Sea Surface Wind Correction Using HF Ocean Radar and Its Impact on Coastal Wave Prediction

YUKIHARU HISAKI

University of the Ryukyus, Okinawa, Japan

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ABSTRACT

Both wind speeds and wind directions are important for predicting wave heights near complex coastal areas, such as small islands, because the fetch is sensitive to the wind direction. High-frequency (HF) radar can be used to estimate sea surface wind directions from first-order scattering. A simple method is proposed to correct sea surface wind vectors from reanalysis data using the wind directions estimated from HF radar. The constraints for wind speed corrections are that the corrections are small and that the corrections of horizontal divergences are small. A simple algorithm for solving the solution that minimizes the weighted sum of the constraints is developed. Another simple method is proposed to correct sea surface wind vectors. The constraints of the method are that corrections of wind vectors and horizontal divergences from the reanalysis wind vectors are small and that the projection of the corrected wind vectors to the direction orthogonal to the HF radar–estimated wind direction is small. The impact of wind correction on wave parameter prediction is large in the area in which the fetch is sensitive to wind direction. The accuracy of the wave prediction is improved by correcting the wind in that area, where correction of wind direction is more important than correction of wind speeds for the improvement. This method could be used for near-real-time wave monitoring by correcting forecast winds using HF radar data.

1. Introduction

Wind estimation and wave prediction are important for coastal oceanography and engineering, and practical applications such as ship navigation, marine construction, and fisheries. High-frequency (HF) ocean radar is a useful tool for measuring coastal ocean currents, and there have been numerous studies of coastal currents measured by HF radar. HF radar can also estimate ocean wave directional spectra by inversion (e.g., Hashimoto and Tokuda 1999; Hashimoto et al. 2003; Hisaki 1996, 2015, 2016a; Lukijanto et al. 2011; Wyatt 1990; Wyatt et al. 2011); however, these studies are very limited because a high signal-to-noise ratio (SNR) of Doppler spectra is required.

HF radar can estimate the sea surface wind direction from the first-order scattering by assuming that the wind direction is the same as the wave direction at the Bragg wave frequency (e.g., Fernandez et al. 1997; Heron and Prytz 2002; Huang et al. 2004, 2012; Chu et al. 2015), although there are differences between them (Hisaki 2002, 2007; Wyatt 2012). The position of the cyclone and atmospheric front can be detected from the HF radar–estimated wind direction (Heron and Rose 1986; Georges et al. 1993; Harlan and Georges 1997; Hisaki 2002). Other applications of only wind direction estimation to meteorology or oceanography are few.

Wind speed is critical for prediction of wave height. Wind direction is also crucial for wave-height prediction near coasts, such as for small islands and complex coastlines, because the fetch is sensitive to wind direction. It may be possible to improve wave prediction near coasts by considering the wind direction estimated from HF radar.

There have been previous studies on wind speed estimation from HF radar. There are three types of methods for estimating wind speed from HF radar. The first method is the estimation of wind-wave energy from the second-order scattering of Doppler spectra (e.g., Dexter and Theodoridis 1982; Heron et al. 1985; Green et al. 2009; Zeng et al. 2016). The advantage of this method is that calibration by other instruments is not required; the drawback is that a high signal-to-noise ratio is required to evaluate wind-wave energy from the second-order scattering of Doppler spectra, and that...

Corresponding author: Yukiharu Hisaki, hisaki@sci.u-ryukyu.ac.jp

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the contribution of the swell to wave energy must be separated.

The second method involves estimation of wind speed only from first-order scattering using the relationship between wind-wave energy and first-order scattering (Stewart and Barnum 1975; Shen et al. 2012; Kirincich 2016). This method has the advantage that the first-order scattering is robust to noise and that a high SNR is not required as in the first method; however, calibration using other instruments is required.

The third method uses multifrequency radar (Vesecky et al. 2004). Only first-order scattering is used for inferring vertical current shear in this method. However, the cost of a multifrequency radar system is higher than that of a single-frequency radar system, and the relationship between wind speed and vertical current shear is complicated.

Reanalysis wind data are readily available, and wave hindcasting is possible. The spatial resolution of reanalysis wind data is much coarser than that of HF radar–estimated wind and wave parameters. For example, the spatial resolution of National Centers for Environmental Prediction (NCEP) data is approximately 0.3°, whereas the spatial resolution of HF radar is on the order of 0.01°. It is useful to correct from NCEP reanalysis wind data (e.g., Saha et al. 2014) with low spatial resolution to wind data with high spatial resolution. We propose a simple method for this.

The objectives of the paper are as follows. The first objective is to describe the method that corrects from the sea surface NCEP winds at low spatial resolution to those at higher spatial resolution using the HF radar. The second objective is to explore the impact of wind correction on wave prediction near the coast of a small island. This method is categorized as one of the second-type methods as described above, but it is easy to obtain wind data for calibration.

Many studies have developed methods to interpolate from HF radar–estimated radial velocities to total vectors on the grid points by the open boundary modal analysis method (e.g., Kaplan and Lekien 2007), or the variational method (e.g., Yaremchuk and Sentchev 2009). The present method is the first attempt to regrid sea surface wind vectors from the first-order scattering level. A method of correcting reanalysis wind data by assimilating HF radar surface currents has also been proposed (Lewis et al. 1998; Barth et al. 2011). The present method is much more simple, and the computer cost is much more lower than that required for the assimilation method.

In sections 2a and 2b the principle is reviewed and the method of estimating wind direction from HF radar is described. A new method for correcting sea surface winds is provided in section 2c. Another method for correcting sea surface winds is described in section 2d. The wind data, wave data, and Doppler spectra are documented in sections 2e and 2f. The wave model is described in section 2g. The results of the corrected winds are explained in section 3a. The comparisons of predicted waves are explored in section 3b. The results of the sensitivity of the wave prediction to the parameters used for correcting winds are presented in section 3c. The results of the other method are provided in section 3d. The conclusions are summarized and discussed in section 4.

2. Method

a. Basic principle

The first-order scattering is proportional to the wave spectrum at the Bragg wave vector (Barrick 1972),

$$
\sigma_1(m\omega_B) = S(-2mk_0), \quad m = \pm 1,
$$

where $k_0$ is the radio wave number vector, $\omega_B$ is the radial Bragg wave frequency, $\sigma_1$ is the first-order radar cross section, and $S(k)$ is the wave spectrum as a function of the wavenumber vector $k = (k\cos\theta, k\sin\theta)$. In Eq. (1) the sign $m = 1$ corresponds to the Doppler spectral peak at the positive Doppler frequency and the sign $m = -1$ corresponds to the Doppler spectral peak at the negative Doppler frequency. The Doppler spectrum is proportional to the radar cross section, and the ratio of the first-order scattering is

$$
R = \frac{\sigma_1(\omega_B)}{\sigma_1(-\omega_B)} = \frac{S(-2k_0)}{S(2k_0)} = \frac{D(\phi_B - \theta_w)}{D(\phi_B - \theta_w + \pi)},
$$

where $D(\theta)$ is the directional distribution at wavenumber $2k_0$, $\phi_B$ is the radar beam direction, $k_0$ is the radio wavenumber, and $\theta_w$ is the mean wave direction at wavenumber $2k_0$, which is assumed to be equal to the wind direction.

