Application of Tikhonov regularization method to wind retrieval from scatterometer data II: cyclone wind retrieval with consideration of rain*

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According to the conclusion of the simulation experiments in paper I, the Tikhonov regularization method is applied to cyclone wind retrieval with a rain-effect-considering geophysical model function (called GMF+Rain). The GMF+Rain model which is based on the NASA scatterometer-2 (NSCAT2) GMF is presented to compensate for the effects of rain on cyclone wind retrieval. With the multiple solution scheme (MSS), the noise of wind retrieval is effectively suppressed, but the influence of the background increases. It will cause a large wind direction error in ambiguity removal when the background error is large. However, this can be mitigated by the new ambiguity removal method of Tikhonov regularization as proved in the simulation experiments. A case study on an extratropical cyclone of hurricane observed with SeaWinds at 25-km resolution shows that the retrieved wind speed for areas with rain is in better agreement with that derived from the best track analysis for the GMF+Rain model, but the wind direction obtained with the two-dimensional variational (2DVAR) ambiguity removal is incorrect. The new method of Tikhonov regularization effectively improves the performance of wind direction ambiguity removal through choosing appropriate regularization parameters and the retrieved wind speed is almost the same as that obtained from the 2DVAR.

Keywords: scatterometer, Tikhonov regularization, cyclone wind retrieval, rain effects

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1. Introduction

Wind retrieval from scatterometer data is a widely used technique for measuring the global ocean surface wind.[1] Current operational applications include the detection of tropical and extratropical hurricane force cyclones[2] and the comparison with global model for numerical weather prediction.[3]

Present operational scatterometers include scatterometer (SCAT), advanced scatterometer (ASCAT) and QuikSCAT.[4] QuikSCAT,[1] which is the SeaWinds scatterometer on the QuikSCAT satellite, is a spaceborne Ku-band (13.402 GHz) scatterometer. It is equipped with a conical scanning antenna reflector, illuminated by two antenna feed horns to produce two antenna beams. The inner beam operates at a nominal incidence angle of 46° with horizontal polarization and the outer beam operates at a nominal 54° incidence angle with vertical polarization. During a satellite pass, a wind vector cell (WVC) will be observed in fore- and aft-looking azimuth directions by the antenna. The dimension of QuikSCAT WVC is 25 km across track and 25 km along track.[1,4] Considering that the typhoon is a mesoscale weather system, QuikSCAT can still be a powerful candidate to typhoon track and intensity development monitoring.[2]

Geophysical model function (GMF) which gives the radar cross section (σ_0) as a function of the wind vector at 10-m anemometer height, incidence angle, azimuth angle, radar frequency and polarization, is the basis of the inversion.[4] The present operational GMF is established by a statistical result of numerous National Centers for Environmental Prediction (NCEP) model winds and normalized radar cross section (NRCS) under fair weather condition. For Ku band, the operational GMF is NASA scatterometer-2 (NASASCAT2). The performance of QuikSCAT with the NSCAT2 is uncertain under the condition of rain and wind speeds above 20 m/s, especially for the cyclone wind retrieval.[5] The development of the GMF and retrieval algorithm under rain condition using spaceborne scatterometer is still under active research. Many studies[6−9]dealt with the effects of rain on Ku-band scatterometer measurements and showed

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that without considering the rain effect, the retrieved wind speed is far smaller than the actual wind speed. The rain effect must be considered when QuikSCAT data are used to study the cyclone wind retrieval.

Because of the nature of radar backscatter from the ocean surface, the inversion generally yields more than one solution. These multiple solutions are referred to as ambiguities. If the scatterometer observations are used to detect the cyclone wind information, it is necessary to select the solution that is the most likely "true" wind. A number of ambiguity removal methods have been proposed,[10] including the spatial filters, the variational method, the first-rank method, the closest-to-background method,[11] and so on.

