Variational assimilation in combination with a regularization method for sea level pressure retrieval from QuikSCAT scatterometer data II: simulation experiment and actual case study*

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The sea level pressure field can be computed from sea surface winds retrieved from satellite microwave scatterometer measurements, based on variational assimilation in combination with a regularization method given in part I of this paper. First, the validity of the new method is proved with a simulation experiment. Then, a new processing procedure for the sea level pressure retrieval is built by combining the geostrophic wind, which is computed from the scatterometer 10-meter wind using the University of Washington planetary boundary layer model using this method. Finally, the feasibility of the method is proved using an actual case study.

Keywords: scatterometer, sea level pressure, variational assimilation, regularization, QuikSCAT

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1. Introduction

The tropical cyclone is one of the world's most destructive weather systems. In history, there have been eight typhoon disasters that have killed at least 100000 people. More than 90 tropical cyclones arise each year, so there is an urgent need to observe and monitor them.[1,2]

Satellite remote sensing technology is widely used in the study of typhoons. In particular, the QuikSCAT, which is the Seawinds scatterometer on the QuikSCAT satellite, was designed to retrieve ocean surface winds from its measurements (see Fig. 1).[3−6] Given that the typhoon is a mesoscale weather system and the swath of QuikSCAT is 1800 km, QuikSCAT could be a powerful candidate to track typhoons and monitor their intensity development.[1,7] The surface wind measurements from QuikSCAT have had a profound effect on research and applications in meteorology and oceanography.[7,8] An application of interest to meteorologists in general and weather forecasters in particular, is the ability to compute a sea level pressure (SLP) field from satellite wind measurements,[8] particularly to compute the tropical cyclone's SLP field.

Various schemes have been designed to compute a tropical cyclone's SLP fields from scatterometer sea surface wind fields, but there are mainly two well-developed methodologies: one uses a planetary boundary layer (PBL) model.[9−14] At present, the most representative PBL model is the University of Washington PBL (UWPBL) model. Some researchers have used this model to derive a tropical cyclone's SLP from scatterometer-derived winds.[15−19] The other methodology is a variational method, which is based on an idea of Sasaki. Harlan and O'Brien[20] first applied this method to assimilate the tropical cyclone's SLP field from Seasat-A scatterometer data. Zierden *et al.*,[21] Hilburn *et al.*[22] made some improvements in subsequent studies.

In part I of this paper, we devised a new method using variational assimilation in combination with Tikhonov regularization and avoided the difficulty of ill-posedness when dealing with boundary value conditions (BVC).[20,23] The PBL model, especially the UWPBL model, is a two-layer similarity model with parameterizations for stratification, variable surface roughness, and humidity, gradient wind, isallobaric

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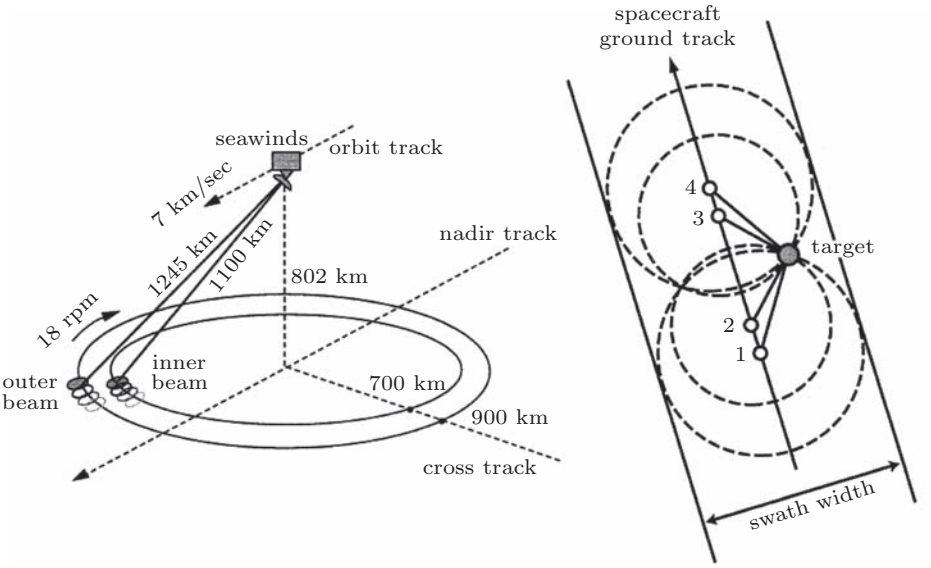


Fig. 1. Scanning geometry of the Seawinds scatterometer on the QuikSCAT spacecraft. Two antenna beams enable the sampling of a wind vector cell from up to four different azimuth directions.[3]

wind, thermal wind, and organized large eddies (OLE) effects.[12] It well describes the PBL's physical processes. So we design a new processing procedure of the tropical cyclone's SLP retrieval by combining the geostrophic wind computed from the UWPBL model with the method we devised in part I of this paper.