The wavenumber of the swell not generated locally is smaller than the Bragg wavenumber. No previous studies have detected the effect of the swell on the first-order Bragg scattering. It is valid to assume that the impact of nonlocally generated swell on the wind direction estimation by HF radar is small. In contrast, the swell associated with a sudden change in the wind direction affects the wind direction estimation by HF radar, because the wave direction at Bragg wavenumber $2k_0$ does not change simultaneously with a wind shift.

We solved

$$
F_q(\theta_w, \beta) = \log[D(\pi + \theta_w - \phi_B)] - \log[D(\theta_w - \phi_B)] - \log(R) = 0,
$$

(3)
where

\[ D(\theta) = \text{sech}^2(\beta \theta) \]  

(4)

is the Donelan-type directional distribution (Donelan et al. 1985) and \(|\theta| \leq \pi\) in Eq. (4). Parameter \(\beta\) in Eq. (4) determines the half-width of the directional distribution, and parameter \(\beta\) decreases as the wave frequency increases.

b. Wind direction calculation from HF radar

The Doppler spectra from two radars are used for the analysis. If the ratios \(R\) of the two first-order Bragg peaks at a position are obtained from two radars, then we can evaluate \(\theta_w\) and \(\beta\) by solving Eq. (3). However, often we can obtain the ratio of the first-order scattering \(R\) from only one radar.

The Doppler spectra are estimated on radial grids with centers at the radar positions. The wind directions are evaluated at the regular grid points in the \(x-y\) plane, where the \(x\) direction is eastward and the \(y\) direction is northward. The procedure to evaluate wind directions at the regular grid points from Doppler spectra estimated on radial grids is described below.

The parameters \(\theta_T = \theta_w\) and \(\beta_T = \beta\) are estimated by seeking the minima of \(\sum D_{ij}(\theta_w, \beta)\) in Eq. (3), where \(\sum\) denotes the summation for all Doppler spectra from which \(R\) are evaluated on the radial grids. The first-order scattering levels are interpolated onto the regular grid points and the ratios \(R\) are estimated for each radar. If the ratio \(R\) is obtained from only one radar, then the solution of Eq. (3) cannot be evaluated, because the number of unknowns is two (\(\theta_w\) and \(\beta\)), while the number of equations is one. In this case, \(\beta = \beta_T\) is substituted into Eq. (3), where \(\beta_T\) was estimated from all Doppler spectra. Equation (3) can be solved by the substitution of \(\beta = \beta_T\). There are two solutions for Eq. (3), which is called the left–right ambiguity with respect to the radar beam direction. The left–right ambiguity with respect to the radar beam direction is resolved by selecting the solution \(\theta_w\) that is closer to \(\theta_T\).

The HF radar–estimated wind directions satisfying \(|\theta_w - \theta_T| \leq \theta_e\) are used for the analysis, where \(\theta_e\) is the threshold of the difference between \(\theta_w\) and \(\theta_T\) set by the user. The value of \(\theta_e\) is \(\theta_e = 75^\circ\). If the wind directions are unidirectional in half of the study area, and the wind directions in the other half of the study area are opposite of them and also unidirectional, then the difference between the area-averaged wind direction and the wind direction in the area is \(90^\circ\). This is an extreme case, so we set the maximum difference between the area-averaged wind direction and the wind direction to be \(\theta_e = 75^\circ\).

If \(R\) cannot be obtained or \(|\theta_w - \theta_T| > \theta_e\), then the wind direction \(\theta_w(m, n)\) is evaluated as

\[ \theta_w(m, n) = \arctan \left\{ \frac{\sum_i w_{ij} \sin[\theta_w(i, j)]}{\sum_i w_{ij} \cos[\theta_w(i, j)]} \right\}, \]

where \((i, j)\) and \((m, n)\) are regular gridpoint numbers, and \(w_{ij}\) is the weight, which is inversely proportional to the square of the distance between the regular grid \((i, j)\) and \((m, n)\). Equation (5) is used only to fill the gaps in the gridded field of \(\theta_w\). The values of \(\theta_w(i, j)\) estimated from \(R\) and NCEP wind directions at the four corners of the study area—26.1°N, 127.15°E; 26.6°N, 127.15°E; 26.1°N, 127.9°E; and 26.6°N, 127.9°E in the present case—are used for interpolation or extrapolation in accordance with Eq. (5).

c. Wind vector correction from wind direction

We obtained \(\theta_w\) for all of the regular grid points. The wind speeds were also corrected from reanalysis wind speeds using HF radar–estimated \(\theta_w\). The constraints are that the corrections of wind speeds and horizontal divergences are small and that

\[ (V_c - V_r)^2 \to \min, \]

\[ (\nabla \times V_c - \nabla \times V_r)^2 \to \min, \]

where \(V_c\) is the corrected wind vector, \(V_r\) is the reanalyzed NCEP wind vectors, \(V_c = |V_c|, V_c = |V_r|\), and \(\nabla\) denotes the horizontal gradient. This is written by seeking the minima of the objective function as

\[ Q_r = \sum_{ij} (V_c(i, j) - V_r(i, j))^2 \]

\[ + \lambda_r \sum_{ij} (\nabla \times V_c(i, j) - \nabla \times V_r(i, j))^2, \]

\[ = \sum_{ij} \delta_{ij}^2 + \lambda_r \sum_{ij} D_d(i, j)^2, \]

where

\[ D_d(i, j) = D_v(V_c, i, j) - D_v(V_r, i, j), \]

\[ = C_u(u_r, i, j, \Delta x) + C_c(v_r, i, j, \Delta y) - C_u(u_r, i, j, \Delta x) - C_c(v_r, i, j, \Delta y), \]

where \(D_v(V_c, i, j)\) is the horizontal divergence of \(V_c = (u_c, v_c)\) at grid point \((i, j)\) in the standard central difference scheme; \(C_u(u_r, i, j, \Delta x)\) and \(C_c(v_r, i, j, \Delta y)\) denote the central difference of \(u_r\) and \(v_r\), respectively, with respect to \(x\) and \(y\) at grid point \((i, j)\); \(\delta_{ij}\) is the correction of wind speed; and \(\lambda_r\) is a weight. The parameters \(\Delta x\) and \(\Delta y\) are the spatial resolution in
the $x$ direction (eastward) and $y$ direction (northward), respectively. The $\lambda_w$ in Eq. (8) is expressed as

$$\lambda_w = \frac{a_w \Delta x^2 \Delta y^2}{\Delta x^2 + 2 \Delta y^2}, \quad (10)$$

where $a_w$ is a parameter, and $a_w$ is introduced to remove the spatial resolutions $\Delta x$ and $\Delta y$ in the weighting.