Vogelzang *et al.*[10] presented a 2DVAR method of removing ambiguity and pointed out that it performs well in a statistical sense. In combination with the multiple solution scheme (MSS), it suppresses the noise component in SeaWinds data at high resolution. However, a disadvantage of MSS is an increased dependency on information from the background and the structure functions compared with traditional GMF inversion schemes. In some cases this may lead to large wind retrieval errors for example, the cyclone wind retrieval from scatterometer data.

The aim of the paper is twofold: to present the rain-effect-considering GMF (GMF+Rain) and a case study of its effect in wind retrieval in Section 2 and to provide the new method Tikhonov regularization and investigation of its behaviour through comparison with the operational 2DVAR method to confirm its validity in Section 3. This paper ends with the conclusions in Section 4.

2. Wind retrieval with rain rate

2.1. Rain-effect-considering GMF

As for wind retrieval from scatterometer data, the SeaWinds data processor (SDP) is developed within the satellite application facility for numerical weather prediction (NWP SAF) sponsored by European Organization for the exploitation of meteorological satellites (EUMETSAT).[11] The main steps of SDP processing chain are the inversion through the GMF and the ambiguity removal with the 2DVAR method. The main information about SDP is described in Refs. [5] and [11].

The GMF used in SDP does not consider the effect of rain, thus it will cause a large error in wind retrieval when the rain exists, especially in cyclone wind retrieval where rain always exists around the eye of the cyclone.[6] So it is important to consider the rain effect in the GMF when SDP program is applied to the cyclone wind retrieval, combined with the special sensor microwave/imager (SSM/I) rain rate data.

Rain drops within the atmosphere have three possible effects on microwave signals.[8,9] First, rain drops scatter some energy of the incident signal back to the sensor and thus increase the power backscattered to the scatterometer. Secondly, rain drops absorb the signal, causing an extinction of the signal. Thirdly, the rain drops strik against the ocean surface and change the surface roughness and hence the radar cross section.

Following the model proposed by Zhang *et al.*[6] and Nielsen,[9] the rain-effect-considering GMF (GMF+Rain) can be expressed as

$$\sigma^0_{\rm obs} = \sigma^0_{\rm wind}\alpha_{\rm att} + \sigma_{\rm eff}, \tag{1}$$

where $\sigma^0_{\rm obs}$ represents the rain modified NRCS which is measured by the sensor, $\sigma^0_{\rm wind}$ represents the NRCS caused by the wind, $\alpha_{\rm att}$ denotes the attenuation effect of rain and $\sigma_{\rm eff}$ refers to the effect of rain. For a specific incidence angle θ, $\alpha_{\rm att}$ and $\sigma_{\rm eff}$ can be expressed each as an exponential function of integrate rain rate $R_{\rm ir}$ (dB)

$$\alpha_{\rm att} = 10^{-10^{f_{\rm a}(R_{\rm ir})/10}/10}, \tag{2}$$

$$\sigma_{\rm eff} = 10^{f_{\rm e}(R_{\rm ir})/10}, \tag{3}$$

where

$$f_{\rm a}\left(R_{\rm ir}\right) = \sum_{n=0}^{2} C_{\rm a}\left(n\right) R_{\rm ir}^{n}, \tag{4}$$

$$f_{\rm e}\left(R_{\rm ir}\right) = \sum_{n=0}^{2} C_{\rm e}\left(n\right) R_{\rm ir}^{n}. \tag{5}$$

The corresponding model coefficients for $C_{\rm a}(n)$ and $C_{\rm e}(n)$ are given in Table 1.

Table 1. Ku-band quadratic model functions of $\alpha_{\rm att}$ and $\sigma_{\rm eff}$.

	$C_{\rm a}(0)$	$C_{\rm a}(1)$	$C_{\rm a}(2)$	$C_{\rm e}(0)$	$C_{\rm e}(1)$	$C_{\rm e}(2)$
Inner beam	–5.2410	0.4076	0.0167	–24.6335	0.4108	0.0160
Outer beam	–4.6036	0.4432	0.0171	–24.5579	0.2802	0.0115

2.2. Case study

Following the GMF+Rain model proposed in Subsection 2.1, the collocated SeaWinds data and SSM/I data are put into the wind retrieval with modified SDP program and compared with the results without considering the rain effects (just by using the GMF in SDP). The case is an observation of a hurricane force cyclone raging over the northwest Pacific which was observed by SeaWinds on 6 October 2009.

