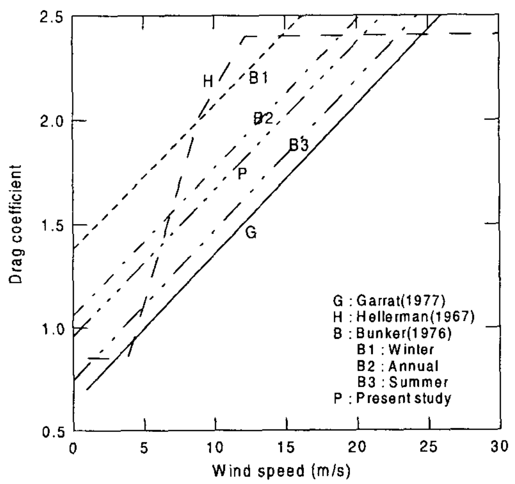

Fig. 2 The drag coeficients in relation to the wind speed in the bulk formula

The numerical model is formulated using a finite difference discretization on a grid with spatial and temporal increment (Kim, [1996]). The minimization determines the best fit of the data when the optimal solution is approached. Many different minimizations are available.

The distribution of wind stress has been used to explain the general features and transports of ocean circulation (Sverdrup, [1947] ; Munk, [1950]). Such studies require the information on the distribution of wind stress curl.

By assuming a three-layer ocean with the permanent thermocline and mixed layer as depth of interfaces, the thickness of the upper layer that is assumed to be changed only by wind-driven transport of the upper layer can be obtained in Fig. 3. For the three-layer system (Veronis, [1988]), the heights $z=0$, $z=H_3$, $z=H_2$ and $z=H_1$ correspond, from the bottom to the bottom, the middle and the top layer, respectively. In the present simplified calculation, the density stratification is idealized in terms of three homogeneous layers with uniform densities ρ_1, ρ_2, ρ_3 in the top, middle and bottom layer, respectively. The locations of the bounding surfaces are shown in Fig. 3 along with the thickness of each layer. In this model, the bottom layer is assumed to be motionless.

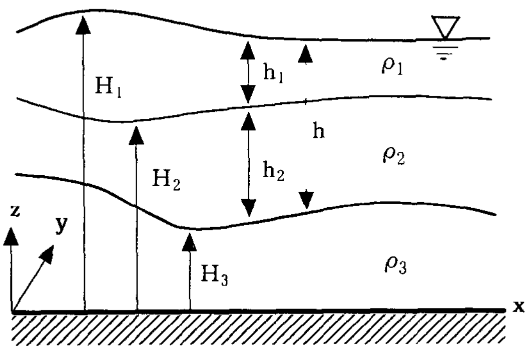

Fig. 3 Schematic representation of the three-layer model

From the vertically integrated conservation equations for momentum and mass for the top and middle layers, the Sverdrup transport relation for the total mass transport, $\rho V \equiv \rho_1 V_1 + \rho_2 V_2$, follows,

$$\beta \rho V = \rho_1 \chi \cdot \nabla \times \tau \qquad (1)$$

where $\beta = \partial f/\partial y$, $\chi \cdot \nabla \times \tau = -\partial \tau_x/\partial y$, χ is the vertical component of the wind stress curl, f is the Coriolis parameter, ρ is the density of seawater and τ is the wind stress.

The thickness of the upper layer, h, is given by the following equation,

$$\frac{1}{2}\frac{\partial}{\partial x}(g_1 h_1^2 + g_2 h^2) = \left[-\frac{f}{\beta}\frac{\partial \tau_x}{\partial y} + \tau_x \right] \tag{2}$$

where, x is positive eastward, h_1 and h_2 are the thickness of the top and middle layers, respectively. The right hand side term is proportional to the vertical velocity induced at the base of the Ekman layer, is independent of x, and describes the zonal momentum balance between the integrated zonal pressure gradient and the applied surface stress. And, $g_1 = g\triangle\rho/\rho_3$, $g_2 = g(\rho_3 - \rho_2)/\rho_3$, $\triangle\rho$ is $(\rho_2 - \rho_1)$, g is gravity, $f = 2\omega\sin\phi$ is the Coriolis parameter, τ_x is the zonal component of the wind stress, ω is the angular frequency of the earth's rotation and ϕ is the latitude. Integration (2) with respect to x yields