The parameter $a_w$ is set as 4 here. In general, $\lambda_w$ is the ratio between the inverse error variance of the wind divergence $\sigma_D$ and its magnitude $\sigma_V$.

$$\lambda_w = \frac{\sigma_V^2}{\sigma_D^2},$$

$$= 4 \left( \frac{1}{\Delta x^2} \left\{ \cos^2[\theta_w(i + 1, j)] + \cos^2[\theta_w(i - 1, j)] \right\} + \frac{1}{\Delta y^2} \left\{ \sin^2[\theta_w(i, j + 1)] + \sin^2[\theta_w(i, j - 1)] \right\} \right)^{-1}, \quad (11)$$

which is obtained from the propagation of uncertainty. Equation (10) and $a_w = 4$ are obtained by replacing $\cos^2[\theta_w(i + 1, j)]$, $\cos^2[\theta_w(i - 1, j)]$, $\sin^2[\theta_w(i, j + 1)]$, and $\sin^2[\theta_w(i, j - 1)]$ with 1/2. We will present the result for $a_w = 4$ in sections 3a and 3b. The sensitivity of wave prediction to $a_w$ is investigated in section 3c.

The reanalyzed wind vector at the grid point $(i, j)$ is $V_i(i, j) = [u(i, j), v(i, j)] = V_c(i, j)\{\cos[\theta_c(i, j)], \sin[\theta_c(i, j)]\}$, and the corrected wind vector is $V_c(i, j) = [u(i, j), v(i, j)] = [V_i(i, j) + \delta_{ij}][\cos[\theta_c(i, j)], \sin[\theta_c(i, j)]\}$. The unknown to be estimated to minimize $Q_r$ in Eq. (8) is the wind speed correction $\delta_{ij}$. This is obtained by solving $\partial Q_r/\partial \delta_{ij} = 0$. Thus, we obtain

$$(1 + \lambda_w \Psi) \delta_{ij} = \lambda_w \left\{ \frac{\cos[\theta_c(i, j)]}{\Delta x} \right\} \times [D_d(i + 1, j) - D_d(i - 1, j)] + \frac{\sin[\theta_c(i, j)]}{2 \Delta y} \times [D_d(i, j + 1) - D_d(i, j - 1)] + \Psi \delta_{ij}, \quad (12)$$

where

$$\Psi = \frac{1}{2} \left\{ \frac{\cos^2[\theta_c(i, j)]}{\Delta x^2} + \frac{\sin^2[\theta_c(i, j)]}{\Delta y^2} \right\}, \quad (13)$$

which is introduced to express Eq. (12) simply. The right-hand side of Eq. (12) is not dependent on $\delta_{ij}$. Therefore, Eq. (12) shows the iterative equation to solve the linear equation $\partial Q_r/\partial \delta_{ij} = 0$ by the Gauss–Seidel method. The boundary condition is that the gradient of $D_d(i, j)$ normal to the boundary is zero. The wind speed is positive. However, we estimate $\delta_{ij}$ as an unconstrained minimization problem. If the solution is $\delta_{ij} < -V_r(i, j)$ at any grid point, then the value of $a_w$ is reduced by half at the time, and the computation is performed again; however, these cases were few. The method for minimizing the objective function $Q_r$ in Eq. (8) is called the error-free wind direction method (EFWDM).

d. Error-permitted wind direction method

It is assumed that the wind estimation error from the HF radar is small in the EFWDM. This assumption is not correct, and the method in which wind direction errors are taken into account is described. In this method, the objective function to be minimized is

$$Q_p = \sum_{ij} (V_w - V_r)^2 \left[ \sigma_w(i, j) \cdot V_r(i, j) \right]^2$$

$$+ \sigma_r^2 \cdot [\nabla \cdot (V_c(i, j) - V_r(i, j))], \quad (14)$$

where $\sigma_w = \{\cos[\theta_c(i, j)], \sin[\theta_c(i, j)]\}$ is the unit vector orthogonal to the HF radar–derived wind direction $\sigma_c = \{\cos[\theta_c(i, j)], \sin[\theta_c(i, j)]\}$, $\sigma_r^2$ is the error variance of HF radar–derived wind direction, $V_w$ is a parameter, and $\sigma_r^2$ is the error variance of NCEP wind components. The term $\sigma_c \cdot V_c$ on the right-hand side of Eq. (14) indicates the projection of the corrected wind vector in the direction orthogonal to the HF radar–estimated wind direction. The equation $\partial Q_p/\partial V_c = 0$ is written as

$$\frac{\partial Q_p}{\partial V_c} = 2 \{\sigma_r^2 \cdot (\sigma_c \cdot V_c) \cdot V_c + \sigma_r^2 (V_c - V_r) \cdot \nabla [\sigma_r^2 \cdot (V_c - V_r)] = 0, \quad (15)$$

where $\sigma_r^2 = V_w \sigma_r$. Equation (15) is the linear equation with respect to unknown $V_c(i, j) = V_c(\cos \theta, \sin \theta) = [u(i, j), v(i, j)]$, and it is solved by using the Gauss–Seidel method using Eqs. (A1) and (A2) iteratively (refer to the appendix).

The value of $\sigma_r^2$ is between $35^8$ and $40^8$ (Kirincich 2016) and the value of $\sigma_w$ is from approximately 1 to 2 m s$^{-1}$ (Peng et al. 2013), both of which are evaluated in the open ocean. We set the value of $\sigma_r^2 = 37.5^8$ and $\sigma_w = 1.2$ m s$^{-1}$. The value of $\sigma_r^2$ is evaluated from the propagation of uncertainty as Eq. (11), and $\sigma_D^2 = (\Delta x^2 + \Delta y^2)/(2(\Delta x^2 \Delta y^2)) \sigma_r^2$.

