Applications of QuikSCAT in typhoon observation and tracking

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Abstract: This paper developes a method to retrieve the typhoon intensity and location of the typhoon center from QuikSCAT. The typhoon intensity is derived by searching the maximum of the wind speed where the typhoon is present. The method to derive the location of typhoon center is based on the knowledge of typical wind field structure of mature typhoon, by searching the center of the helix structure of wind direction, local minimum of the wind speed around the typhoon eye, or the local minimum of the back scattering coefficient. To improve the accuracy of wind vector retrieval in typhoons, the Holland's typhoon model is employed in the process of ambiguity removal to correct the wind direction error caused by the failure of Circular Median Filter (CMF) around the eye wall, while the Geophysical Model Function (GMF) NN-T-GMF is used as a replacement of the QSCAT-1 to reduce the bias induced by the inaccurate of the existing business operational GMF at high winds. Based on this method, the track and changes of typhoon intensity for typhoon Ioke and Kaemi are extracted from continuous QuikSCAT data. The results are comparable with the best-track analysis result form National Hurricane Center, indicating that QuikSCAT can be a powerful instrument to monitor and track typhoons.

Key words: QuikSCAT, Retrieve, typhoon tracking, typhoon observation

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1 INTRODUCTION

A tropical cyclone is the generic term for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical oceans with organized convection (i.e. thunderstorm activity) and definite cyclonic surface wind circulation. Tropical cyclone with maximum sustained surface wind of more than 32.7m/s is known as typhoon or hurricane. It is one of the world's most destructive weather systems. In history, there were 8 typhoon disasters that each killed at least more than 100,000 people. More than 80 tropic cyclones are produced each year (Elsberry, 1994), so there is a strong need to observe and monitor the tropic cyclone.

In the past, the observation of typhoon is limited by the lack of in-situ measurement data. With the development of the satellite remote sensing technology, the satellite remote sensors are widely used in typhoon tracking. For example, by analysing features of the cloud map which is seen by satellite visible remote sensor, the location of the typhoon can be determined. But the visible remote sensor can only work at daytime, and it can not provide the information of the typhoon intensity. The spaceborne microwave scatterometer can measure the sea surface wind vector from the sea surface roughness measurement. Compared to visible and infrared remote sensor, scatterometer can work in night. Furthermore, it can extract both the location of the eye and the typhoon intensity. Considering typhoon is a mesoscale weather system, QuikSCAT can still be a proper candidate to typhoon tracking and intensity development monitoring, although it is limited by the low resolution.

This paper developes a method to retrieve the typhoon intensity and location of the typhoon center from the QuikSCAT. The Holland's typhoon model is employed in the process of ambiguity removal to correct the wind direction error around the eye wall, which is probably induced by the present of rain. Once the wind field of typhoon is retrieved, the typhoon intensity can be derived directly by searching the maximum of the wind speed where the typhoon is present. The method to derive the location of typhoon center makes use of the knowledge of typical structure of wind field for mature typhoon, so that the location of the typhoon center can be extracted according to QuikSCAT wind direction, wind speed or the σ^0 respectively. Based on this method, the track and changes of typhoon intensity for typhoon Ioke and Kaemi are extracted. In addition, a high wind Geophysical Model Function (GMF) NN-T-GMF is used as a replacement of the existing GMF QSCAT-1 in the wind field retrieval process, so that the bias induced by the inaccurate of the GMF at high winds can be reduced.

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2 QUIKSCAT WIND VECTOR RETRIEVAL ALGORITHM

QuikSCAT, which is one of the most successful space-borne scatterometers satellite, was launched in 1999, and is still in operation today. QuikSCAT operates at a frequency of 13.4 GHz. It employs a single 1m parabolic antenna dish with twin offset feeds for vertical and horizontal polarization. The antenna spins at a rate of 18 rpm, scanning two pencil-beam footprint paths at incidence angles of 46° (H-pol) and 54° (V-pol). At an orbit altitude of 800 km, the diameters of the two scan circles are approximately 1400 and 1800 km. Using two scanning beams, each point on the Earth within the inner 700 km of the swath is viewed from four different azimuth directions. They are viewed twice by the inner beam looking forward then aft and twice by the outer beam in a similar fashion. The instrument will collect data over ocean, land, and ice in a continuous, 1,800km-wide band centered on the spacecraft's nadir subtrack, making approximately 1.1 million ocean surface wind measurements and covering 90% of Earth's surface each day (Bender *et al*., 1993; Lungu, 2001).

As with all scatterometers, QuikSCAT emits radar signals that are Bragg-scattered from the centimeter-scale ocean waves. The return signal, which is called the normalized radar cross section (NRCS), is denoted as σ^0. The centimeter-scale ocean waves are directly influenced by sea-surface wind, and the relationship between σ^0 and sea-surface wind is expressed by Geophysical Model Function (GMF). Using GMF, sea-surface wind vectors can be retrieved from back-scattering measurement (Freilich, 2000). Because the exiting GMF such as QSCAT-1 is a nonlinear function, and the existence of various noise sources in the σ^0 measurements will also increase nonlinearity of the retrieve problem, the inversion of σ^0 measurements to wind vector can not be straightforward. Retrieve algorithm such as maximum-likehood estimator (MLE) is used to retrieve wind vector from σ^0 (Chi & Li, 1988). Because of the harmonic dependence of the σ^0 on wind direction, retrieval algorithms often result in multiple wind vectors per retrieval cell, which will always introduce 180° wind direction ambiguity. Therefore "ambiguity removal" arithmetic such as Circular Median Filter (CMF) is applied to select a unique wind vector from "ambiguity" (Schultz, 1990). In the case of typhoons, rain is always present. The existence of rain will cause a decreasing directional sensitivity, which will lead to failure of CMF and induce errors in wind direction retrieval (Halterman & Long, 2006). As an alternative way to CMF, the Holland's typhoon model is employed in the process of ambiguity removal. The ambiguity with the direction closest to Holland's typhoon model wind field is selected as the "true wind". This procedure is not expected to be error-free, but should be effective in areas not far from the eye-wall (Holland, 1980; Yueh *et al*., 2001; Yueh *et al*., 2003). The whole wind vector retrieval algorithm can be illustrated by Fig.1.

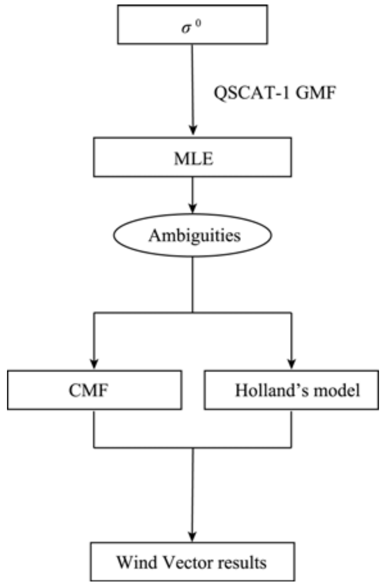

Fig. 1 Flow chart of QuikSCAT wind vector retrieval algorithm in typhoons

Considering the case of typhoon Ioke on August 30, 2006, which was seen by QuikSCAT 37474th revolution around 0600 (UTC time). Using the retrieval process shown in Fig. 1, the wind field is retrieved, and the result is shown in Fig. 2. In Fig. 2 (a), the wind field results just using circular median filter for ambiguity clear is illustrated, the black contour is used to indicate the area where the CMF is failed to select the "true wind" from ambiguities. To our knowledge of typhoons, the wind direction of mature typhoons has a helical structure. So in the area of black contour, the error of wind direction occurs. This error of wind direction is also confirmed by a comparison to NCEP wind direction. As an alternative way to CMF, the ambiguity with the direction closest to Holland's typhoon model wind field is selected as the output, the result is show in Fig. 2(b). The wind direction in Fig. 2(b) shows a helical structure, which is consistent with the wind direction reported by NCEP, indicating that the wind direction errors in black contour have been well corrected.