Figure 1 illustrates the wind fields for hurricane Melor retrieved from QuikSCAT rev 53632 data. The bottom left panel (c) illustrates the NCEP forecasts, which have a poor representation of the hurricane.

The upper left panel in Fig. 1(a) shows the wind field for the selected wind ambiguity from 2DVAR and MSS scheme which is used to reduce the noise, to be noted as a no-rain model product. The no-rain model product was retrieved using the NSCAT2 GMF and was not corrected for rain effects. The observed wind speeds around the centre are higher than the NCEP modeled ones, especially to the south of the centre. This is not surprised: it is well known that NWP models tend to underestimate the strongest winds in cyclones of hurricane force intensity.

The upper right panel in Fig. 1(b) shows the wind field retrieved using the GMF+Rain geophysical model function, to be noted as a rain model product which indicates stronger wind speeds to the south of eyewall than the no-rain model product. At the same time, a higher SSM/I rain rate appears in the region to the south of eye wall. The results are likely to be due to the attenuation effects of rain, which suppress NCRS for extreme high wind conditions and underestimate the wind speed when the rain effect is not considered in GMF.

The maximum wind speed in the no-rain model product is about 36 m/s, far smaller than the 62 m/s wind speed indicated by the best track data from Japan Meteorological Agency (JMA). While the maximum wind speed in the rain model product which exceeds 50 m/s is closer to the JMA wind speed. The result indicates that the wind retrieval is improved with the NSCAT2 GMF+Rain model compared with that obtained from the no-rain model.