This method is called the error-permitted wind direction method (EPWDM). The EPWDM is similar to the least squares method of HF radar radial-velocity interpolation on the regular grid (e.g., Yaremchuk and Sentechev 2009).
e. Reanalysis wind data

The NCEP Climate Forecast System (CFS) reanalysis wind data are used for hindcasting (http://nomads.ncdc.noaa.gov/data/cfrr/). Hourly forecast data and six-hourly analysis data are used. The hourly forecast data are corrected. The errors of the forecasted wind vectors are evaluated from six-hourly analysis data and forecast data at 6-h intervals. The hourly errors are interpolated with respect to time from the six-hourly errors. The hourly forecast wind data are corrected from the interpolated errors. The spatial resolution of the NCEP CFS reanalysis wind data is approximately 0.3°, and the data are spatially interpolated.

f. HF radar Doppler spectra

The period of analysis of Doppler spectra by HF radar is from 0000 local standard time (LST) 26 May (1500 UTC 25 May) to 1200 LST 2 July (0300 UTC July 2) in 2001. The observation is also described in Hisaki (2009, 2014). Figure 1a shows the observation area. The radar locations were A (26.42°N, 127.72°E) and B (26.58°N, 127.22°E) in Fig. 1a. Radar A was located on Okinawa Island; radar B was located on Aguni Island. Southerly winds were dominant during the observation period, and the fetch was often limited in the observation area. The radar frequency was 24.515 MHz, and the Bragg frequency was \( f_B = \frac{\omega_B}{(2\pi)} = 0.505 \text{ Hz} \). The range resolution was 1.5 km and the azimuthal resolution was 7.5°. The temporal resolution of the radar system was 2 h. The beam formation was controlled electronically in real time (Hisaki et al. 2001). The time of radiowave radiation from each radar was different by 5 min to avoid the radiowave interference. The Doppler spectra were interpolated with respect to time at 1-h intervals.

The \( \theta_w \) were evaluated on 0.01° \( \times \) 0.01° regular grids. The range of the estimation was from 127.15° to 127.9°E and from 26.1° to 26.6°N (Fig. 1a). The number of grids in the x direction is \( N_x = 76 \), and the number of grids in the y direction is \( N_y = 51 \).

An ultrasonic wave (USW) gauge is used to observe wave heights and periods. The position of the USW was 26.26°N, 127.65°E, where the water depth was 53 m (U in Fig. 1a). The two-hourly significant wave heights (USW wave period; \( T_p \)) were estimated by the zero-up-crossing method from the 20-min time series of surface elevations at 0.5-s intervals (Hisaki 2014).

g. Wave model

The configuration of the wave model to predict wave parameters is almost the same as that in Hisaki (2014). The main difference from Hisaki (2014) is the wind data. The objectively analyzed surface winds from the 12-hourly Japan Meteorological Agency (JMA) data were used in Hisaki (2014), whereas hourly NCEP CFS reanalysis wind data were used in the present study. The wave model is explained briefly. The energy balance is used to predict the wave spectrum \( F = F(f, \theta, \mathbf{x}, t) \), where \( \mathbf{x} \) is the position, \( t \) is the time, \( f \) is the wave frequency, and \( \theta \) is the wave direction. The source function \( S = S(f, \theta, \mathbf{x}, t) \) in the energy balance equation is composed from the wave energy input as a result of the influence of wind \( S_{in} \), wave energy dissipation by wave breaking \( S_{db} \), wave energy transfer by nonlinear interactions \( S_{at} \), and dissipation by shallow-water processes \( S_{sh} \). The parameterization of the source function is the same as that of the Wave Model (WAM) cycle 3 (WAMDI Group 1988). However, the source function for wind input \( S_{in} \) was calculated using Janssen’s parameterization (Janssen 1991).

The wave spectra were predicted by the nested grid. The coarse grid area was from 125.55° to 128°E and from 23.95° to 28.9°N with a spatial resolution of 0.05° (Fig. 1b). The wave spectra on the upwind boundary were evaluated by solving \( \partial F/\partial t = S \). The effect of the swell from outside the region on wave height at the USW point was small in the analysis period. Verification of wave prediction from the proposed method of wind correction works well only in the absence of swell. The fine grid area was from 127.15° to 127.9°E and from 26.1° to 26.6°N. The spatial resolution was 0.01° (Fig. 1a). The water depth was considered in the fine-resolution wave model. The water depth data were supplied by the Marine Information Research Center, Japan Hydrographic Association. The time steps were 240 s for the coarse grid and 30 s for the fine grid. The wave frequency resolution (ratio of adjacent frequencies) was 1.1 and the resolution of the wave direction was 15°.

The predicted wave height \( H_p = 4M_{1/2}^2 \) and period \( T_p = M_1^2M_{-1} \) were estimated from the predicted wave spectrum \( F(f, \theta) \), where

\[
M_q = \int_0^{2\pi} \int_0^\infty F(f, \theta) d\theta df. \tag{16}
\]

Herein, predicted wave heights from HF radar–corrected winds \( \mathbf{v}_c \) and from NCEP reanalysis winds \( \mathbf{v}_r \) are \( H_p = H_p(\mathbf{v}_c) \) and \( H_p = H_p(\mathbf{v}_r) \), respectively. Predicted wave periods from HF radar–corrected winds and from NCEP reanalysis winds are \( T_p = T_p(\mathbf{v}_c) \) and \( T_p = T_p(\mathbf{v}_r) \), respectively.

3. Results

a. Wind fields

Figure 2 shows an example of sea surface wind vectors (speeds and directions). The surface winds on
FIG. 1. (a) HF radar observation area. HF wind–corrected area and the wave prediction area at fine spatial resolution (red box). Shown are radar positions A, and B, USW position U, and wind stations N and T. (b) Wave prediction area (blue box) at larger spatial resolution.
FIG. 2. (a) NCEP CFS sea surface wind vectors ($\mathbf{V}_r$) at 1400 LST (0500 UTC) 21 Jun 2001.
(b) Shown are wind vectors for which the directions $\theta_w$ are estimated from dual radar (blue vectors), wind vectors for which the directions $\theta_w$ are estimated from only radar A (red vectors) and only radar B (green vectors), and wind vectors for which the directions $\theta_w$ are interpolated or extrapolated from Eq. (5) (black vectors).
the shallow reef, which is treated as land in the wave model, are not indicated in Fig. 2. Figure 2a shows winds $V_r$ at 1400 LST (0500 UTC) 21 June 2001. The wind directions are northeastward in Fig. 2a. The fetch is long in the observation area in Fig. 2a. Figure 2b shows winds $V_c$ at the time. The blue vectors denote the wind vectors for which the directions $\theta_w$ are estimated from dual radar. The red and green vectors in Fig. 2b denote wind vectors for which the directions $\theta_w$ are estimated from single radars A and B, respectively. The black vectors in Fig. 2b indicate wind vectors for which the directions $\theta_w$ are interpolated or extrapolated from Eq. (5). The area in which wind directions $\theta_w$ are estimated from radar A (red and blue in Fig. 2b) is smaller than the corresponding area for radar B (green and blue in Fig. 2b). The wind directions in Fig. 2b are more complicated than those of NCEP reanalysis winds in Fig. 2a. The wind directions around (26.4°N, 127.4°E) are northeastward, which are close to those in Fig. 2a. The wind directions near the USW (U in Fig. 2) are northwestward, and the fetch at that point is small.