$$g_1 h_1^2 + g_2 h^2 = g_1(h_{1x_0})^2 + g_2(h_{x_0})^2 - 2\left[-\frac{f}{\beta}\frac{\partial \tau_x}{\partial y} + \tau_x \right](x_0 - x) \tag{3}$$

where the subscript x_0 represents a value of at $x = x_0$. At x_0 the zonal flow vanishes so the layer thicknesses must be constant. The zonal transport equation with negligible meridional component of the wind stress is

$$f\,U = \frac{\partial}{\partial y}(g_1 h_1^2 + g_2 h^2) \tag{4}$$

and it implies that with no zonal transport across the coast the thickness h is independent of the y direction, i.e., in a north-south direction.

In the present simplified three-layer model, the sign and the magnitude of $\partial\tau_x/\partial y$ are the important factors in determining the local thickness of the upper layer. Since this model is for the large scale ocean circulation, more data covering the extensive area is desirable. Unfortunately, the only available data are from the NFRDI and JMA Buoy's data.

3. Results and Discussions

In this study, data obtained in 20 years from 1972 to 1992 are analyzed [Tabel 1]. Fig. 4 shows the monthly mean values of wind speed obtained by the Buoy's data, Na [1992], Kang [1994] and present study. These results show a good consistency in speed and direction (Kim, [1996]).

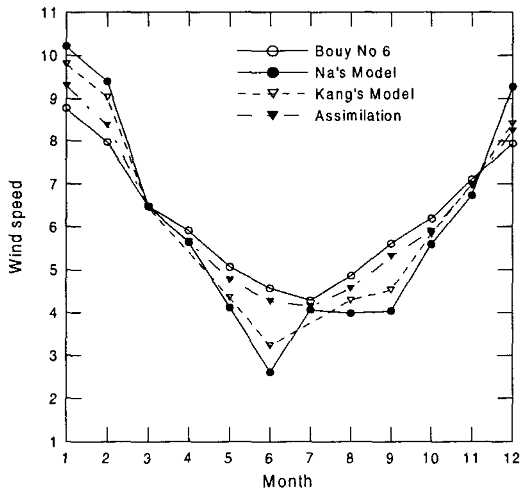

Fig. 4 Monthly mean values of wind speed obtained by the Buoy's data, model's records, and present study

The wind stress parameter is treated as unknowns and recovered simultaneously by an optimization process using the limited memory quasi-Newton conjugate gradient method [Fig. 5]. The drag coefficient C_D for the control parameter can be determinate by a minimizing the cost function. The initial estimates for C_D is given as 1.35×10^{-3}. Fig. 6(a) shows the variations of the objective function, the norm of the gradient, and the data misfit with the number of iterations in the minimization procedure. All values have been normalized by their own initial values to allow a direct comparison of the convergence rate. After 9 iterations, it drops to 5% of its initial value and reaches a steady state. The drag coefficient is adjusted gradually and finally reaches 1.25×10^{-3} [Fig. 6(b)].

Above experiment indicates that the variational adjoint method makes it possible to determine the model unknown parameter and the forcing parameter simultaneously.