3 DETERMINATION OF TYPHOON INTENSITY AND THE LOCATION OF THE TYPHOON CENTER

QuikSCAT can measure the back-scattering coefficient of the sea surface, from which the sea surface wind field can be retrieved. Besides, typhoon is a mesoscale weather systems, the resolution of the wind vector cell of QuikSCAT is about 25km×25km. So if a typhoon is happened to be seen by QuikSCAT, the detail features of typhoon such as the typhoon center and typhoon intensity can be obtained. In this section, the method to retrieve the typhoon intensity and the location of typhoon center from a single pass of QuikSCAT which happened to "see" the typhoon is described.

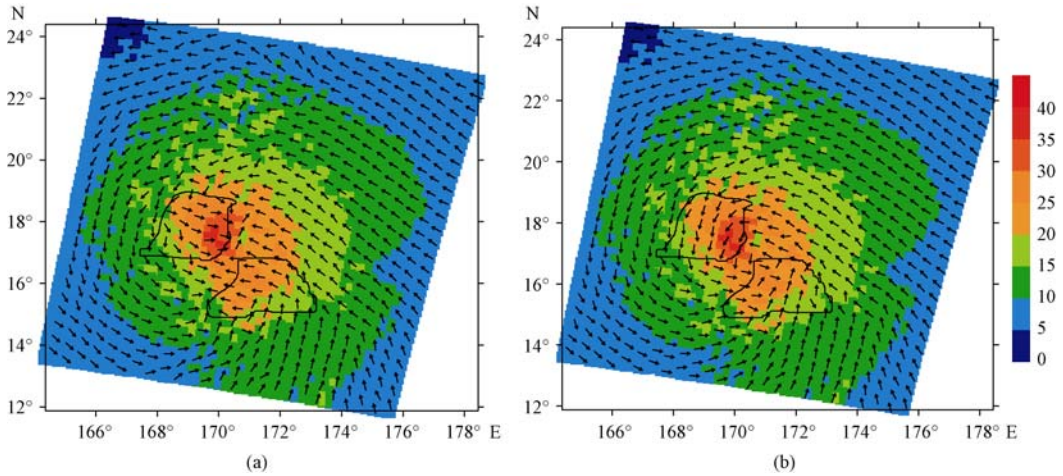

Fig. 2 Wind field results using CMF (a) and Holland's typhoon model (b) for ambiguity clear
Ioke 2006-Aug-30 06:50 UTC QSCAT rev 37474

3.1 Determination of typhoon intensity

The typhoon intensity is revealed by the maximum sustained wind speed. In our study, the maximum of the QuikSCAT wind speed in typhoon is chosen to represent the typhoon intensity. From the retrieval algorithm described in section 2, the typhoon wind field can be retrieved first, then the area of typhoon can be determined, and then the maximum wind speed in this area is chosen to be the typhoon intensity.

3.2 Locating the eye of typhoon

According to the knowledge of typical wind field structure of a mature typhoon, three methods to determine the location of typhoon center from QuikSCAT are developed. (1) Determining the location of typhoon center according to wind direction. Since the wind direction of typhoon has a helical structure, the center of the vortex-like distribution wind direction should correspond to the location of typhoon center (Elsberry, 1994). (2) Determining the location of typhoon center according to wind speed. Since the wind speed at the eye of typhoon is much lower than the wind speed at the eye-wall which is around the eye, the location of the eye can be derived by searching the location where the wind speed is the minimum of the wind field in typhoon area. (3) Determining the location of typhoon center according to σ^0. According to the GMF, the stronger wind speed corresponding greater σ^0 when the azimuth angle is constant. Since the difference of the wind direction between nearby wind vector cell is small, similar to (2), the local minimum of the σ^0 in typhoon area should correspond to the typhoon center. By searching the location of the local minimum of σ^0, the location of typhoon center can be derived.

As an example, the pass 37532 of QuikSCAT on September 3rd 2006 which happened to "see" typhoon Ioke is used to get the location of the typhoon center. In Fig. 3(a), the location of typhoon center is determined according to wind direction. In this figure, the wind direction chart shows a clear vortex feature, the vortex center corresponding to the typhoon center can be easily found with naked eye, and the location is marked by a thick arrow. Fig. 3(b) corresponds to the QuikSCAT wind speed, the local minimum of the wind speed in high wind area can be easily found, which is also marked by a thick arrow. This local minimum should correspond to the typhoon center. In Fig. 3(c), the σ^0 derived by QuikSCAT inner beam at aft looking condition is illustrated. A local minimum of σ^0 can also be easily found in this figure, which is corresponded to typhoon center. In general circumstances, the location of typhoon center deter-

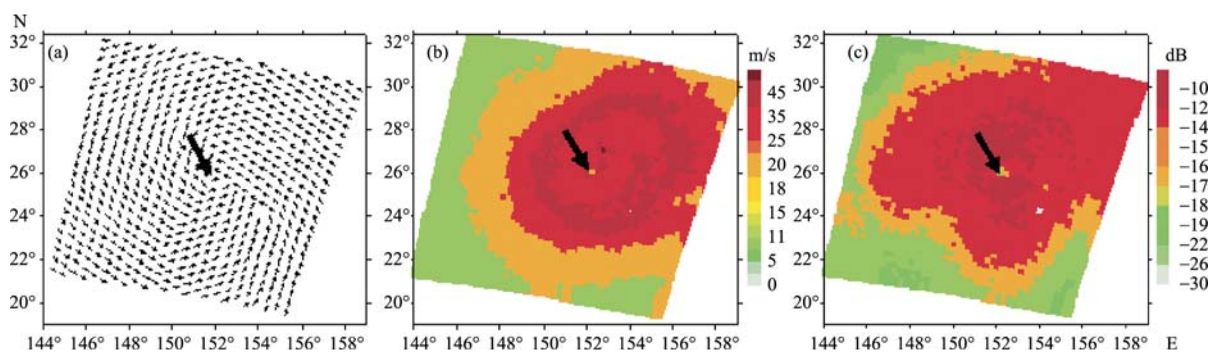

Fig. 3 Determination of typhoon center Ioke 2006-Sep-3 08:25 UTC QSCAT rev 37532 according to wind direction (a), wind speed (b) and σ^0 (c)

mined according to QuikSCAT wind direction, wind speed and σ^0 should be coincidence. However, due to the influence of rainfall and other factors, the location of typhoon center determined by those three methods may be not coincident. Besides, the wind speed field may appear more than one local minimum. In this case, the local minimum closest to the location of the eye which is determined according to wind direction is chosen as the “true” location of typhoon center. If no local minimum of wind speed can be found, then the “true” location of the eye is chosen to be the one which is determined according to wind direction. Since the location of the eye determined according to wind speed and the σ^0 are always coincident, in the following studies, only the wind direction and wind speed are used to determine the location of typhoon center.

4 APPLICATION IN TYPHOON TRACKING AND TYPHOON INTENSITY MONITORING

From the method described in section 3, if a typhoon is happened to be seen by QuikSCAT, the typhoon intensity and location of the typhoon center at the time the typhoon was seen by QuikSCAT can be derived. In addition, QuikSCAT has global coverage. It can cover about 90% area of the ocean in all over the world everyday. In most areas, QuikSCAT can pass there one or two times each day, so that continuous daily sampling data for typhoons can be provided by QuikSCAT. With these continuous daily sampling data, the track of typhoons and changes of typhoon intensity can be extracted.