Part II of this paper is organized as follows. The scatterometer data and *in situ* comparison data are described in Section 2. A simulation experiment and its tests for the validity of the new method are introduced in Section 3. In combination with the method devised in part I with the determination of geostrophic wind in the UWPBL model, a new processing procedure for the tropical cyclone's SLP retrieval is designed in Section 4. The feasibility of this method is supported by an actual case study in Section 5. Finally, a summary is given in Section 6

2. Data

This study uses the "SeaWinds on QuikSCAT" L2B surface wind vectors distributed by the Jet Propulsion Laboratory (JPL), Physical Oceanography Distributed Active Archive Centre (PODAAC) after removal of those wind vector measurements that have been contaminated by rain and/or ice.[24−27] Milliff *et al.*[28,29] have shown that the rain flag may be too conservative and that omitting all of the rain-flagged vectors can bias estimates of derivative quantities, such as the wind stress curl. However, the surface pressure patterns obtained from scatterometer winds are relatively insensitive to localized patches of either missing or erroneous vectors, so we have applied the rain flag as recommended by PODAAC. The L2B winds are provided in swaths that are 1800-km wide; wind vectors are given in 25 km×25 km wind vector cells with as many as 76 cells across the satellite swath. We use the selected vector out of the up-to-four possible ambiguous vectors as the scatterometer-derived wind field.[8]

Buoy surface pressure measurements are obtained from the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Centre (NDBC) in the form of hourly reports (information online at http://ndbc.noaa.gov/rsa.shtml).

The National Centre for Environmental Prediction-National Centre for Atmospheric Research Reanalysis (NCEPR) is used as the background pressure field for the variational assimilation in combination with the regularization method. The reanalysis data are obtained from the dataset ds083.2 from the National Centre for Atmospheric Research (NCAR). We extract the SLP, 2-m air temperature, sea surface temperature, and 2-m humidity from this dataset as the input environmental variables for the UWPBL model. These data are available on a 1° global grid at

6-hour intervals. Linear interpolation in time is used to obtain the datum (SLP, 2-m air temperature, sea surface temperature, and 2-m humidity) corresponding to the time of the QuikSCAT overpass.

3. Simulation experiment

In order to test the validity of the proposed method, we assume the NCEPR 1° × 1° SLP data is the 'true' tropical cyclone's SLP. We choose September 25, 2006 at 0600 UTC, and the domain, 30° N–50° N and 155° E–180° E. The NCEPR 1° × 1° tropical cyclone's SLP data are available on a 1° global grid. We interpolate the SLP data by Delaunay triangulation[22] to a 0.25° grid and smooth the interpolated SLP with a low-pass Filter.[15] We treat the resulting SLP as the 'true' tropical cyclone's SLP for the simulation experiment. Geostrophic vorticity is given by

$$\zeta_{\rm g} = \frac{1}{\rho f}\Delta p + \frac{\beta}{f}u_{\rm g} = \frac{1}{\rho f}\Delta p - \frac{\beta}{\rho f^2}\frac{\partial p}{\partial y}, \qquad (1)$$

where p is the SLP, ρ is taken as a constant (1.225 kg·m^{-3}), f is the Coriolis parameter, and $\beta = {\rm d}f/{\rm d}y$. In the centred finite difference form, equation (1) becomes

$$\begin{aligned}\zeta_{\rm gij} = {} & \frac{1}{\rho f_j}(p_{i+1,j} + p_{i-1,j} - 2p_{i,j})/\Delta x^2 \\ & + \frac{1}{\rho f_j}(p_{i,j+1} + p_{i,j-1} - 2p_{i,j})/\Delta y^2 \\ & - \frac{\beta}{\rho f_j^2}(p_{i,j+1} - p_{i,j-1})/2\Delta y, \end{aligned} \qquad (2)$$

where i denotes the cell position along the latitude, j denotes its position along the longitude; Δx and Δy denote the grid spacings and are computed directly from the latitude and longitude of the corresponding data points respectively. All calculations are performed on the 0.25° grid.