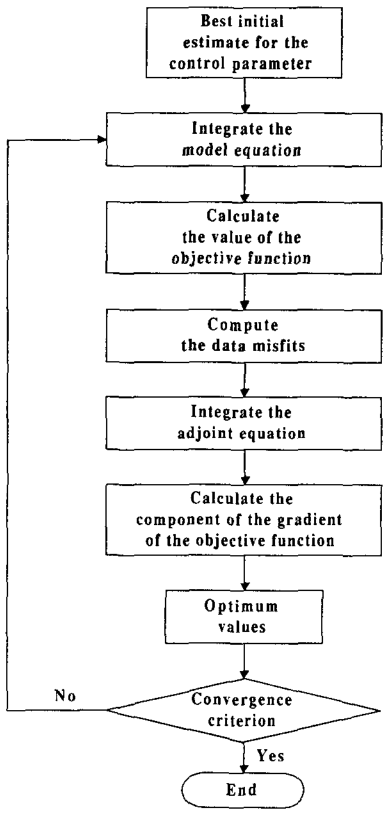

Fig. 5 The procedure of an optimization approach

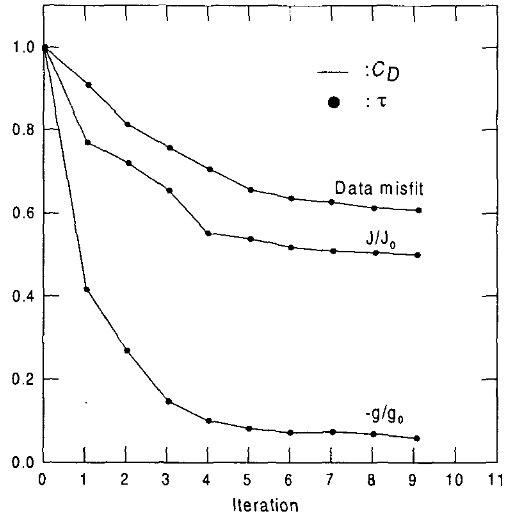

Fig. 6(a) The variation of the objective function, the norm of the gradient, and the data misfit

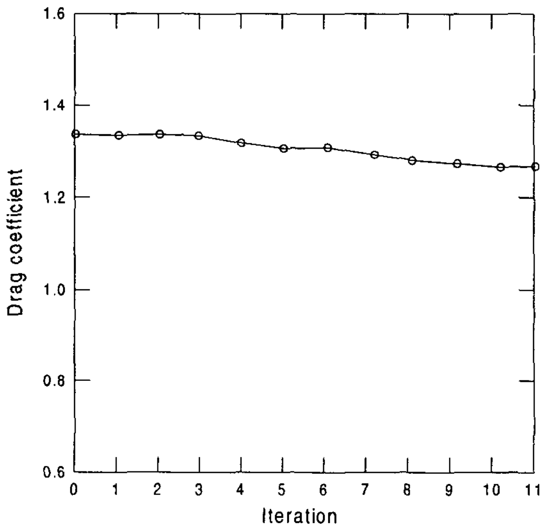

Fig. 6(b) The variation of the drag coefficient

It is important to note that the choice of the initial values for the control parameters are arbitrary; however, the solution is independent of the initial guess. But as discussed in the previous section, for the efficiency of an optimization process, the parameters' initial guess should be as reasonable as possible. For this reason, prior knowledge of the physical background is desired to help obtain a good choice. This experiment has been restricted to an identical twin run, i.e., the "observations" are results from the model without noise.

Fig. 7 shows that the meridional Ekman fluxes in summer [June, Aug.] and winter [Dec., Feb.] are northward and southward probably in response to the south-eastward and north-eastward wind, respectively. Volume fluxes and volume transport was estimated by the Ekman transport through the zonal boundaries in the study area. Summations of the Ekman transports through the northern and the southern boundaries are about 0.61 Sv in summer and 1.4 Sv in winter. Summations of the Ekman transports across Line 209 and Line 208 boundaries are about 0.96 Sv in summer and 1.24 Sv in winter.

It is interesting to note that during the months of maximum northward transport through the strait the wind-driven northward flow is stronger than the flow of the winter season [Fig. 7]. Furthermore, the wind-driven meridional transport is seasonally changing. The wintertime transport is twice stronger than that of summer and it could inhibit the northward flow of the Tsushima Current through the Korea Strait to minimize the resultant volume transport during the winter season.

Therefore it could be speculated that the Tsushima Current and its seasonal variation is influenced by the strength of southward flow driven by the wind stress over the East Sea of Korea. This study just shows the qualitative picture that explains the seasonal behavior of the meridional transport by the variation of wind stress curl corresponding to the Tsushima Current.