An atmospheric front in the area cannot be observed in the JMA synoptic weather chart during the period. The spatial variability of winds at the grid points for which the wind direction is estimated by the HF radar (color vectors) is large in Fig. 2a. The winds changed from southerly to southwesterly during the period, and this variability was due to the small-scale variability associated with the change. The variability of wind vectors also resulted from the HF radar–estimated wind direction error, which is taken into account in the EPWDM.

Figure 3 shows the hourly data acquisition rate of only the HF radar–estimated wind direction $\theta_w$. For example, the number of hourly data $\theta_w$ estimated from single radar
Fig. 4. (a) Time series of $V_c$ from the EFWDM and for $a_w = 4$ at the USW position. (b) As in (a), but for $V_r$. (c) As in (a), but for observed wind vectors at the station on the island.
A without using Eq. (5) on the grid 26.28°N, 127.65°E was 144. The ratio in Fig. 3a is \( \frac{144}{901} \approx 16\% \), where 901 is the number of hourly time series from 0000 LST 26 May to 1200 LST 2 July. The data acquisition rate of radar A was lower than that of radar B, which means that the Doppler spectrum data from radar A are poor (Hisaki 2009, 2014). However, the distance between radar B and the USW point (U in Fig. 3) is 55 km (Fig. 1), and the data quality of Doppler spectra at that position is not good. The data acquisition rate of radar B is only approximately 11% at the position (Figs. 3b and 3c).

The data acquisition rate of the dual radar is at most 50% (Fig. 3c). The rate is less than 4% at the USW point. The maximum data acquisition rate of the single or dual radar is approximately 85%. The rate is approximately 70% in the area around 26.4°N, 127.5°E. However, the rate is at most approximately 30% around the USW (Fig. 3d), and \( \mathbf{V}_c \) at that point are extrapolated in most cases.

Figure 4 shows the time series of hourly wind vectors. Figure 4a and 4b show the time series of HF radar–corrected winds and NCEP reanalysis winds at the USW position, respectively. Figure 4c shows the time series of winds at the station on Okinawa Island. The position of the wind station was N (26.21°N, 127.69°E) in Fig. 1a, and the elevation of the station above sea level was 28 m. The elevation of the anemometer from the ground was 48 m. The wind speeds on land are smaller than those on
sea, and the wind speed increases with increasing altitude. These time series of winds are similar to each other. The southerly winds are dominant during the analysis period. Fetch-limited conditions frequently occur at the USW position (Fig. 1). The wind directions changed significantly on 31 May, associated with passage of an atmospheric front.

Figure 5 shows comparisons between $V_r$ and $V_c$. Figure 5a shows the root-mean-square difference (RMSD) between HF radar–estimated wind directions and NCEP reanalysis wind directions, which is defined as $R_d(\theta_r, \theta_w) = \langle (\theta_r - \theta_w)^2 \rangle^{1/2}$, where $\langle \ldots \rangle$ denotes averaging, and $|\theta_r - \theta_w| = 180^\circ$ in the case of directions. The HF radar–estimated wind directions in Fig. 5a are only those from $R$ in Eq. (2). The RMSD values are indicated at grids where the data acquisition rate is more than 10% (Fig. 3d). The RMSD is smaller at grid points with a higher acquisition rate. For example, the RMSD is approximately 40 cm around 26°4 N, 127°5 E, where the data acquisition rate is high for dual radar (Fig. 3c) and for both radar individually (Fig. 3d).

Figure 5b shows the RMSD values of the wind directions of $V_r$ and $V_c$. The RMSD is large to the west of 127°3 E, which is associated with the large RMSD area (26°4 N, 127°2 E) in Fig. 3a. Figure 5c shows the mean values of wind speeds as $\langle V_c - V_r \rangle = \langle \delta_{\theta} \rangle$. The mean wind speeds are smaller around the area (26°4 N, 127°5 E), which is associated with the high acquisition...
Fig. 7. Comparisons of USW wave heights, predicted wave heights from NCEP winds, and HF radar-corrected winds from the EFWDM and for \( a_w = 4 \). (a) Time series of USW \( H_s \) (black line), and \( H_p \) from \( V_c \). Shown are wind directions \( \theta_v \) on the USW grid point estimated from \( R \) (blue points) and corrected wind directions on the USW grid point interpolated or extrapolated from Eq. (5) (red points). (b) Scatterplots between predicted wave heights from HF radar-corrected winds \([H_p(V_c)]\) and USW \( H_s \). Shown are the regression line estimated from predicted and USW wave heights when corrected wind directions on the USW
The predicted wave heights from HF radar–corrected winds and NCEP reanalysis winds are compared in Figure 6. The mean differences in predicted wave heights \( (H_p(V_r) - H_p(V_c)) \) are shown in Figure 6a. The mean wave heights from HF radar–corrected wave heights are smaller than those from NCEP reanalysis winds in most of the study area. This is related to the HF radar–corrected and NCEP reanalysis wind speeds. The HF radar–corrected wind speeds are smaller than the NCEP reanalysis wind speeds (Fig. 5c). The wave directions are almost northward, because of the occurrence of southerly winds. The wave heights \( H_p(V_r) \) are smaller than \( H_p(V_c) \) in the northern part of the study area.

Figure 6b shows the RMSD between \( H_p(V_r) \) and \( H_p(V_c) \). The RMSD \( \{R_d(H_p(V_r), H_p(V_c))\} \) is large in the western coast area of Okinawa Island around the USW point. In contrast, the RMSDs around the area of the western coast area of Okinawa Island around the USW point were investigated by the bootstrap method (e.g., Trenberth 1984) was estimated from the time series of in situ observed wave heights \( H_s \) and predicted wave heights \( H_p(V_r) \) at the USW point from \( V_r \). Figures 7c and 7d show the time series and scatterplot of in situ observed wave heights and predicted wave heights \( H_p(V_r) \) at the USW point from \( V_r \). There are differences between the predicted wave heights and the USW wave heights around 31 May in both Figs. 7b and 7d. An atmospheric front passed during that period (Fig. 4). The correlation coefficient and RMSD between predicted wave heights from \( V_r \) and in situ observations are \( r[H_s, H_p(V_r)] = 0.73 \) and \( R_d[H_s, H_p(V_r)] = 0.30 \text{ m} \) (Fig. 7d), respectively. The correlation coefficient and RMSD between predicted wave heights from \( V_r \) and in situ observations are \( r[H_s, H_p(V_r)] = 0.78 \) and \( R_d[H_s, H_p(V_r)] = 0.26 \text{ m} \) (Fig. 7b), respectively. The correlation for HF radar–corrected winds is higher and the RMSD is smaller than the corresponding values for NCEP reanalysis winds.