From August 19th to September 6th 2006, QuikSCAT has passed typhoon Ioke for 36 times. In these passes, eye of typhoon has been viewed by QuikSCAT for 24 times, and the whole structure of the typhoon for 17 times. Using the method described in section 3, the typhoon intensity and location of the typhoon center for each pass can be derived. To get the track of typhoons and changes of typhoon intensity, the typhoon intensity and location of the typhoon center is arranged in time sequence, and then an interpolation process is applied. The results are shown in Fig. 4 and Fig. 5. Fig. 4 illustrates the QuikSCAT wind fields of typhoon Ioke for each pass, and the location of the typhoon center is marked by “×”. Fig. 5(a) illustrates QuikSCAT typhoon track for Typhoon Ioke, and the NHC typhoon track is also illustrated in this figure for purpose of comparison. Fig. 5(b) shows the Comparison of QuikSCAT and NHC typhoon intensity change for Typhoon Ioke. With the same method,

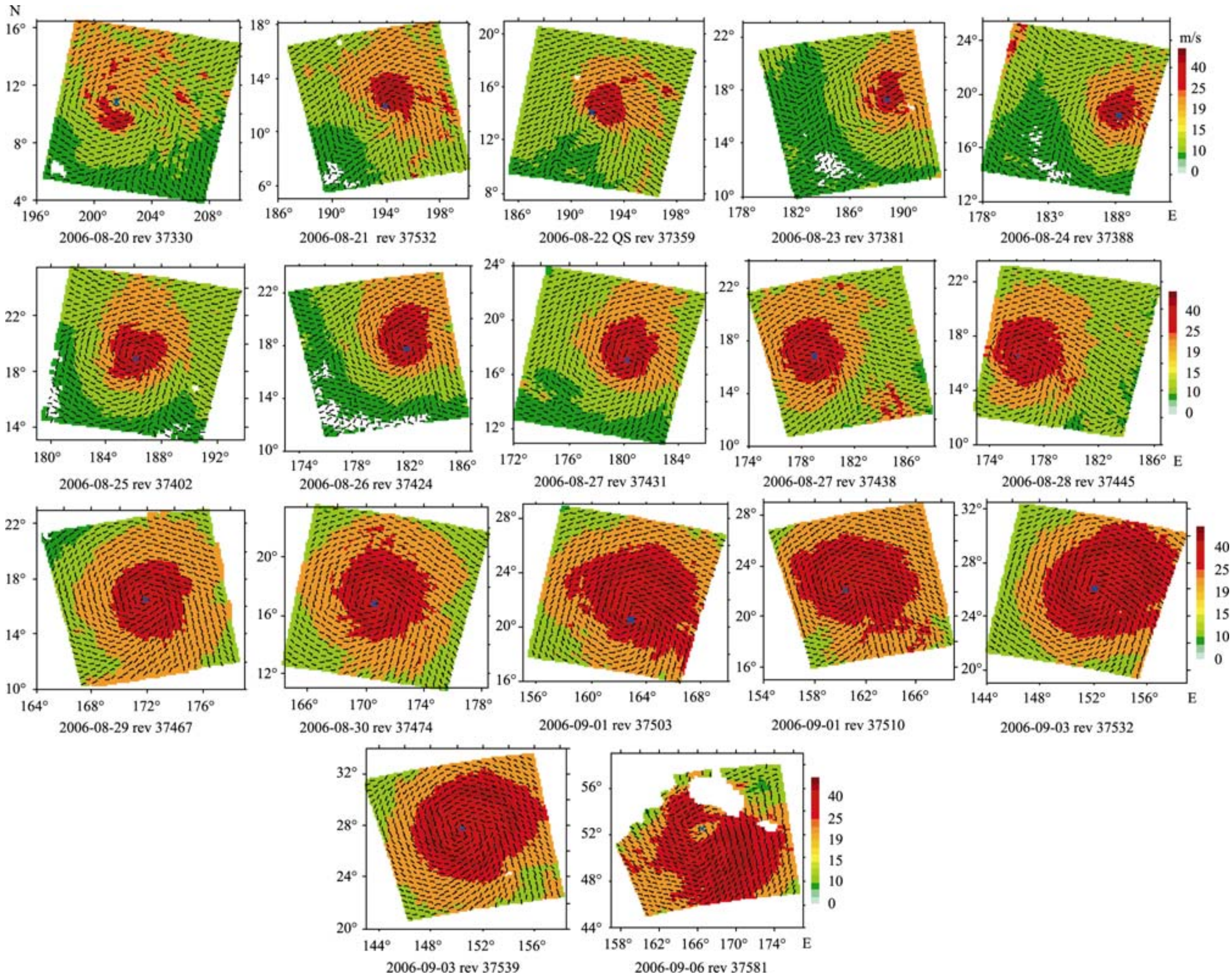

Fig. 4 QuikSCAT wind fields of Typhoon Ioke, the location of typhoon center is marked by “×”

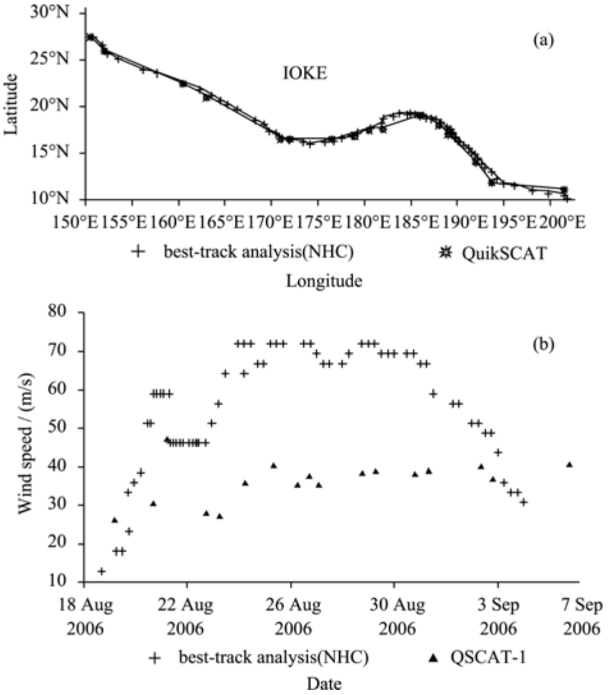

Fig. 5　Comparison of QuikSCAT and NHC typhoon track (a) typhoon intensity change (b) for Typhoon Ioke

the track of typhoons and changes of typhoon intensity for typhoon Kaemi (2007) can be derived, the wind fields for each pass is shown in Fig.6, and the comparison of QuikSCAT and NHC typhoon track and typhoon intensity change is shown in Fig.7. In these figures, the results of typhoon track derived from QuikSCAT are basically consistent with the best track analysis result distributed by United States National Hurricane Center (NHC). It should be noted that in case of typhoon Kaemi, there is no data near the shore. This is because that the backscattering measurement of QuikSCAT is contaminated by the strong echo of land in the area near shore, no useful information can be extracted in these area. Besides, the results of the typhoon intensity change derived from QuikSCAT show a large deviation to the results of NHC. Comparing to NHC, the results from QuikSCAT always under-estimate the typhoon intensity. This is because the GMF QSCAT-1 used in the retrieval process is developed using a semi-empirical approaches, which empirically correlate σ^0 to wind vectors from in-situ measurements or Numerical Weather Prediction. This approach is effective for light and moderate winds, but less accurate for high winds due to the lack of in-situ data and problematic accuracy of numerical wind analysis for high winds. Under high winds, σ^0 is always overestimated by the GMF, which can lead to underestimation of wind speed. Thus, the performance of QSCAT-1 is uncertain for wind speed greater than 20m/s (Yueh *et al*., 2001; Yueh *et al*., 2003). Besides, QuikSCAT works at Ku band, the signal of electro-magnetic wave in this band is very sensitive to rain. The influences on the backscattered signal due to rain are attenuation, rain volume backscatter, and changes in sea surface roughness, all of which can introduce errors into the process of estimating surface winds. Rain modifies the signal received by the radar, resulting in the wind vector estimates having greater error than rain-free cases. Furthermore, the reduction of maximum wind speed due to the spatial averaging could also induce errors(Yueh *et al*., 2001; Yueh *et al*., 2003; Zeng & Brown, 1998; Lecomte & Saavedra de Miguel, 1998).