According to the dimensional analysis for the Tikhonov functional and comparative analysis for the data, the following sensitivity analysis for p_0 and $\zeta_{\rm g}$ yields $k_\zeta = 1$, $\alpha = 1 \times 10^{-13}$ m^{-2} as optimal parameters. They produce a smooth SLP field while preserving the physical structures present in the QuikSCAT winds and relative vorticity.

3.1. Sensitivity analysis of boundary value p_0

In the sensitivity analysis of boundary value p_0, we assume the simulated 'true' boundary value $p_0^{\rm true}$ and the simulated 'measured' boundary value p_0 is configured by adding a proportional noise (δ) to the simulated 'true' boundary value $p_0^{\rm true}$. The noise lies in a uniform distribution, and δ changes from 0.005 to 0.3. That is to say, the simulated 'measured' boundary value p_0 has a proportional noise of 0.5%–30% as compared with the simulated 'true' boundary value $p_0^{\rm true}$. The computation results are given in Table 1, and the retrieval pressure fields under different noises are shown in Fig. 2, showing that the noise not only influences the accuracy of boundary pressure value, but also the accuracy of the whole pressure field. When the noise proportional value increases to 0.05, the result becomes unreliable. The boundary value p_0 really influences the accuracy of the SLP retrieval, and it is very important to take this value into consideration when we retrieve the SLP field from the scatterometer-derived wind field.

Table 1. Retrieval results for different boundary pressure noises.

	Initial pressure		results	
δ	P_0/hpa RMS	P/hpa RMS	P_0/hpa RMS	P/hpa RMS
0.005	2.987	0.627	1.998	0.580
0.01	5.974	1.253	3.980	1.127
0.05	29.868	6.265	19.858	5.537
0.1	59.736	12.531	39.709	11.053
0.2	119.472	25.062	79.411	22.085
0.3	179.207	37.593	119.113	33.117