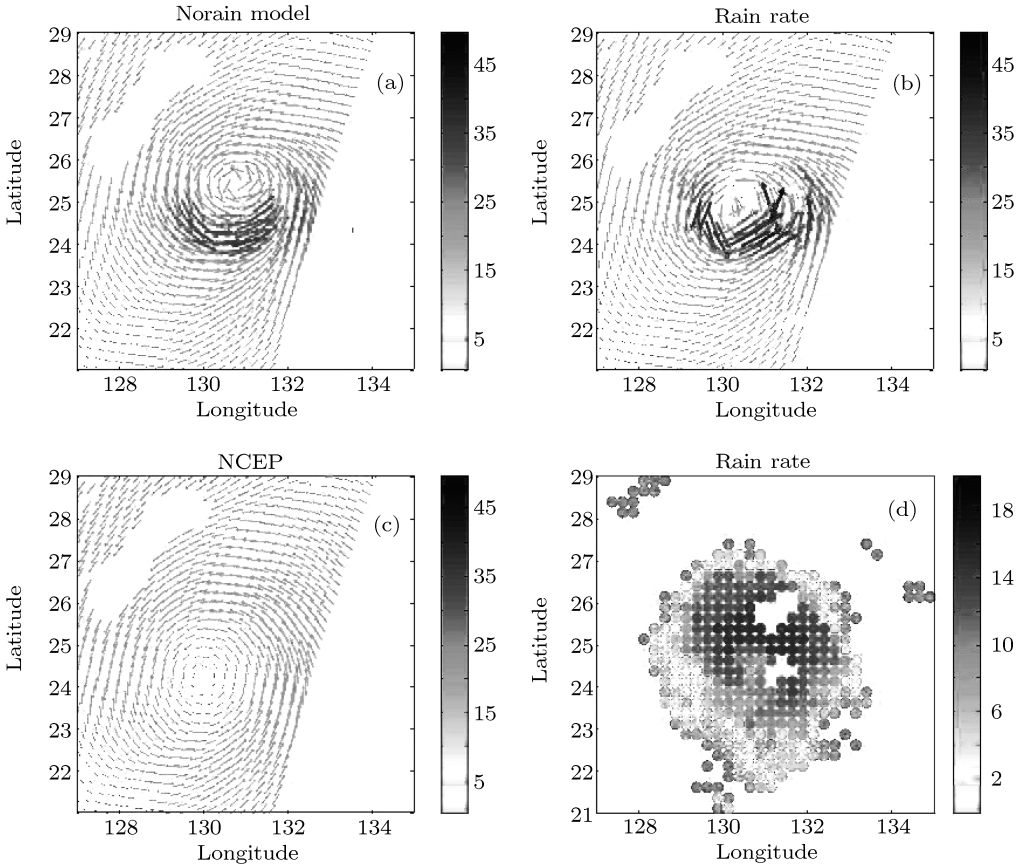


Fig. 1. QuikSCAT winds for hurricane Melor from rev 53632. The upper left panel (a) shows the wind field with the NSCAT2 GMF and upper right panel (b) with the GMF+Rain (NSCAT2+Rain). The NCEP wind is in the bottom left panel (c). The bottom right panel (d) is the SSM/I rain rate.

However, wind directions around the centre of the cyclone obviously do not fit into the overall circulation pattern, which can be observed both in the no-rain model product and in the rain-model product. There is more wind direction misfit when the rain effect is considered in GMF. This is because when the MSS of inversion is used, the background exerts a great effect on minimization. When the background error is large, the ambiguity removal with 2DVAR will cause a large error. In this case, the NCEP forecast background in Fig. 1 has a poor presentation of the cyclone and causes the error in the direction ambiguity removal with 2DVAR. It will be shown in the following section that the error is mitigated with the Tikhonov regularization method in the ambiguity removal process. The error can be suppressed by relying more on the scatterometer observations, in particular by relaxing the variational quality control.

3. Improvement with regularization method

3.1. Regularization method

The Tikhonov regularization method is first proposed by the Tikhonov to solve the ill-posed problem in mathematic inverse problem research and now is widely used in many areas including retrieval from satellite data. The regularization method has a deep connection with the variational problem.[12−14]

Supposing a problem of

$$Ax = b, \tag{6}$$

giving the observation of b^δ, which satisfies

$$\left\|b^\delta - b\right\| < \delta, \tag{7}$$

where the δ represents the error of observation, the $\|\ \|$ is a predefined norm, with the least squares method, the solution of x satisfies

$$\|Ax - b^\delta\| = \min! \tag{8}$$

The solution of Eq. (8) is not unique for some cases. To select one solution from the possible solutions, a penalized part is always added to the minimization function, called the Tikhonov functional. The ordinary form is

$$J(x) = \|Ax - b^\delta\|^2 + \gamma\|x - x_b\|^2 = \min! \tag{9}$$

where γ is the Tikhonov regularization parameter and x_b is the first guess of x. More information of the Tikhonov regularization method was presented by Huang and Wu.[12]

The biggest difference between the regularization method and the 2DVAR is that the regularization method adds a regularization parameter to the stable function part of the cost function to make the solution more reliable. The cost function of regularization method for scatterometer wind retrieval can be expressed as[16]

$$J(x) = J_0(v_0^i, \delta x) + \gamma J_b(\delta x), \tag{10}$$

with $\delta x = (x - x_b) = \begin{pmatrix} u \\ v \end{pmatrix}$, v_0^i is the vector of scatterometer retrieved multiple wind solutions, $J_0 = \|Ax - b^\delta\|^2$ is the observation term and $J_b = \|x - x_b\|$ is the background term.

From the knowledge of the regularization inverse method, when the true solution is known, the accuracy of retrieved wind will first increase as γ increases and when the value of γ exceeds a special value, the accuracy will decrease; but there still exists a situation where the accuracy will go to a certain value as γ increases to infinity.[13,15] Because the true solution is always not known, the regularization parameter γ is determined by the observation error δ with discrepancy principle,[15] and so on. More often, the value of γ is chosen by experience in practice. The simulation experiments[15] have shown that the regularization method is effective when the background error is large especially and the best regularization parameter is easy to choose. In the next section, a cyclone wind retrieval case will be studied to validate the effectiveness of the Tikhonov regularization method.