Although sizable bias exists in the result of typhoon intensity, the trend of QuikSCAT typhoon intensity development is similar to the result reported by NHC. Considering the uncertainties of the different factors in the wind vector retrieval in typhoons, the results of typhoon tracking and typhoon intensity derived here are acceptable.

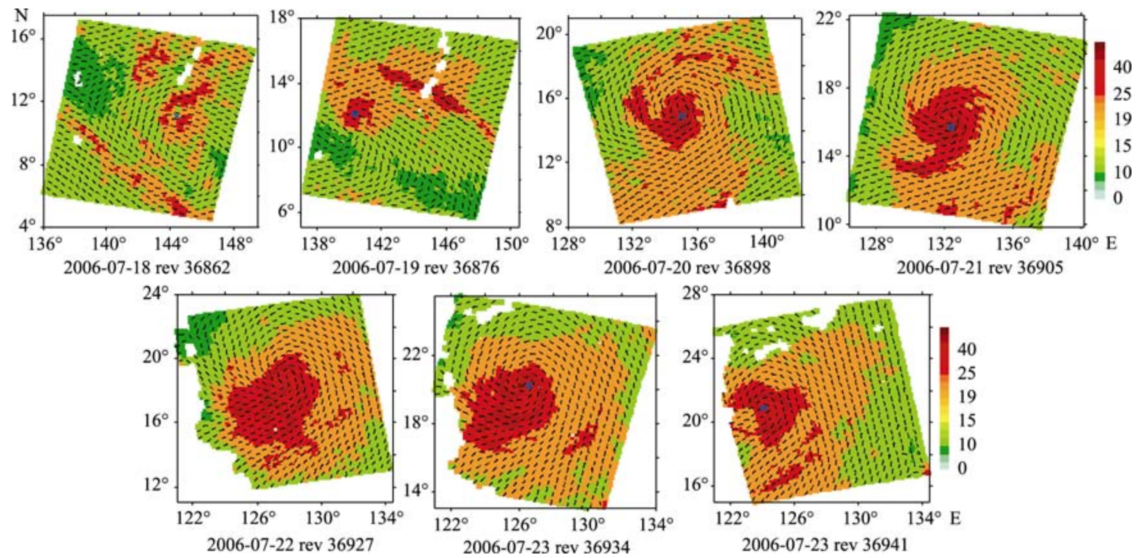

Fig. 6　QuikSCAT wind fields of Typhoon Kaemi, the location of typhoon center is marked by “×”

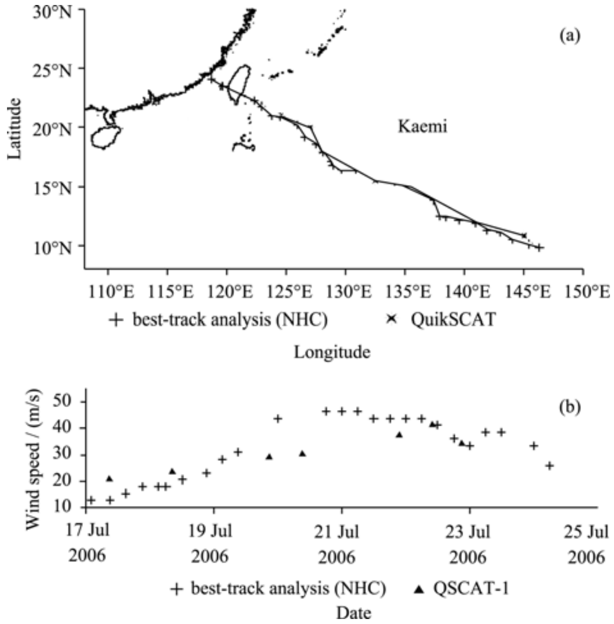

Fig. 7 Comparison of QuikSCAT and NHC typhoon track and (a) typhoon intensity change (b) for Typhoon Kaemi

5 CORRECTION TO THE RESULT OF TYPHOON INTENSITY CHANGE

Since the GMF QSCAT-1 appears to overestimate the σ^0 at high wind, in this section, the NN-T-GMF, which is a revised high-wind GMF based on QSCAT-1, is used in QuikSCAT wind vector retrieval in typhoons. The collocated SSM/I wind speed (>16m/s), the QuikSCAT wind direction and the QuikSCAT σ^0 are used as the training data-set, and the neural network (NN) approach is used as a multiple nonlinear regression technique in the NN-T-GMF to correct the QSCAT-1 at high winds. The resulted high-wind GMF NN-T-GMF is a hybrid GMF, which has three parts. For the wind speed exceeding 20m/s, the revised form of GMF from NN training is used; while QSCAT-1 is used for wind speed less than 16m/s. At the speed range from 16m/s to 20m/s, the σ^0 is chosen to be the interpolation of the revised form and QSCAT-1 to insure the continuation of the σ^0 predicted by the NN-T-GMF. Fig.8 shows a comparison of σ^0 response to wind speed for QSCAT-1 and NN-T-GMF. The σ^0 is given at up-wind direction for outer beam of QuikSCAT. The relationship between σ^0 and wind direction for the outer beam is presented in Fig. 9. In these two figures, the σ^0 estimated by NN-T-GMF is much less than the σ^0 estimated by QSCAT-1 when the wind speed is greater than 20m/s, which shows a correction to the overestimation of the σ^0 by QSCAT-1.

With the application of NN-T-GMF, the result of typhoon intensity change of typhoon Ioke is corrected, and the result is shown in Fig. 10. Comparing to the result of the intensity development of typhoon Ioke using QSCAT-1, the corrected result using NN-T-GMF shows an improved agreement with the results from best-track analysis. To further improve the accuracy of typhoon intensity, other factors such as the rain influence and the reduction of maximum wind speed due to the spatial averaging should be taken into consideration in the wind vector retrieval process.

