 Proceedings of ICCES'08, pp.817-823

Numerical Prediction of the Ocean Surface Wind in a Bay and Application for Ship Navigation

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Summary

This paper deals with the numerical estimation of the ocean surface wind in a bay. Such estimates are very important because the wind reacts to environmental problem, such as the effects of a marine structure or a sailing ship. The estimation of the ocean surface wind was carried out in Osaka Bay in Japan using the mesoscale meteorological model MM5. The calculated numerical results were compared with the observed ones. It was confirmed that the ocean surface wind in Osaka Bay was accurately estimated. As an application of the estimation of wind in the bay, navigational simulations of a sailing ship under the effects of the wind were conducted using the numerical data of the ocean surface wind. It was proved that the effects of the wind in coastal waters on a sailing ship could be accurately estimated in a navigational simulation for optimum weather routing as the final object.

Introduction

Recently, much attention has been given to estimates of ocean surface winds in coastal areas as a part of ocean engineering, and many studies have been conducted. In particular, studies of electric power generated by wind fans have been conducted as a response to environmental problems. Also, studies of damage by wind of marine structures such as oil drilling problem have been conducted. On the other hand, ships are endangered by low pressure or typhoon passing through shipping lane. Smaller vessels are also placed in jeopardy such as capsizing by strong wind.

This subject of this paper is estimating ocean surface winds in coastal sea areas. First, the numerical computation of ocean surface winds was carried out using the mesoscale meteorological model MM5. Secondly, as the application of the above estimation, navigational simulations of a sailing ship under the effects of wind were conducted using the numerically calculated data of ocean surface winds. Few studies have been conducted to apply to the navigational simulation in the coastal zone. It was recognized that estimates of winds in coastal area potentially useful for contributing to shipping safety.

Basic Equation of MM5

MM5 is a mesoscale meteorological model developed in cooperation with Pennsylvania State University and National center for Atmospheric Research in USA [1]. The grid of the direction of the z axis is generated by the σ coordinate system

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as follows:

$$\sigma = \frac{P - P_t}{P_s - P_t} \quad (1)$$

where the origin in the Cartesian coordinate system was placed on a ground surface and the z axis is in the upward direction. p is the air pressure at an arbitrary height, p_s is the surface pressure, and p_t is a specified constant top pressure of calculated region.

The basic equations of MM5 are as follows [2]:

(Equation of air pressure)

$$\frac{\partial p'}{\partial t} - \rho_0 g w + \gamma p \nabla \cdot V = -V \cdot \nabla p' + \frac{\gamma p}{T}\left(\frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta\right) \quad (2)$$

where p' is perturbation pressure of p_a, ρ_0 is the standard air density of kg/m^3, g is the acceleration of gravity, w is velocity component of the z direction, γ is the heat rate, V is the horizontal vector of the wind, T is the air temperature of K, Q is the in-adiabatic efficiency of J/(kg·s), c_p is the specific heat at constant pressure, T_0 is the standard air temperature, θ_0 is the potential temperature and D_θ is the diffusion of θ_0.

(Horizontal momentum equations)

$$\frac{\partial u}{\partial t} + \frac{m}{\rho}\left(\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial p'}{\partial \sigma}\right) = -V \cdot \nabla u + v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) - ew\cos\alpha - \frac{uw}{r_{earth}} + D_u \quad (3)$$

$$\frac{\partial v}{\partial t} + \frac{m}{\rho}\left(\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial p'}{\partial \sigma}\right) = -V \cdot \nabla v - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) - ew\sin\alpha - \frac{vw}{r_{earth}} + D_v \quad (4)$$

where u and v are the velocity components of the east and north directions of the horizontal wind, m is the horizontal curvature term, ρ is the air density, m is the map factor, p^* is $P_s - P_t$, f is the coefficient of Coriolis, α is the rotation angle of the grid and the northern axis of the grid, D_u, and D_v are the components of the coefficients of the horizontal diffusion and r_{earth} is the vertical curvature term.