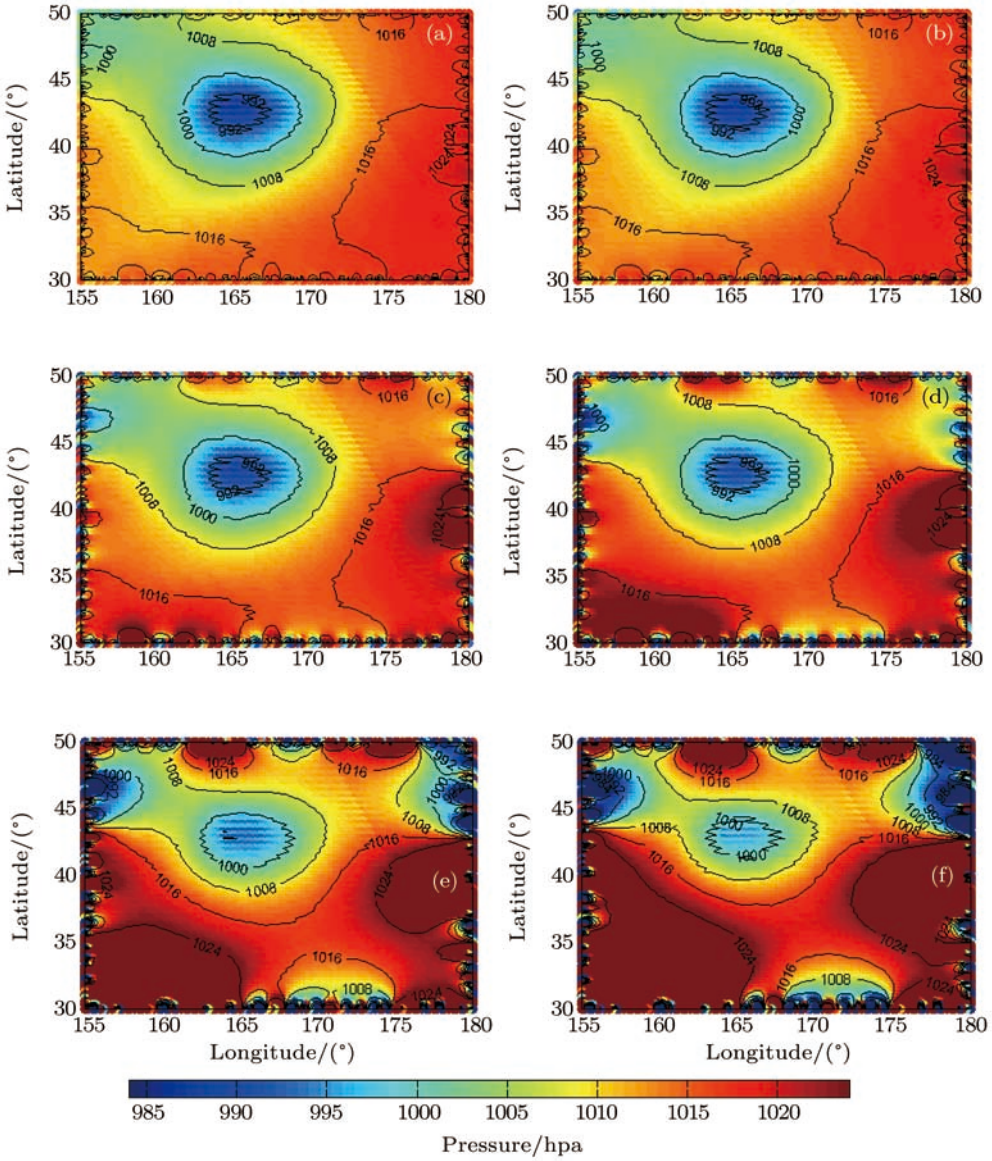


Fig. 2. (colour online) Retrieval results for different boundary pressure noises (pressure, units: hpa): (a) the noise $\delta = 0.005$, (b) $\delta = 0.01$, (c) $\delta = 0.05$, (d) $\delta = 0.1$, (e) $\delta = 0.2$, (f) $\delta = 0.3$.

3.2. Sensitivity analysis of geostrophic vorticity ζ_g

In the sensitivity analysis of geostrophic vorticity ζ_g, we assume that the simulated 'true' geostrophic vorticity value ζ_g^{true} and the simulated 'measured' geostrophic vorticity value ζ_g are configured by adding a proportional noise (δ) to the simulated 'true' geostrophic vorticity value ζ_g^{true}. The noise lies in a uniform distribution, and δ changes from 0.005 to 0.3. This is to say, the simulated 'measured' geostrophic vorticity value ζ_g has a proportional noise of 0.5%–30% compared with the simulated 'true' geostrophic vorticity value ζ_g. The computation Results are given in Table 2.

Table 2. Retrieval results for different geostrophic vorticity noises.

δ	Results P/hpa RMS
0.005	0.107
0.01	0.115
0.05	0.185
0.1	0.282
0.2	0.482
0.3	0.685

3.3. Sensitivity analysis of both p_0 and ζ_g

In the sensitivity analysis of both p_0 and ζ_g, we assume that both of the simulated 'true' values (p_0^{true}, ζ_g^{true}) and the simulated 'measured' values (p_0, ζ_g) are

configured by adding a proportional noise (δ) to the simulated 'true' values ($p_0^{\rm true}$, $\zeta_{\rm g}^{\rm true}$). The noise lies in a uniform distribution, and δ changes from 0.005 to 0.3. This is to say, the simulated 'measured' values (p_0, $\zeta_{\rm g}$) have a proportional noise of 0.5%–30% as compared with the simulated 'true' values ($p_0^{\rm true}$, $\zeta_{\rm g}^{\rm true}$). The computation results are given in Table 3.

Table 3. Retrieval results for different boundary pressures and geostrophic vorticity noises.

	Initial pressure		Results	
δ	P_0/hpa RMS	P/hpa RMS	P_0/hpa RMS	P/hpa RMS
0.005	2.987	0.627	1.998	0.583
0.01	5.974	1.253	3.980	1.132
0.05	29.868	6.265	19.858	5.556
0.1	59.736	12.531	39.709	11.090
0.2	119.472	25.062	79.411	22.159
0.3	179.207	37.593	119.113	33.227

According to the above analyses, we find that the magnitudes of the two retrieval parameters are quite different from each other when we retrieve the boundary pressure p_0 and geostrophic vorticity $\zeta_{\rm g}$ at the same time, and we also find that the SLP retrieval is the most seneitive to the boundary pressure value p_0. Meanwhile, the method described in this paper can improve the boundary pressure value, and further improve the whole pressure field.

4. The processing procedure of an actual retrieval

We design the processing procedure of a tropical cyclone's SLP retrieval using the variational assimilation in combination with the regularization method (see Fig. 3).

Step 1 Using the QuikSCAT L2B surface wind vectors distributed by PODAAC and the two-layer UWPBL model, we compute the geostrophic wind field corresponding to the 10-m sea surface wind field.