Figure 7e shows the time series of differences in predicted wave heights from USW wave heights \( H_p(V_r) - H_s \) and \( H_p(V_r) - H_i \) for the EFWDM. Figure 7f shows the scatterplot of these differences. The wave-height differences are almost the same as each other; however, the absolute value \( |H_p(V_r) - H_s| \) is smaller than \( |H_p(V_r) - H_i| \) for the case in which the difference in predicted wave heights from USW wave heights is large. The slopes of the regression lines in the scatterplot are greater than 1, which shows that \( |H_p(V_r) - H_i| \) is smaller than \( |H_p(V_r) - H_s| \) in most of the samples.

The statistical significance of the improvement at the USW point was investigated by the bootstrap method (e.g., Emery and Thomson 1998), although this was based on comparisons at only one point. The effective sample size \( N_e \) (e.g., Trenberth 1984) was estimated from the time series of wave heights, and \( N_e \) is 33. The \( N_e \) triplets of wave heights \( H_s, H_p(V_r), H_p(V_c) \) were resampled, and the correlations and RMSD were compared for 10^4 samples. The possibility of \( r[H_s, H_p(V_r)] < r[H_s, H_p(V_c)] \) is 82%, and the possibility of \( R_d[H_s, H_p(V_r)] > R_d[H_s, H_p(V_c)] \) is 96%. The improvement of RMSD of the wave-height prediction is statistically significant at the 95% confidence level.
The predicted wave heights were compared with USW wave heights for the case in which wind directions at the USW position are estimated from the first-order scattering (Fig. 3a) and not from interpolation or extrapolation [Eq. (5)]. The blue symbols in Fig. 7 indicate wave data when the wind directions at the USW position are estimated from the first-order scattering. The number of two-hourly data is 74. The correlations are $r_c[H_s, H_p(V_r)] = 0.76$ (Fig. 7d) and $r_c[H_s, H_p(V_w)] = 0.82$ (Fig. 7b), respectively. The RMSDs at those times are $R_d[H_s, H_p(V_w)] = 0.31$ m (Fig. 7b) and $R_d[H_s, H_p(V_r)] = 0.27$ m, respectively. The effective sample size in this case was estimated as serial data, and the probabilities of $r_c[H_s, H_p(V_r)] > r_c[H_s, H_p(V_w)]$ and $R_d[H_s, H_p(V_r)] < R_d[H_s, H_p(V_w)]$ were evaluated by the bootstrap method. The probabilities are 97% and 99.8%, respectively, which shows significant improvement in wave-height prediction resulting from correcting wind vectors.

Figure 8 shows comparisons of wave periods. The wave periods in Fig. 8 from the USW are significant wave periods; those from the predicted wave spectra are spectral mean periods [Eq. (16); section 2g], which are different from each other. The correlation between wave periods from NCEP reanalysis winds and USW periods is $r_c[T_s, T_p(V_r)] = 0.52$ (Fig. 8b), while the correlation between wave periods from corrected winds and USW periods is $r_c[T_s, T_p(V_w)] = 0.57$ (Fig. 8d), which seems to show improvement in wave period prediction. We also attempted to evaluate the statistical significance of the improvement by the bootstrap method. However, the effective sample size $N_e$ is 5, and the statistical significance cannot be confirmed. A possible reason for small size $N_e$ is that the trends in time series of wave periods are apparent (Figs. 8a and 8c). The correlations of wave periods when the wind directions at the USW position are estimated from the first-order scattering are $r_c[T_s, T_p(V_r)] = 0.58$ and $r_c[T_s, T_p(V_w)] = 0.56$. The difference in the correlation $r_c[T_s, T_p(V_r)] - r_c[T_s, T_p(V_w)]$ is smaller than that from total time series data, and the statistical significance cannot be confirmed.

c. Wave prediction for various parameters

The sensitivity of wave prediction to the weight parameter $a_w$ in Eqs. (10) and (8) was explored. If the parameter $a_w$ ($\lambda_w$) is small, then the solution $\delta_i = V_c - V_r$ to minimize $Q_r$ of (8) is close to 0. The HF radar–corrected winds are close to winds changing only the NCEP reanalysis wind directions and $V_c \sim V_i(\cos\theta_w, \sin\theta_w)$ in this case.

Table 1 summarizes the results of comparisons of wave parameters. Case 1-1 in Table 1 is the case of Figs. 7 and 8. The mean $V_c$ at the USW position is smaller than that of NCEP reanalysis winds by 0.17 m s$^{-1}$ (Fig. 5c). Case 1-2 in Table 1 is a comparison of the NCEP reanalysis wind predicted wave parameters (Figs. 7, 8c, and 8d). Case 1-3 is a comparison between the USW wave parameters ($H_s$ and $T_p$) and the predicted wave heights ($H_p$ and $T_p$) for $a_w = 1$. The difference between the NCEP wind speeds and corrected wind speeds is smaller than that for $a_w = 4$ (case 1-1). However, the correlation and RMS differences show improvement compared with case 1-2. The wind direction is also critical for predicting wave height at the USW location. Case 1-4 in Table 1 is the comparison for $a_w = 16$. The HF radar–corrected wind speeds are smaller than those for $a_w = 4$. However, the correlations and RMS difference of wave parameters are almost the same as those for $a_w = 4$ and $a_w = 1$.

We also predicted the wave parameters from NCEP forecast winds. Case 1-5 is the wave parameter comparisons for HF radar–corrected winds from NCEP forecast winds. Case 1-6 is the wave parameter comparisons for NCEP forecast winds. The accuracies of the predicted wave parameters in case 1-5 are better than those in case 1-6. The correlations of wave parameters in case 1-5 are better than those in case 1-2.