3.2. Case study

In this section, the same case used in Subsection 2.2 will be studied in more detail in order to gain more insight into the role of the Tikhonov regularization parameter in the cost function, since it controls the relative balance between observations and background in the cost function when the background error is large.

Figure 2 shows the cyclone wind field retrieved through the SDP with the GMF+Rain model for 2DVAR and different Tikhonov regularization parameters set for the regularization method. The upper left panel of Fig. 2 shows the same results as those of Fig. 1

for the 2DVAR ambiguity removal. Just as the analysis from Subsection 2.2, with the standard setting for 2DVAR, some wind directions around especially the south and the east of the centre obviously do not fit into the overall circulation pattern. The upper right panel (Fig. 2(b)) is obtained with the regularization parameter set to be 0.1, the bottom left (Fig. 2(c)) and right panel (Fig. 2(d)) are for wind field with regularization parameters set to be 0.05 and 0.01 respectively. From the wind colour (representing the wind speed) in Fig. 2, the retrieved wind speeds are almost the same for 2DVAR and regularization method. This is easy to understand because the ambiguity solutions in MSS have almost the same wind speeds. The different ambiguity removal methods mainly influence the wind direction but have little influence on wind speed.

With the new ambiguity removal way of the Tikhonov regularization method and setting the regularization parameter to be smaller than 1.0, it effectively imposes more weight on the observation part of the cost function. In cases where ambiguities and background are far apart, the priori probabilities become constant and 2DVAR can distinguish the ambiguities only by their distance from the background. As a result, 2DVAR starts behaving like being closest to background and will select the ambiguity with its direction closest to the background (in MSS all ambiguities in a WVC have similar wind speeds). This is what happens in the upper left panel of Fig. 2 in which many wrong wind directions are selected. When the regularization parameter of the new method of regularization is set to be smaller than 1.0, the observation part of cost function has more weight in the selection process, resulting in selections that may deviate more from the background as in the remaining panels of Fig. 2. So the ambiguity removal now selects ambiguity closer to the observation and fit better into the general circulation pattern.

Also, there are still a few wind directions around the east of the centre which seem not to fit the general circulation for $\gamma = 0.01$ in Fig. 2. The wind field retrieved with $\gamma = 0.1$ and $\gamma = 0.05$ seems better than that with $\gamma = 0.01$. When the case of $\gamma = 0.5$ is considered, which case is not shown in Fig. 2, the general circulation of the retrieved wind field is also not as good as those with $\gamma = 0.1$ and $\gamma = 0.05$. This is to say, the best regularization parameter is between $\gamma = 0.05$ and $\gamma = 0.1$ for this case.