Step 2 Using the Delaunay triangulation and interpolation method,[23] we interpolate the NCEPR $1^\circ \times 1^\circ$ SLP field onto the 0.25° regular grid over the domain, then use the low-pass filter to smooth the interpolated SLP field and consider the smoothed SLP field as the initial SLP field.

Step 3 Geostrophic vorticity is given by Eq. (1). In centred finite difference form, equation (1) becomes Eq. (2), and then the geostrophic vorticity $\zeta_{\rm g}$ is computed from the initial SLP field on the 0.25° regular grid over the domain.

Step 4 Using the Delaunay triangulation and interpolation method,[23] we interpolate the geostrophic winds in the QuikSCAT swath region onto the 0.25° regular grid over the domain. In centred finite difference form, the relative vorticity ζ_s becomes

$$\begin{aligned}\zeta_{sij} = {} & \big(v'_{i+1,j} - v'_{i-1,j}\big)/2\Delta x \\ & - \big(u'_{i,j+1} - u'_{i,j-1}\big)/2\Delta y, \end{aligned} \tag{3}$$

where u' and v' are along the latitude and along the longitude wind components, respectively.

Step 5 By blending the relative vorticity ζ_{sij} with the geostrophic vorticity ζ_{gij}, we obtain the new geostrophic vorticity ζ_{gsij}, where $\zeta_{gsij} = \zeta_{sij}$ in the swath region and $\zeta_{gsij} = \zeta_{gij}$ outside the swath. The boundary SLP value comes from the initial SLP field. We employ variational assimilation in combination with the regularization method to solve this problem, through successive overrelaxation. The values of $k_\zeta = 1$, $\alpha = 1 \times 10^{-13}$ m^{-2} produce a smooth SLP field, while preserving the physical structures present in the QuikSCAT winds and relative vorticity.

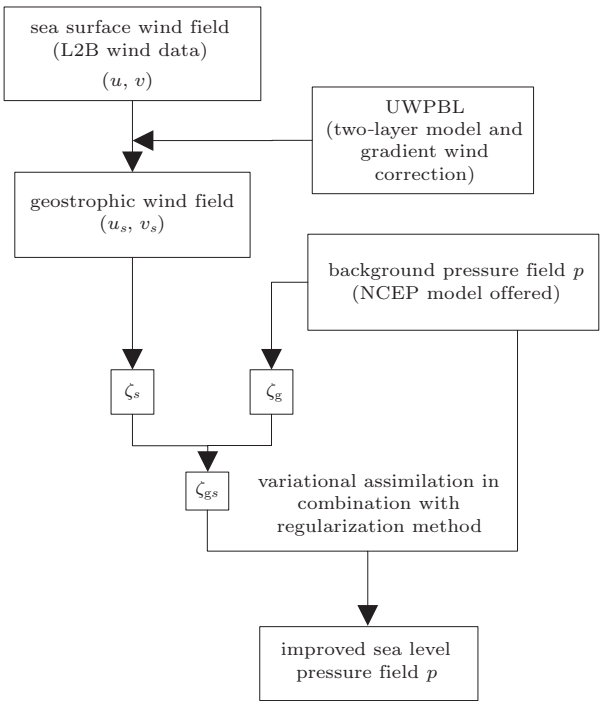


Fig. 3. The processing procedure of a cyclone's SLP retrieval.

5. Case study

In order to validate the applicability of this method, we now apply it to a cyclone event (typhoon YAGI) that occurred on September 25, 2006, at 05:29 UTC in the Eastern Pacific Ocean. Both the NCEPR SLP field and the NOAA hourly buoy data are used and interpolated linearly in time to obtain the data corresponding to the time of the QuikSCAT overpass. The retrieve domain is 30° N–50° N, 130° W–180° W. The buoy measurements at buoy stations 46002 (42.570° N, 130.460° W), 46005 (46.100° N, 131.001° W), 46006 (40.754° N, 137.464° W), and 46059 (38.047° N, 129.969° W) are obtained from NOAA NDBC. The initial background pressure field is shown in Fig. 4. The SLP field retrieved with the UWPBL model is shown in Fig. 5. The SLP field retrieved with the variational assimilation in combination with the regularization method is shown in Fig. 6.