Table 1 shows that the correction of wind directions by HF radar is effective for improving wave prediction at the USW location, in which fetch is sensitive to wind direction. This improvement is not so sensitive to weight $a_w$ [Eqs. (10) and (8)]. The improvement can be observed for forecast winds, which shows that near-real-time wave prediction using HF radar is possible.

d. Results of the EPWDM

Figure 9 shows comparisons of wind vectors estimated from the EPWDM with the NCEP winds. Figure 9a shows the RMSD of wind directions for $V_w = 1$ m s$^{-1}$ [Eq. (14)] from NCEP winds $[R_d(\theta_w, \theta_i)]$. The RMSDs are from 15° to 30° in most of the area in Fig. 9a, while RMSDs are from 15° to 50° in most of the area in Fig. 5b. The spatial pattern in Fig. 9a is similar to that in Fig. 5b. The values of $R_d(\theta_w, \theta_i)$ are larger around the area of 26.4°N, 127.2°E. The values of $R_d(\theta_w, \theta_i)$ are small on the western coast of Okinawa Island but are larger around the USW point in both Figs. 5b and 9a.

Figure 9b shows the difference of wind speeds. The corrected wind speeds from the EPWDM for $V_w = 1$ m s$^{-1}$ are smaller than those from the EFWDM. The wind speed is smaller in the area where the difference between HF radar–derived wind directions and NCEP wind directions is large. Figure 9c shows the RMSD of wind speeds, which exhibits a pattern similar to that of Fig. 9b. The RMSD is large in the area where $|V_c - V_r|$ is large.
Figure 9d shows the RMSD of wind directions for $V_W = 4$ m s$^{-1}$ from NCEP winds [$R_d(\theta_r, \theta_s)$]. The RMSD values are smaller than those for $V_W = 1$ m s$^{-1}$ in Fig. 9a. The difference in mean wind speeds and the RMSDs (Figs. 9e and 9f) for $V_W = 4$ m s$^{-1}$ are smaller than those for $V_W = 1$ m s$^{-1}$. The corrected wind field from the EPWDM is similar to the reanalysis wind field for larger $V_W$. The wind speeds $V_c$ from the EPWDM are smaller than both $V_r$ and those from the EFWDM, especially in the area where the differences between $\theta_w$ and $\theta_s$ are large.

The wave data are predicted from corrected winds from the EPWDM. Table 2 summarizes the comparison. Cases 2-1 and 2-2 show comparisons of predicted wave parameters for $V_W = 1$ m s$^{-1}$ and $V_W = 4$ m s$^{-1}$.

The wind speed at the USW point for case 2-1 is the smaller than that in Table 1. The RMSD of wave heights [$R_d(H_s, H_p)$] for case 2-1 is smaller than that in Table 1, but the correlation [$r_r(H_s, H_p)$] is lower than that for most of the cases in Table 1. The wave prediction for case 2-1 is better than that for case 2-2.

4. Discussion and conclusions

New methods to correct sea surface wind using HF radar are developed; these methods are called EFWDM and EPWDM. The wind directions can be estimated from first-order scattering, which is robust to noise. If the first-order scattering from dual radar can be used, then the wave direction at the position is estimated by
Table 1. RMSEs and correlations of USW wave parameters with predicted wave parameters from NCEP winds and HF radar–corrected winds from the EFWDM.

<table>
<thead>
<tr>
<th>Case 1-1</th>
<th>$a_w$ [Eq. (10)]</th>
<th>$(V - V_r)$ (m s$^{-1}$)</th>
<th>$r_d(H_p, H_p)$</th>
<th>$R_d(H_p, H_p)$ (m)</th>
<th>$r_d(T_p, T_p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>-0.17</td>
<td>0.78</td>
<td>0.26</td>
<td>0.57</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.73</td>
<td>0.30</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-0.06</td>
<td>0.78</td>
<td>0.26</td>
<td>0.57</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>-0.37</td>
<td>0.78</td>
<td>0.26</td>
<td>0.57</td>
</tr>
<tr>
<td>5</td>
<td>4 (forecast)</td>
<td>0.08</td>
<td>0.77</td>
<td>0.31</td>
<td>0.59</td>
</tr>
<tr>
<td>6</td>
<td>— (forecast)</td>
<td>0.27</td>
<td>0.74</td>
<td>0.35</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Solving Eq. (3). If the first-order scattering from only single radar can be used, then the wave direction at the position is estimated by solving Eq. (3). The value $\beta$ in Eq. (3) and the solution close to $\theta_T$ are selected in this case. The wave directions are interpolated or extrapolated from Eq. (5) for positions where the first-order scattering cannot be used.

The wind speeds are corrected from reanalysis data. The constraints for estimating wind speeds are that the correction of wind speeds is small and that the correction of horizontal divergence is small in the EFWDM. The constraints are changed to the minimization problem iteratively is developed.

Southerly winds were dominant during the HF radar analysis period (Fig. 4). The fetch is often limited near the western coast of Okinawa Island. The area in which the difference between mean corrected wind speeds and mean reanalysis wind speeds is large is related to the area where the difference $|\langle H_p(V_r) - H_p(V_c) \rangle|$ is large (Figs. 5c and 6a). In contrast, the RMSD of predicted wave heights $\{R_d[H_p(V_r), H_p(V_c)]\}$ is large for the western coast of Okinawa Island. The wind direction is important for the prediction of wave heights in the area. The fetch-limited condition occurs more frequently for HF-corrected winds than for NCEP winds in the area.

The RMSD of predicted wave periods $\{R_d[T_p(V_c), T_p(V_r)]\}$ is also large in this area (Fig. 6b). The mean wave periods from HF radar–corrected winds are longer than those from NCEP winds on the western coast of the island, although the fetch is often limited in this area. A possible explanation for this is that the contribution of long waves that are not generated in the area to the spectral mean period is larger for HF radar–corrected winds than for NCEP winds. The impact of wind correction on wave period prediction is smaller than on wave-height prediction. A possible reason for this is that the contribution of nonlocally generated long waves to the wave period is larger than the contribution of these waves to wave height.

Figure 7 and Table 1 show that wave prediction near the small island, where the fetch condition is sensitive to wind direction, can be improved by correcting the wind direction using HF radar. The improvement is not as sensitive to the weight parameter $a_w$. This shows that correction of wind direction is more important than correction of wind speed in the study area. This improvement also holds for NCEP forecast winds. If it were possible to download the forecast winds immediately after forecasting winds, then it might be possible to use the present method for near-real-time monitoring of wave conditions.

There are some problems to be improved in the EFWDM in the future. One problem is determining the optimum value of $a_w$ by comparing in situ observations. The other subject to be improved in the EFWDM is interpolation or extrapolation to fill the data gaps of wind direction. There have been numerous studies on filling data gaps for HF radar currents (e.g., Yaremchuk and Sentschev 2011). We adopted Eq. (5) in the present method. Improvement of the method to fill data gaps as performed for HF radar currents will be the subject of future work.