(Vertical momentum equation)

$$\frac{\partial w}{\partial t} - \frac{\rho_0}{\rho}\frac{g}{p^*}\frac{\partial p'}{\partial \sigma} + \frac{gp'}{\gamma p}$$
$$= -V \cdot \nabla w + g\frac{P_0}{p}\frac{T'}{T_0} - \frac{gR_d}{c_p}\frac{p'}{p} + e(u\cos\alpha - v\sin\alpha) + \frac{u^2+v^2}{r_{earth}} + D_w \quad (5)$$

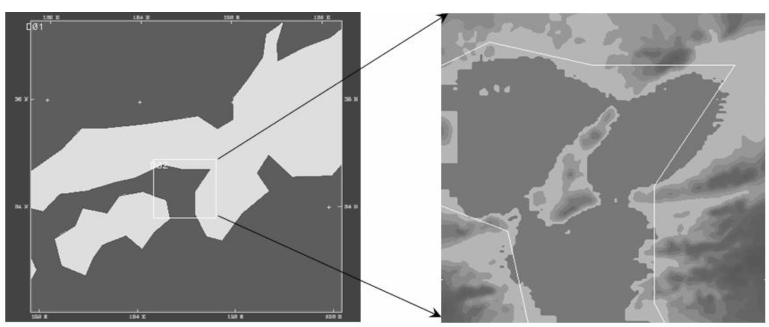
where p_0 is the standard air pressure, T' is the perturbation temperature of K, R_d is the constant value of dry air, and D_w is the vertical diffusion.

(Temperature equation)

$$\frac{\partial T}{\partial t} = -V\nabla T + \frac{1}{\rho c_p}\left(\frac{\partial p'}{\partial t} + V \cdot \nabla p' - \rho_0 g w\right) + \frac{Q}{c_p} + \frac{T_0}{\theta_0}D_\theta \quad (6)$$

Conditions for the Wind Simulation

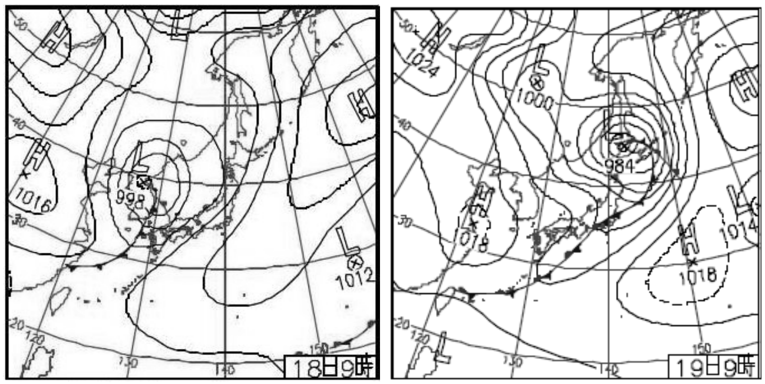
The numerical calculation of the ocean surface wind was conducted at Osaka Bay in Japan. Figure 1 shows the computational area. Two kinds of calculated domains were created for the simulation of the wind using 2-way nesting in MM5. The left side of the figure is the mother domain with a wide region, and the right side is the inner domain, which includes Osaka Bay. The regular grid intervals of the x and y directions are 3km in the mother domain and 1km in the inner domain respectively. The grid numbers of the horizontal plane are 198×198 in the mother domain and 120×120 in the inner domain, both irregular grid numbers in the vertical direction are 23. The calculated time steps are 9 sec in the mother domain and 3 sec in the inner domain. The numerical calculation of the ocean surface wind was carried out by 2 way nesting by changing both domains alternately.



(a) Mother Domain (b) Inter Domain

Figure 1: Two kinds of calculation domains in MM5

As shown in the weather charts in Fig. 2, the simulation of the ocean surface wind in Osaka Bay lasted 36 hours during which time the fully developed low pressure passed over the Nippon Sea, located in the north of Osaka. Before the low pressure passed, a strong southern wind blew, and, after that, a northern wind blew.