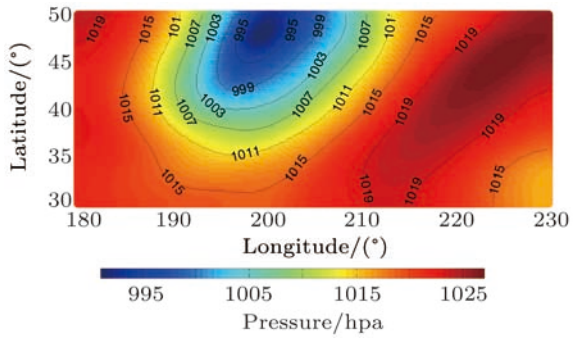


Fig. 4. (colour online) The initial background pressure field (pressure, unit: hpa).

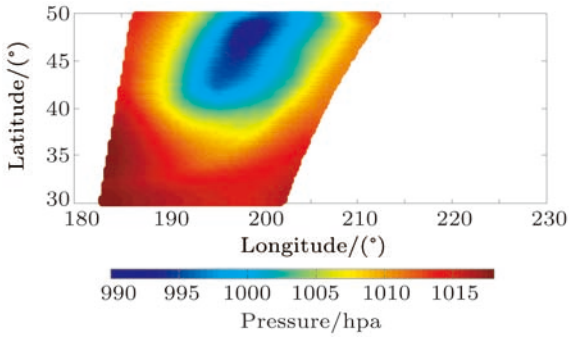


Fig. 5. (colour online) The retrieval result of the UWPBL model (pressure, unit: hpa).

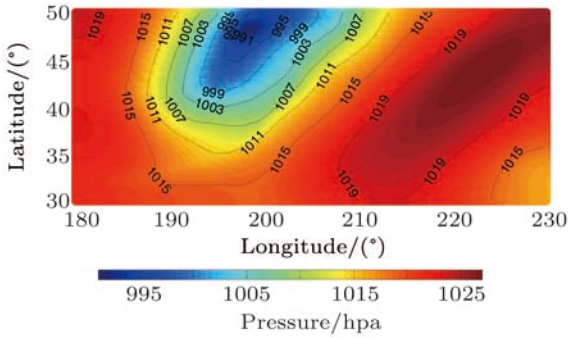


Fig. 6. (colour online) The retrieval result of the variational assimilation in combination with the regularization method (pressure, unit: hpa).

A comparison of the retrieved SLP and the NOAA buoy data is listed in Table 4.

Table 4. Retrieval results.

	Buoy station			Initial background pressure field			Retrieval results	
Number	Location	Pressure/hpa	Pressure/hpa	Location	difference/hpa	Pressure/hpa	Location	Difference/hpa
46002	42.570° N 130.460° W	1018.6	1019.48	42.5° N 130.5° W	+0.88	1019.45	42.5° N 130.5° W	+0.85
46005	46.100° N 131.001° W	1021.05	1021.56	46° N 131° W	+0.51	1021.51	46° N 131° W	+0.46
46006	40.754° N 137.464° W	1021.8	1021.33	40.75° N 137.5° W	−0.47	1021.82	40.75° N 137.5° W	+0.02
46059	38.047° N 129.969° W	1016.25	1016.80	38° N 130° W	+0.55	1016.77	38° N 130° W	+0.52

The SLP field retrieved using this method yields a central pressure for the cyclone similar to that suggested by the UWPBL model (989.823 hpa and 989.973 hpa, respectively). The central pressure of the initial background pressure field is 991.661 hpa. The intensities of the cyclone are improved by 1.838 hpa and 1.688 hpa respectively. The new SLP field is also in closer agreement with the buoy measurements, especially the buoy stations located near the boundary of the domain. Although these measurements may have been assimilated in the NCEPR, this case study validates this new method to a certain extent.

6. Conclusions

Based on former researchers' studies on SLP retrieval from scatterometer measurements, a new variational assimilation in combination with a regularization method is devised to generate SLP fields from QuikSCAT wind, and it improves the former method. The theory is constructed using a devised iteration scheme. According to the simulation experiment, the validity of this method is proved, although the boundary pressure values and the geostrophic vorticity in the retrieval domain are both necessary to retrieve the tropical cyclone's SLP field, it is shown that the retrieval is most sensitive to the boundary pressure value. An example of a tropical cyclone's SLP retrieval is provided for a mid-latitude cyclone in the Eastern Pacific Ocean. The central pressure of the cyclone, and the agreement with buoy measurement are improved. Since the accuracy of the geostrophic vorticity calculated from the QuikSCAT wind data should be further improved,[30−32] the application of this method is an effective way to improve the NCEPR SLP by using the scatterometer data under the present conditions (boundary pressure value of the initial background pressure field is derived from the model). The retrieval method in this paper offers an effective method for the application of future microwave scatterometer data.

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