We also developed the EPWDM. The EPWDM algorithm is better in principle than the EFWDM, since it includes EFWDM as a particular case. However, we could not verify that the EPWDM is better than the EFWDM from the observation. We could not determine which is the best parameter, $a_w$ or $V_w$. The JMA wind station around the HF radar observation area is at 26.21°N, 127.36°E, which is on a small island (T in Fig. 1a). The altitude of the station is 220 m MSL, and the anemometer is 10 m from the ground. Therefore, it is impossible to compare corrected winds with in situ observed winds using the RMSD.

The absolute values of the complex correlations of in situ observed winds at the station T (Fig. 1a) with NCEP winds ($V_r$), with corrected winds from the EFWDM, and with corrected winds from the EPWDM are 0.88, 0.86, and 0.86, respectively. JMA data are incorporated into the NCEP reanalysis, and NCEP
Fig. 9. (a) As in Fig. 5b, but from the EPWDM and \( V_W = 1 \text{ ms}^{-1} \). (b) As in Fig. 5c, but from the EPWDM and \( V_W = 1 \text{ ms}^{-1} \). (c) As in Fig. 5d, but from the EPWDM and \( V_W = 1 \text{ ms}^{-1} \). (d) As in (a), but for \( V_W = 4 \text{ ms}^{-1} \). (e) As in (b), but for \( V_W = 4 \text{ ms}^{-1} \). (f) As in (c), but for \( V_W = 4 \text{ ms}^{-1} \).
Table 2. As Table 1, but for the EPWDM.

<table>
<thead>
<tr>
<th>Case</th>
<th>$V_w$ [m s$^{-1}$, Eq. (14)]</th>
<th>$(V - V_r)$ (m s$^{-1}$)</th>
<th>$r_e(H_s, H_p)$</th>
<th>$R_d(H_s, H_p)$ (m)</th>
<th>$r_e(T_s, T_p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2-1</td>
<td>4</td>
<td>-0.25</td>
<td>0.74</td>
<td>0.28</td>
<td>0.54</td>
</tr>
<tr>
<td>Case 2-2</td>
<td>1</td>
<td>-0.92</td>
<td>0.76</td>
<td>0.25</td>
<td>0.58</td>
</tr>
</tbody>
</table>

The Gauss–Seidel method was used to solve the minimization problem. However, the Gauss–Seidel method works well only when the diagonal elements in the matrix of the linear equation [Eq. (12) or (15)] are dominant. The quasi-Newton algorithm (e.g., Gilbert and Lemaréchal 1989) is less restrictive than the Gauss–Seidel method to the structure of the matrix and is more robust for convergence, which should be used to improve the algorithm. The RMSD between radar-estimated wind direction and NCEP wind direction [$R_d(\theta_e, \theta_w)$] is more than 40° in Fig. 5a. The value of $\sigma_\theta$ is also approximately 40°, which is not small. However, a comparison of NCEP sea surface winds with buoy observations near the coast shows that the RMSD of the wind direction is approximately 40° (Carvalho et al. 2014). The spatial variability of surface winds is large near the complex coast line, and the correction of NCEP winds using HF radar–estimated wind directions can reconstruct the spatial variability of the sea surface wind field near the coast.

The value of $\theta_e$, which is a threshold of the difference (section 2b), is important for reconstruction of the spatial variability of the sea surface wind field. The possible maximum difference in wind directions in the study area is $2\theta_e$ for $|\theta_w - \theta_T| \leq \theta_e$. The maximum difference in wind directions at N and T in Fig. 1a is 128° during the study period. Therefore, the value $\theta_e = 75°$ is valid.

There are certain issues that must be explored. One issue is to verify the methods using sea surface wind observation data that are not incorporated into the NCEP reanalysis wind data. The other issue is that the wave prediction was not good when an atmospheric front passed through the study area. Application of the time-interpolation method, which considers the propagation of atmospheric disturbances (Hisaki 2016b), may improve the prediction.

In addition, a possible improvement to the EPWDM is to replace the first term in the right-hand side of Eq. (14) with $(\theta_c - \theta_w)^2/\sigma_\theta^2$. However, the derivatives of the objective function $Q_p$ with respect to the unknowns [$V_e$ or $(V_e, \theta_e)$] are nonlinear functions of the unknowns. The nonlinear minimization of the objective function $Q_p$ must be solved, but the number of unknowns is twice the number of grid points. This improvement will be the subject of future work.

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APPENDIX

Gauss–Seidel Algorithm for the EPWDM

Equation (15) is written as

$$
\left\{ \sigma_{\theta 0}^{-2} \sin^2[\theta_w(i,j)] + \sigma_u^{-2} + \frac{\sigma_D^2}{2\Delta x^2} \right\} u_e(i,j) = \sigma_{\theta 0}^{-2} \cos[\theta_w(i,j)] \sin[\theta_u(i,j)] v_e(i,j) + \sigma_u^{-2} u_r(i,j)
$$

$$
+ \frac{\sigma_D^2}{2\Delta x} \left\{ \frac{1}{2\Delta x} [u_e(i+2,j) + u_e(i-2,j)] + C_v(v_e, i+1,j, \Delta y) \right\}
$$

$$
- C_v(v_e, i-1,j, \Delta y) - D_v(V_r, i+1,j) + D_v(V_r, i-1,j) \right\},
$$

(A1)
\[
\left\{ \sigma_{\vartheta}^{-2} \cos[\theta_w(i,j)] + \sigma_{\psi}^{-2} + \frac{\sigma_{D}}{2\Delta y} \right\} v_{\vartheta}(i,j) = \sigma_{\vartheta}^{-2} \cos[\theta_w(i,j)] \sin[\theta_w(i,j)] u_{\vartheta}(i,j) + \sigma_{\psi}^{-2} v_{\psi}(i,j) + \frac{\sigma_{D}}{2\Delta y} \left( C_u(u_{\vartheta},i,j+1,\Delta x) - C_u(u_{\vartheta},i,j-1,\Delta x) + \frac{1}{2\Delta y} \left[ v_{\psi}(i,j+2) + v_{\psi}(i,j-2) \right] \right) - D_v(V_{\psi},i,j+1) + D_v(V_{\psi},i,j-1),
\]

(A2)

for \(1 \leq i \leq N_x\) and \(1 \leq j \leq N_y\). The boundary conditions are \(V_{\vartheta}(i,j) = V_{\vartheta}(1,j)\) for \(i < 1\), \(V_{\vartheta}(i,j) = V_{\vartheta}(N_x,j)\) for \(i > N_x\), \(V_{\vartheta}(i,j) = V_{\vartheta}(i,1)\) for \(j < 1\), and \(V_{\vartheta}(i,j) = V_{\vartheta}(i,N_y)\) for \(j > N_y\).

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