Fig. 8 shows the time series of the upper layer thicknesses of observation and assimilation at southwestern East Sea of Korea. The

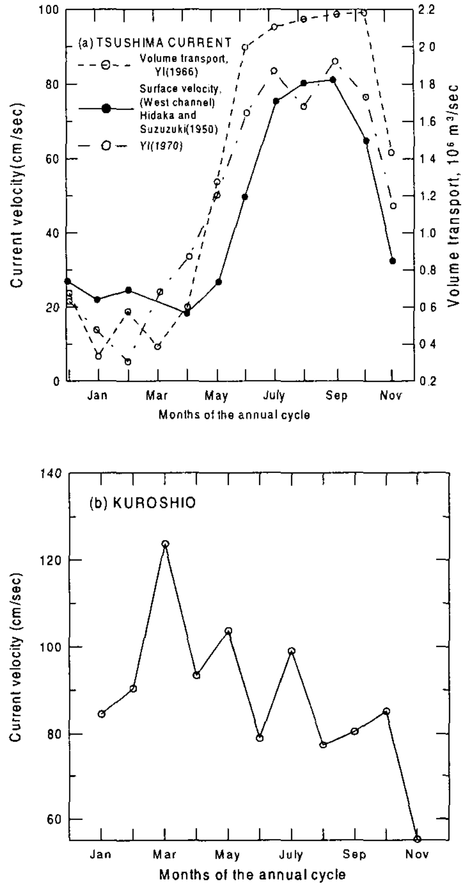

Fig. 7 Volume fluxes and transports

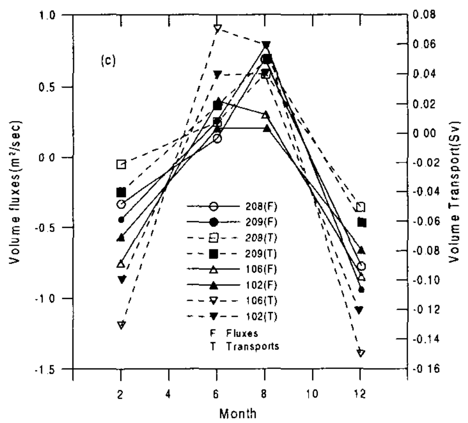

Fig. 7 (continued)

assimilated value is similar to the observed field. The amplitudes of the assimilated upper layer thickness is smaller than the observed values. Though the assimilation process tries to adjust to the observed time variation, the improvement depends on the month.

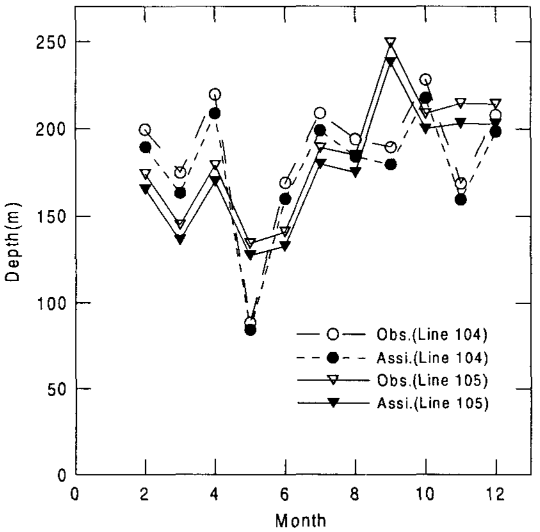

Fig. 8 Comparison of the upper layer thickness

4. Conclusion and Perspectives

In order to estimate the influence of wind stress on the circulation of East Sea of Korea, the wind stress was estimated from the shipboard observation data of the National Fisheries Research and Development Institute along the serial observation lines and JMA Buoy data during 20 years from 1972 to 1992. These monthly and annual mean wind stress distributions were put into the three-layer model which describes the latitudinal variation of the upper layer thickness and elucidates the seasonal variations of the transport by the Sverdrup relation and Ekman current.

The wind field contributes to maintain the almost time-independent distribution of the upper layer thickness feature in a north-south direction and negative wind stress curl to maintain the formation of warm eddy over the East Sea of Korea. Elucidated is the variational characteristics of the East Korean Warm Current due to the variations of the zonally averaged wind stress (southward transport) from the seasonal variations of the meridional transport by the Ekman transport.

Because the shipboard observation is restricted to the relatively calm weather, more reliable buoy data measured even in the severe conditions at several locations will be desirable for the estimation of wind stress and its curl. Therefore, the circulation of East Sea of Korea is considered a phenomena with the permanent thermocline, southward North Korean Cold Current and the seasonal fluctuations of the East Korean Warm Current.

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