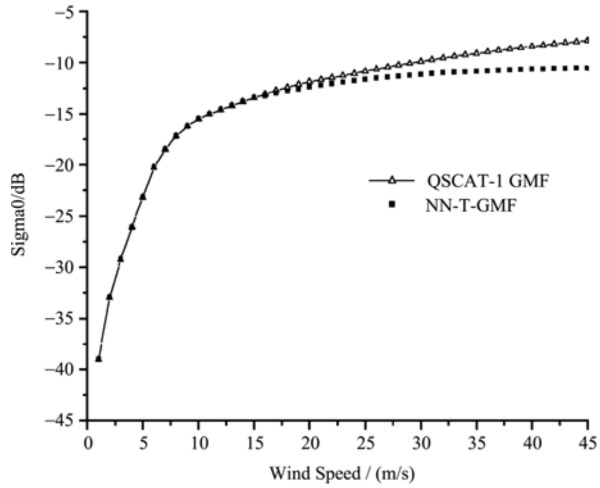

Fig. 8 σ^0 predicted by NN-T-GMF (QSCAT-1) as function of wind speed

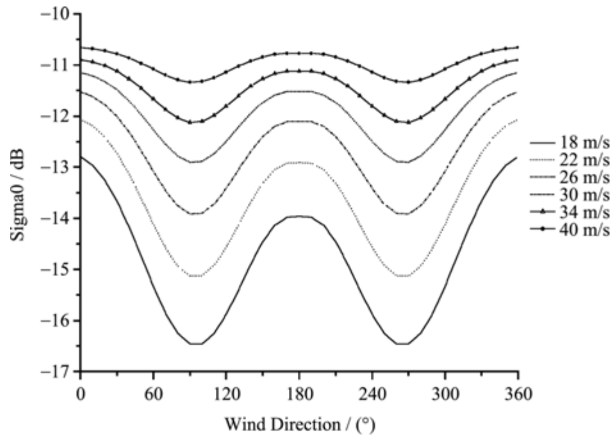

Fig. 9 σ^0 predicted by NN-T-GMF as function of wind direction

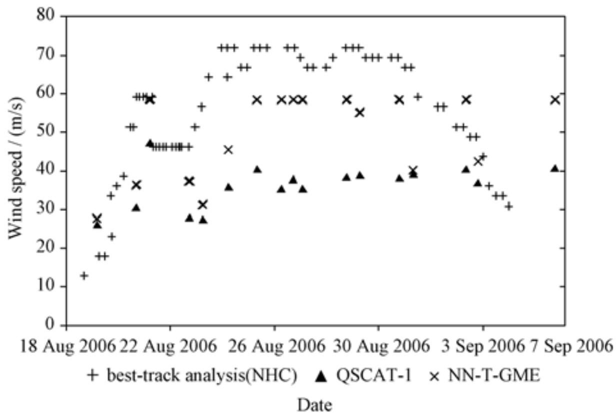

Fig. 10 QSCAT-1, NN-T-GMF and NHC typhoon intensity change for Typhoon Ioke

6 CONCLUSION

This paper developes a method to retrieve the typhoon intensity and location of the typhoon center from the QuikSCAT. In the wind vector retrieval process, the Holland's typhoon model is employed in the process of ambiguity removal to correct the wind direction error caused by the failure of CMF around the eye wall, which is probably induced by the present of rain. Also, a high wind GMF NN-T-GMF is used as a replacement of the existing GMF QSCAT-1 in the wind field retrieval process, so that the bias induced by the inaccurate of the GMF at high winds can be reduced. Once the wind field of typhoon is retrieved, the typhoon intensity can be derived by searching the maximum of the wind speed where the typhoon is present. The method to derive the location of typhoon center makes use of the knowledge of typical structure of wind field for mature typhoon, so that the location of the typhoon center can be extracted according to QuikSCAT wind direction, wind speed or the σ^0 respectively. Based on this method, the track and changes of typhoon intensity for typhoon Ioke and Kaemi are extracted. Comparing to the best-track analysis result form National Hurricane Center, the accuracy of the results of the typhoon tracking and typhoon intensity change from QuikSCAT are acceptable, indicating that QuikSCAT can provide an effective way to observe and track typhoons.

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QuikSCAT 在台风监测中的应用

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摘　要： 利用成熟发展的台风自身在风向上的涡旋型特征和风眼处风速相对周围较低的特征，分别采用搜索 QuikSCAT 反演风向的涡旋中心，风速或后向散射系数的台风中心区域在局部最小值点的方法定位获得了台风中心位置信息。在风矢量反演过程中采用 QSCAT-1 模型、借助 Holland 的台风模式，修正了反演过程中的风向误差，提高了台风中心定位的准确性。同时，将该方法应用到对台风路径和强度监测中，利用 QuikSCAT 对台风的连续观测资料分析得出台风强度和路径信息，其中台风路径结果与美国国家飓风中心(NHC)通过最佳路径分析得到的台风路径结果基本一致，但在台风强度结果上存在较大误差。为提高台风强度监测精度，在反演过程中采用大风地球物理模型 NN-T-GMF 代替 QSCAT-1 模型，使台风强度监测结果精度提高。结果表明, QuikSCAT 可以有效监测海上台风路径和强度发展，为进一步推断台风的强度发展和移动趋势提供帮助。

关键词： QuikSCAT，反演，台风监测，台风路径

中图分类号： TP79/X43　　　　**文献标识码：** A

1 引　言

热带气旋是一种生成在热带洋面上，活动于热带和副热带洋面、岛屿和陆地的气旋性低压环流。最大风力达 12 级及以上(风速>32.7m/s)者，称为台风或飓风。它来临时，常带来狂风、暴雨，在海面上引起巨浪和风暴潮。给海上活动与人类生命带来严重的危害。据统计，全球每年至少产生 80 多个风力达 8 级以上的热带气旋，历史上造成死亡人数达 10 万以上的台风灾难就有 8 次(Elsberry, 1994)。中国是世界上受台风影响最严重的国家之一。因此，对台风路径、强度的监测和预报对于保障人的生命财产安全，减小经济损失具有重要意义。

星载微波散射计通过测量海面后向散射系数间接测量海面风场，它具有大覆盖面积，可连续观测的特点，同时它特有的全天候观测能力和不受云影响等特性，使得其在极端天气条件如台风条件下的应用具有其他类型传感器不可比拟的优越性。微波散射计观测资料可同化到数值气象预报模式中，同时也可为提高台风模型精度和验证模型提供实测数据(Bender 等, 1993)。目前已有多个星载散射计投入业务化运行，其中美国于 1999 年发射的 QuikSCAT 是应用最为成功的微波散射计之一，其风矢量单元设计的分辨率为 25km×25km(Lungu，2001)，可以反映出中尺度天气系统台风的细节信息，为台风强度和路径监测提供有力手段。

2 QuikSCAT 风矢量反演流程

美国于 1999 年发射了 QuikSCAT 卫星，其有效载荷为 SeaWinds 微波散射计。该散射计工作在 13.4GHz，可测量海面后向散射系数。Ku 波段的海面后向散射系数对于海面风矢量的变化较为敏感，它们之间的联系通常可用地球物理模型(GMF)描述。通过对海面后向散射系数的测量，可以反演得出海面风矢量。QuikSCAT 采用内外两个波束的圆锥

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扫描方式，其中内波束采用水平极化方式，入射角为 46°；外波束采用垂直极化方式，入射角为 54°。随着卫星的运动，风矢量单元依次被外波束前视、内波束前视、内波束后视、外波束后视观测，获得至少 4 个不同方位角或入射角的后向散射系数测量结果。风矢量单元设计的分辨率为 25km×25km，内波束覆盖范围为 1400km，外波束为 1800km，一天可覆盖全球大部分海域，在部分区域可获得 2 次/d (升轨和降轨)或者更多的观测结果(Lungu, 2001)。

通过地球物理模型建立的后向散射系数与海面风矢量之间的关系，可从散射计测得的后向散射系数反演得出海面风矢量。由于地球物理模型函数的非线性特征以及散射计的各种测量噪声增加了反演问题的非线性，使得风矢量反演不能采用对模型直接求解的方式。风矢量反演算法主要是通过最大似然法等利用地球物理模型函数以及不同方位角的海面风矢量单元后向散射系数测量结果反演海面风矢量解。由于地球物理模型函数在风向上的二阶调和性质，风矢量反演算法一般会获得多个风矢量解。通过风矢量多解消除算法可从一系列的多解风矢量中选出唯一的风矢量“真解”。本文采用图 1 的反演流程从 QuikSCAT 后向散射系数测量中提取风矢量信息，其中地球物理模型采用 QSCAT-1 模型(Freilich，2000)，反演算法采用最大似然法(Chi & Li，1988)，风矢量多解消除采用圆中数滤波算法(Schultz, 1990)。在极端天气条件如台风情况下，多伴随有强降雨的影响，使得反演得出的风矢量在风眼附近的风向整体偏向于垂直于卫星运行轨迹方向(Halterman & Long, 2006)，导致在风眼附近区域圆中数滤波失效，使得最终得到的风向与实际情况相偏离。为解决这个问题，在风矢量多解去除过程中引入 Holland 的台风模式(Holland，1980；Yueh 等，2001；Yueh 等，2003)，在风眼附近区域从风矢量多解中选择风向与 Holland 的台风模式预测的风向最为接近的风矢量作为“真解”。

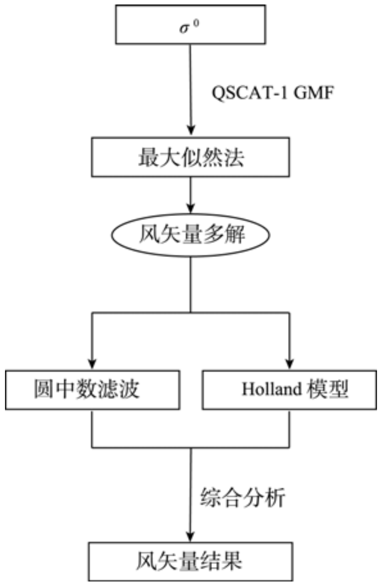

图 1 QuikSCAT 台风反演流程图

利用图 1 流程对 2006-08-30 轨道号为 37474 的 QuikSCAT 对台风 Ioke 的一次观测结果进行反演，所得风矢量如图 2、图 3。其中图 2(a)为仅采用圆中数滤波得到的场，可以看出，在黑色线框内的风向出现明显的偏差。通过在风眼附近区域选择风向与 Holland 的台风模式预测的风向最为接近的风矢量作为“真解”，得出的结果如图 2(b)。可以看出，黑色线框内的风向偏差已经得到修正，风向呈现出明显的涡旋状特征，有助于对台风中心的定位。