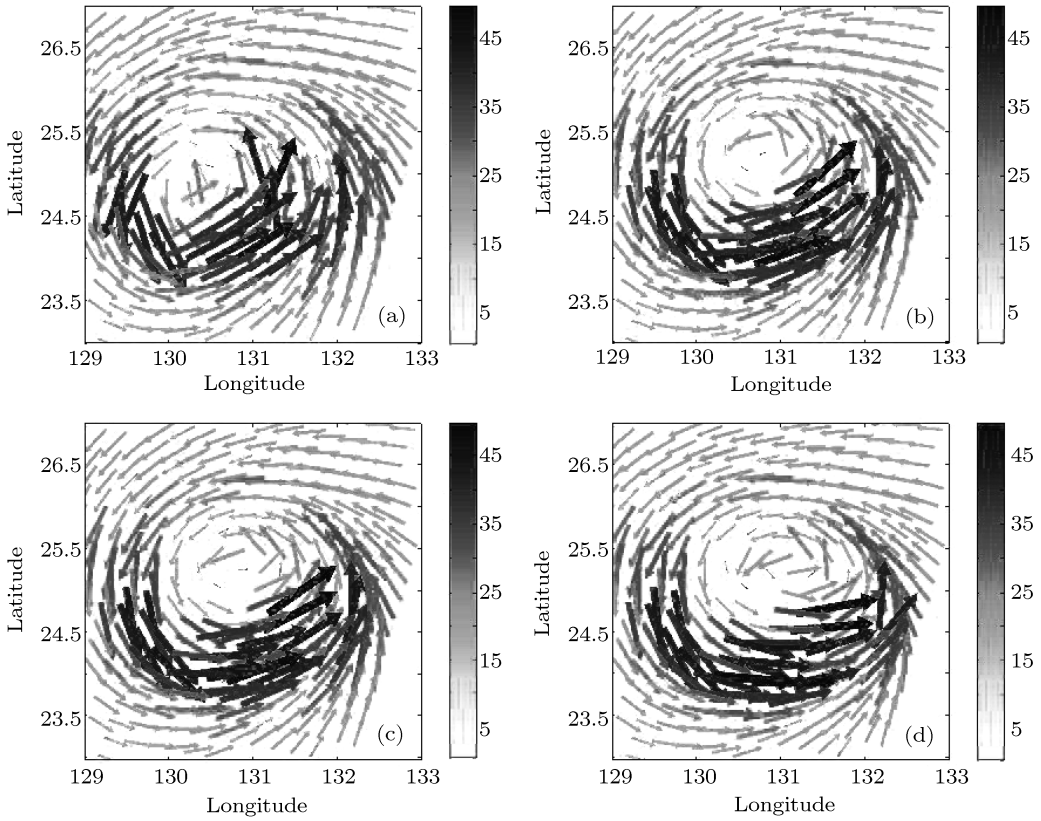


Fig. 2. QuikSCAT winds for hurricane Melor from rev 53632 with GMF+Rain model for different Tikhonov regularization parameters. Wind field with 2DVAR ambiguity removal (top left) shows the same result as that in Fig. 1. The values of regularization parameter γ are 0.1 (top right), 0.05 (bottom left) and 0.01 (bottom right).

Anyhow, by setting the regularization parameter to be smaller than 1.0, the wind retrieval for cyclone has shown a good general circulation and almost the same wind speed with the new ambiguity removal method of the Tikhonov regularization compared with those with the 2DVAR. However, such cases should be handled with care, because the best regularization parameters chosen are different for different cases. Generally speaking, the best regularization parameter is between 0.05 and 0.1 and it will not be very small according to the theory of the Tikhonov regularization in Subsection 3.1.

4. Conclusion

Combined with the NSCAT2 GMF, a new GMF (GMF+Rain) with consideration of the rain effects has been proposed. The GMF+Rain model is applied to cyclone wind retrieval with collocated QuikSCAT data and SSM/I data and to the improvement of the estimate of wind speed for area with rain. The results are corroborated with a comparative analysis with the best track intensity estimates of maximum wind speeds from JMA for cyclone Melor and are satisfactory for the maximum wind speed of GMF+Rain model (almost 50 m/s) closer to the best track intensity (62 m/s) than the GMF result (36 m/s). However, there are more wind directions around the centre of cyclone, which obviously does not fit the general circulation with GMF+Rain compared with the wind field retrieved with NSCAT2 GMF.

For solving the wind direction error with 2DVAR ambiguity removal, a new method of the Tikhonov regularization for ambiguity removal is presented. Because the MSS scheme of inversion increases the influence of neighbouring WVCs and the background, the wind retrieval with MSS cannot present a desirable result when the background error is large. The influence of the background can be controlled by using the Tikhonov regularization method in ambiguity removal with an appropriate regularization parameter. Compared with the case of the 2DVAR ambiguity removal method, the general circulation of the cyclone seems better for the regularization parameter smaller than 1.0 and their difference in wind speed is very small. The best results are obtained when γ value is between 0.1 and 0.05 as shown in the case study, but the best regularization parameter is different from case to case.

Further experiment with the Tikhonov regularization method to optimize the regularization parameter setting is recommended since it is likely that optimum setting depends on the meteorological situation.

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