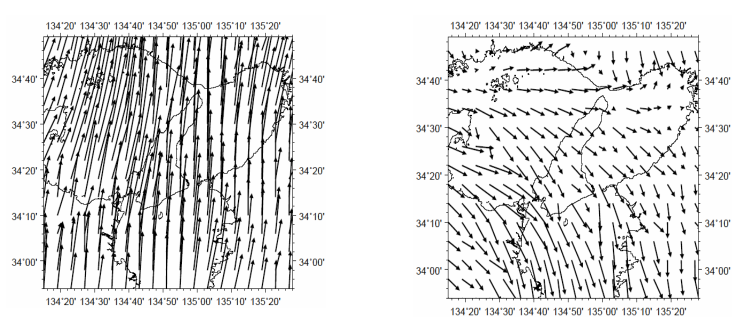
(a) May 18, 2005 (b) May 19, 2005

Figure 2: Weather chart on May 18-19, 2005

Results of the Wind Simulation

The results of the wind simulation are shown in Fig.3. The left side of the figure shows a strong southern wind in Osaka Bay which blew between the warm and cold fronts of the low pressure in the weather chart of Fig.2 (a). The right side of the figure shows the wind in the north-west direction which blew toward the southern blockage front in Osaka Bay after the low pressure passed.

For an examination of the numerical simulation, the calculated and observed results were compared. The local positions of the Meteorological Agency are shown in Fig.4. The comparison of the calculated and the observed results of the wind in Osaka Bay is shown in Fig.5. The wind speed is shown on the left side, and the wind direction, on the right side. Small discrepancies in both sets of results are shown, but general agreement was observed. The differences were attributed that both altitude of the wind are not agreement exactly.



(a) At 16:00, May 18, 2005 (b) At 09:00, May 19, 2005

Figure 3: Simulated ocean surface wind in Osaka Bay

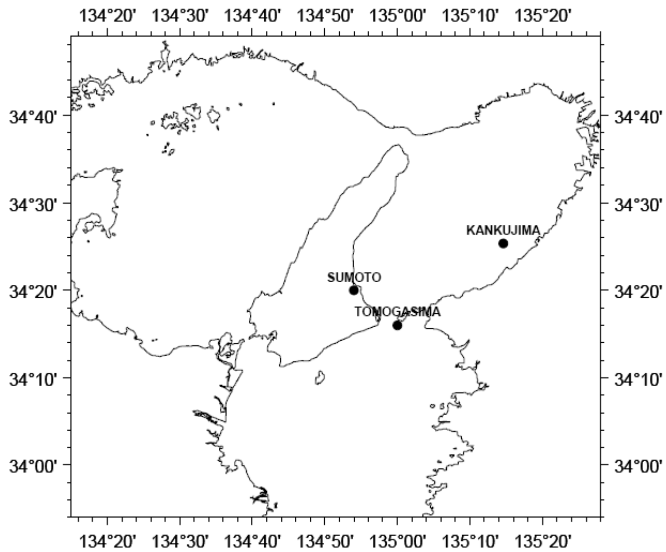


Figure 4: Observation points in Osaka Bay

Navigational Simulations

The numerical simulation of the ocean surface wind was applied to the navigational simulation of the ship for the purpose of weather routing. The navigational computer simulation of a ship subjected to winds in Osaka Bay is shown in Fig.6. Two courses are plotted for a virtual ship. The virtual ship sails at 9 knots with a strong southern wind in Fig.3(a). In the figure, the real line is the course line without the wind and the dotted line is the simulated one with the wind. The mathematical model used in the navigational simulation is the ship maneuverability model of MMG, which is characterized by dividing all hydrodynamic forces and moments working on the vessel into the hull, rudder, and propeller and their interaction. The leeway and drift angle are the angular difference between the ship's heading and the simulated route due to the effects of the wind.