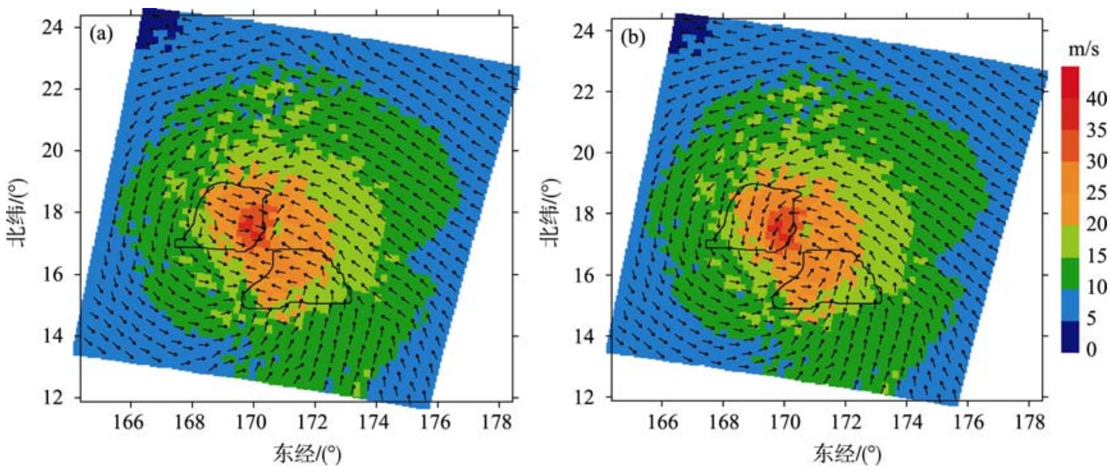

图 2 圆中数滤波得出的风场(a)和引入 Holland 的台风模式去除风矢量多解(b)
(2006-08-30 06:50(世界时)QSCAT 轨道号 37474)

3 台风强度的确定和台风中心的定位

通过 QuikSCAT 在台风发生海域测量获得的后向散射系数，可以反演得出台风风场，为台风监测提供重要的观测手段。由于台风为中尺度天气事件，QuikSCAT 分辨率为 25km，可以反映出台风的一些细节信息。

3.1 台风强度的确定

台风强度的一个重要指标是台风能维持的最大风速。由于散射计的测风能力，使其对于台风强度的监测成为可能。取 QuikSCAT 在台风发生区域反演获得风速的最大值来表征台风在 QuikSCAT 观测时刻的强度,即首先通过上节中的风矢量反演流程从 QuikSCAT 后向散射系数测量结果反演获得台风发生区域的风场，再取该区域风速的最大值作为台风强度。

3.2 台风中心的确定

通过分析 QuikSCAT 对台风的观测结果，在获得台风强度的同时，还可确定台风中心的位置。其定位精度虽不如可见光遥感，但是 QuikSCAT 全天候的工作能力，可弥补可见光遥感夜间无法工作的缺陷，为台风中心定位提供有效补充。相对于普通天气过程，台风在结构上具有明显的特征：台风的风场结构具有气旋式涡旋特征；以台风眼为中心，等距离半径上的台风风速变化不大，风向基本沿等距离圆弧切线方向做准均匀变化。因受地球旋转效应的影响，台风风向在圆弧切线的基础上具有一定的内旋角度(Elsberry，1994)。根据台风的这些结构特征，可从 QuikSCAT 反演得出台风风场或者直接从后向散射系数信息获得台风中心所在的位置。即，(1) 从风向推断出台风中心所在的位置；台风的风场结构具有气旋式涡旋特征，涡旋状分布风向的中心，对应台风中心所在的位置。(2) 通过风速的分布推断台风中心所在的位置；在风眼区风弱、干暖、少云。围绕着眼区，有一环状的最大风速区，平均宽度为 8－50km。通过搜索台风发生区域风速的局部最小值，可以得出台风中心所在的位置。 (3) 通过后向散射系数信息直接获取台风中心所在的位置；原理跟(2)类似。因为在方位角变化不大的条件下，风速越强，对应的后向散射系数越强。所以在风眼处的后向散射系数远低于围绕着风眼大风区的后向散射系数。通过搜索后向散射系数的局部最小值，可以得出台风中心所在的位置。

图 3 通过分析 QuikSCAT 于 2006-09-03 对台风 Ioke 的观测结果定位得出台风中心位置。其中图 3(a)为 QuikSCAT 反演得到的台风风向，图中风向呈现出明显的涡旋特征，通过目视判别可确定涡旋中心的位置，在图中用黑色箭头标记，它对应于台风中心。图 3(b)为对 QuikSCAT 观测资料反演得到的台风风速分布，在图中的大风区域内有明显的极小值出现，该极小值所在的位置对应台风中心的位置，通过目视可判别其位置，在图标记为黑色箭头所指位置。图 3(c)分别为 QuikSCAT 在内波束后视观测条件下观测到的后向散射系数的分布，在后向散射系数取值较大的区域内，有明显的极小值出现，通过目视判别同样可确定其位置，该位置对应台风中心所在的位置。在通常情况下，通过 QuikSCAT 风向、风速、后向散射系数分布分析获得台风中心位置接近。由于受降雨等因素的影响，通过风向与风速确定的台风中心位置有可能出现不重合的情况，且风速的分布在大风区域可能出现多个极小值。在这种情况下，以风向确定的台风中心为圆心，4 个风矢量单元长度(即 100km)为半径的范围内，选取与风向确定的台风中心位置最为接近的风速极小值点

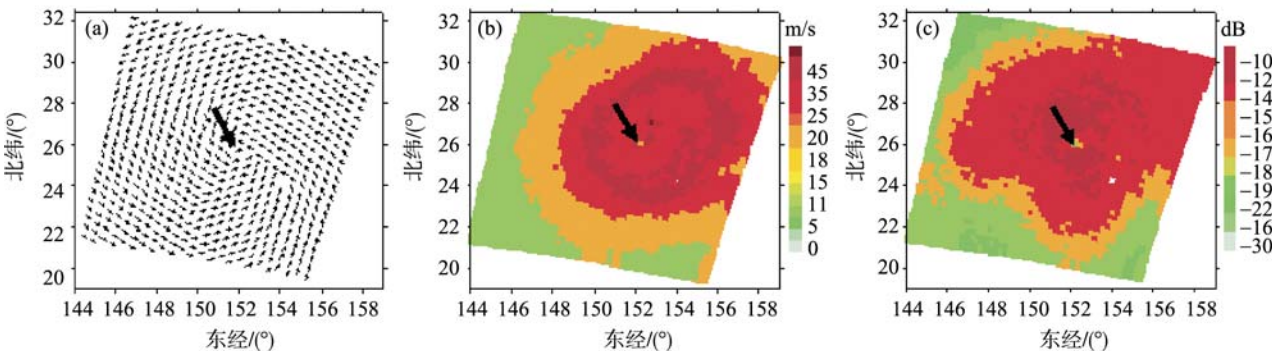

图 3 台风中心的确定

(a) 通过分析风向; (b)通过分析风速; (c)通过分析 σ^0

所在位置作为台风中心的位置。若在该范围内无明显风速极小值出现，则以风向确定的台风中心作为台风中心最终定位结果。由于后向散射系数确定的台风中心多与风速确定的台风中心重合，在后面的分析中，台风中心的定位采用通过风向与风速分析得出的结果。

4 台风强度发展和路径监测

从上节的分析可以看出，利用 QuikSCAT 对台风的单次观测结果，可得出台风在 QuikSCAT 观测时刻的强度信息，并可同时对台风中心定位。由于 QuikSCAT 具有全球覆盖能力，一天可覆盖全球大部分海域，加上其可连续观测的特点，对特定区域每天可获得 1—2 轨甚至更多的观测数据，因此 QuikSCAT 对台风的连续观测结果可为台风强度和路径监测提供一种有效途径。

从 2006 年 8 月 19 日到 9 月 6 日，QuikSCAT 共 36 次观测到台风 Ioke，其中有 24 次观测到了台风中心，17 次较为完整地观测到了整个台风结构。QuikSCAT 对台风的每次完整观测结果，利用上节中介绍的方法，分析得出台风在各 QuikSCAT 观测时刻的强度，并获得了台风中心定位信息，结果如图 4，其中蓝色标记所在的位置为分析定位的台风中心位置。按 QuikSCAT 观测时间的先后顺序排列各次观测结果对应的台风强度和中心位置，通过插值方法，可获得台风 Ioke 路径和强度发展的信息。其中图 5(a)为 Ioke 的路径，图 5(b)为 Ioke 的强度发展。同理，QuikSCAT 对台风 Kaemi 共有 7 次较为完整的观测记录(图 6)，采用同样的方法得到如图 7(a)所示的路径信息和图 7(b)所示的强度信息。可以看出，通过本文的方法对 QuikSCAT 对台风的连续观测资料分析，得到的台风路径与美国国家飓风中心(NHC)通过最佳路径分析结果基本一致。需要注意

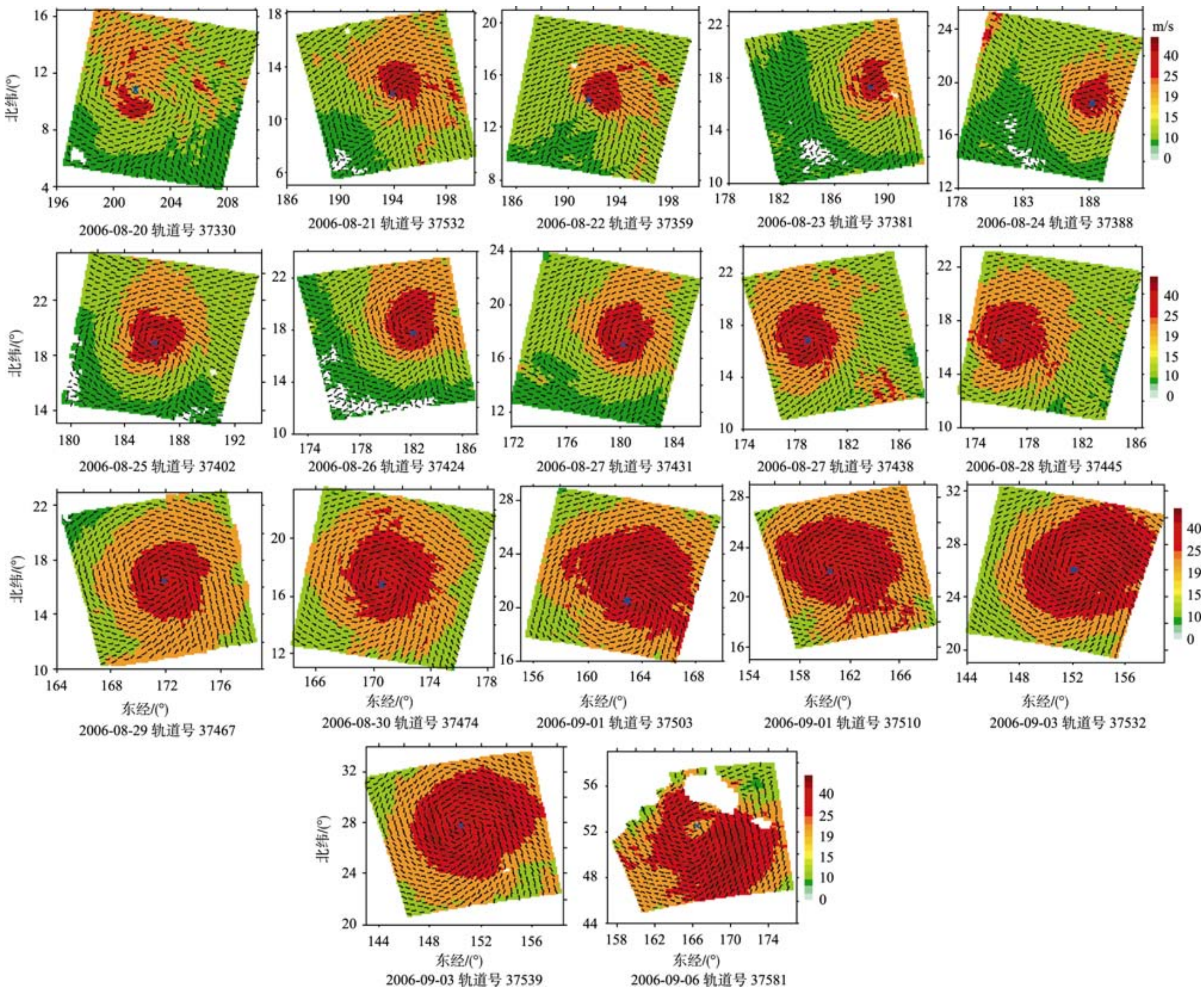

图 4 QuikSCAT 对台风 Ioke 的 17 次完整观测(“×”表示台风中心所在的位置)

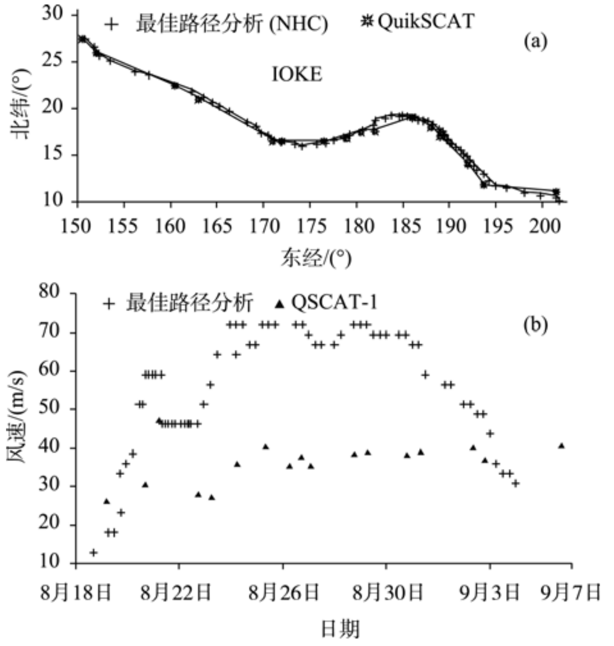

图 5　2006 年台风 Ioke 路径(a)和强度发展(b)