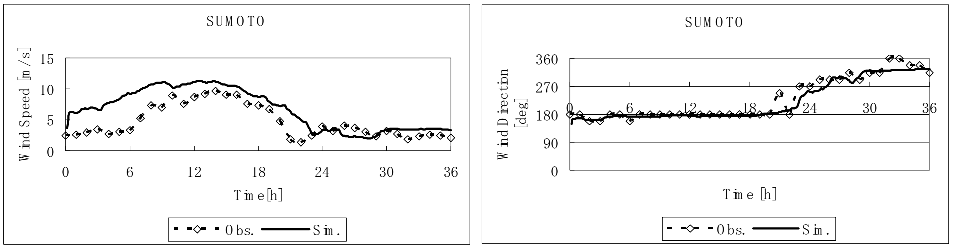
Conclusion

The numerical estimation of the ocean surface wind in Osaka Bay in Japan was carried out by using the mesoscale meteorological model MM5. As the application of wind simulation, a numerical navigational simulation was conducted. The main results were concluded to be as follow:

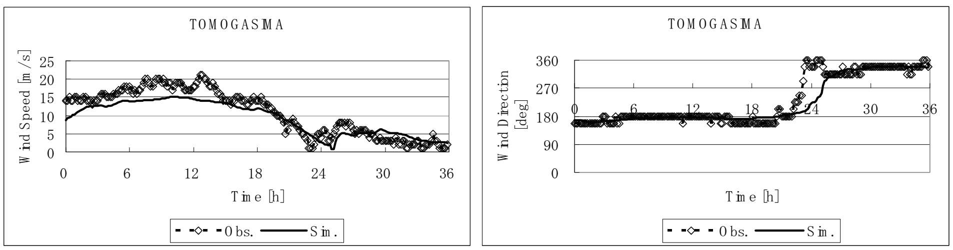
1) The numerical estimation method MM5 of the ocean surface wind provided satisfactory results.

2) The simulated results of the estimated wind are in good agreement with the observed ones.

3) The simulation of the ship navigation using the simulated wind by MM5 is



(a)



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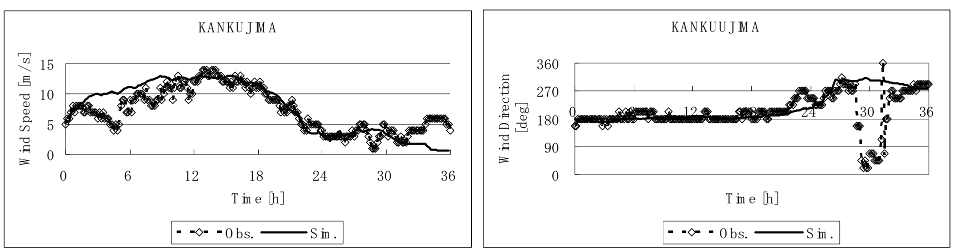

(c)

Figure 5: Comparison of simulated and observed data

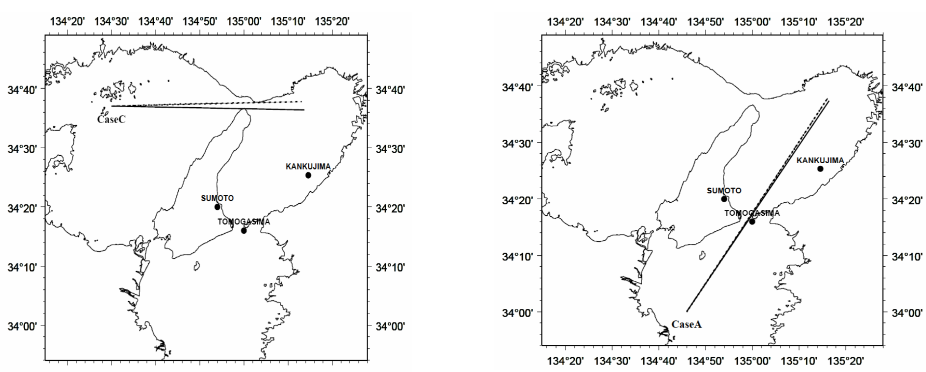

Figure 6: Navigational simulation

effective for the estimation of the drift and the variation in the sailing distance.

References

1. Jimy D., Dave G. et al. (2005): “PSU/NCAR Mesoscale Modeling System, Tutorial Class Notes and User’s Guide: MM5 Modeling System Version 3”, http://www.mmm.ucar.edu/mm5/mm5-home.html
2. Anthes, R. A., and T. T. Warner (1978): “Development of hydrodynamic models suitable for air pollution and other mesometeorological studies,” Mon. Wea. Rev., Vol. 106, pp. 1045-1078.