的是在对 Kaemi 的观测中, 近岸部分由于陆地对散射计回波的污染, 使得风矢量信息部分缺失, 通过本文的方法未能获得台风强度及位置信息, 说明在近岸部分, 这种方法将会受到一定限制。对台风强度的监测与 NHC 的结果还有较大的偏差, 对 QuikSCAT 观测资料反演获得的台风强度普遍偏低, 原因如下: 反演过程中采用的 QSCAT-1 模型为 QuikSCAT 测得的后向散射系数与数值气象预报模式 NCEP 给出的同步风矢量数据通过经验拟合得出的半经验模型, 由于 NCEP 在高风速条件下精度降低, 使经验拟合得出的 QSCAT-1 模型精度在高风速条件下也相应降低。在大风条件下, QSCAT-1 通常高估了后向散射系数, 其结果是使反演得出的风速偏低(Yueh 等, 2001, 2003)。故反演过程中的一部分误差是由 QSCAT-1 模型的精度造成的; 另外台风过程中伴随的强降雨也会对风速反演带来一定的误差。降雨对后向散射系数的影响来自雨滴的体散射, 雨滴冲击海面造成海面粗糙度的改变和雨水对在其中传播的电磁波的衰减作用, 降雨总的效果是这 3 个效果的叠加, 通常情况下, 降雨总的效果是使后向散射系数减小, 从而使得反演得出的风矢量出现偏低的效果; 由于 QuikSCAT 的风矢量单元(分辨率)一般为 25km×25km, 它所测得的风矢量为在风矢量单元内的平均值, 而浮标或 NHC 给出的风速对应为一个点的值。在台风条件下, 风场多具有很大的梯度, 在风矢量单元内, 风速通常变化很大, 特别是在风眼壁附近, 取风矢量单元的平均值来表示单点对应的风速, 通常会使得风速出现偏低的结果(Yueh 等, 2001, 2003; Zeng & Brown, 1998; Lecomte & Saavedra de Miguel, 1998)。通过 QSCAT-1 反演得到的台风强度, 存在一定的误差, 但在发展趋势上与 NHC 分析所得结果相一致。可以认为, 利用 QuikSCAT 对台风的连续观测来监测台风强度和路径是可行的。

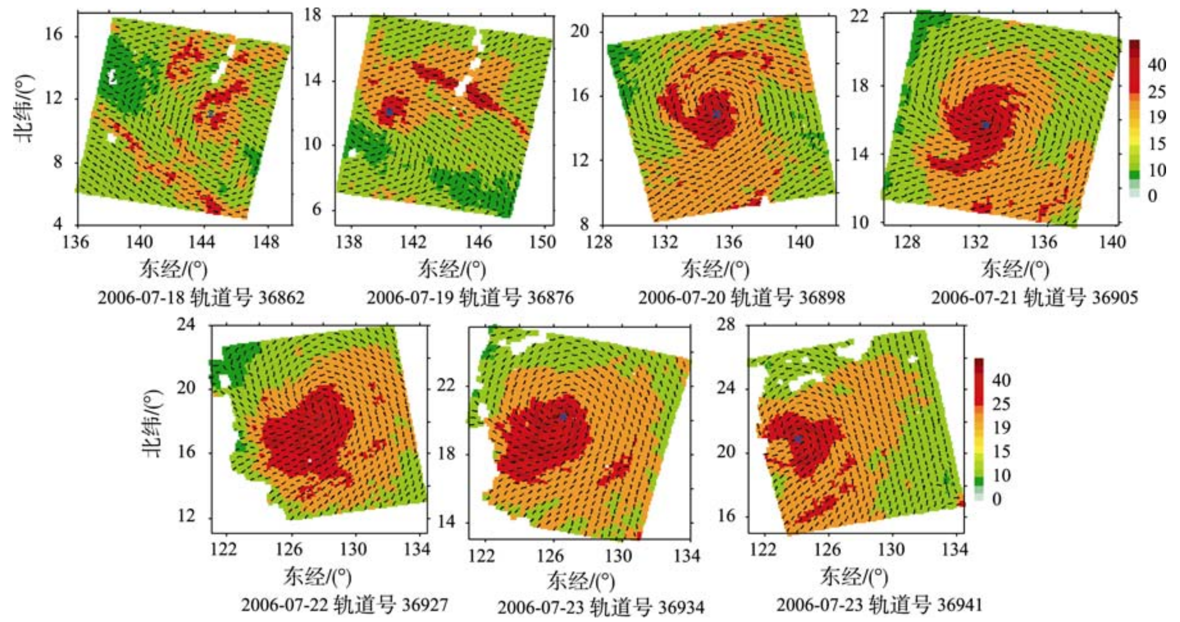

图 6　QuikSCAT 对 Kaemi 的 7 次完整观测

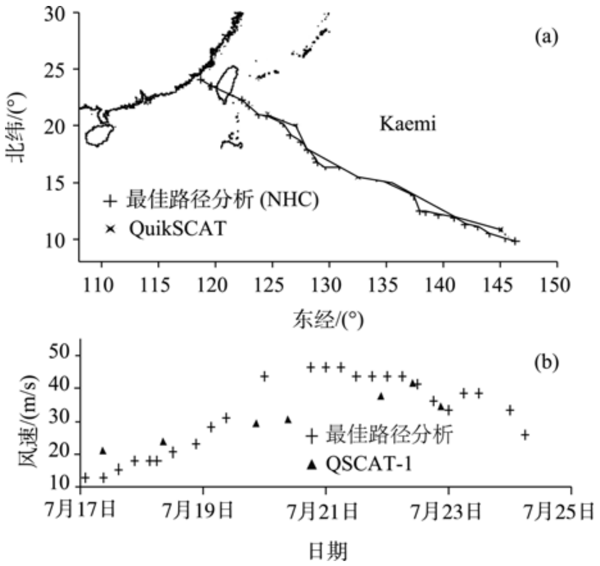

图 7 2006 年 Kaemi 路径(a)和强度发展(b)

5 台风强度反演结果的校正

上一节利用 QuikSCAT 对台风的连续观测资料对台风路径的监测取得了较好的效果，但台风强度的结果还存在较大误差，由于反演过程中所采用的地球物理模型 QSCAT-1 在高风速部分精度降低以及降雨等因素的影响，在部分样点台风强度的误差超过了 50%。本节将采用大风模型 NN-T-GMF 替代现有地球物理模型 QSCAT-1,以校正由于地球物理模型高风速部分精度不高而引起的误差。NN-T-GMF 是对现有地球物理模型 QSCAT-1 的高风速部分进行修正后得到的大风地球物理模型，在高风速部分采用辐射计 SSM/I 测得的风速与散射计同步测量获得的后向散射系数，散射计反演所得的风向建立训练样本，采用神经网络方法训练得到的模型，对低风速部分则采用 QSCAT-1 模型，采用分段函数的形式将两者统一，并在 16—20m/s 风速区间通过线性插值的方法，使最终得到的地球物理模型函数所预测的后向散射系数对风速的变化保持连续、平滑。图 8 为 NN-T-GMF 预测的后向散射系数与 QSCAT-1 模型预测的后向散射系数随风速变化的关系，方位角为顺风方向。图 9 为 NN-T-GMF 预测的后向散射系数随方位角变化的情况。从图中可以看出，NN-T-GMF 对 QSCAT-1 在高风速区对后向散射系数预测偏高的缺陷有明显的校正。

应用 NN-T-GMF，对上节中得到的台风 Ioke 强度监测结果进行校正，所得结果如图 10。通过 NN-T-GMF 得到的台风强度更接近于 NHC 通过最佳路径分析得出的结果，但还存在一定的误差。这是

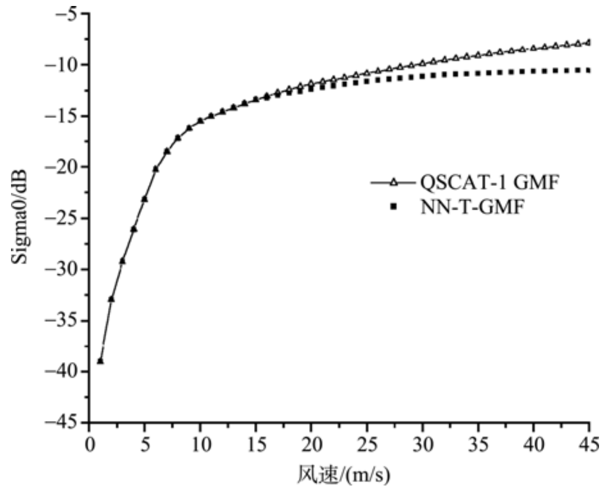

图 8 NN-T-GMF (QSCAT-1)中 σ_0 与风速的关系

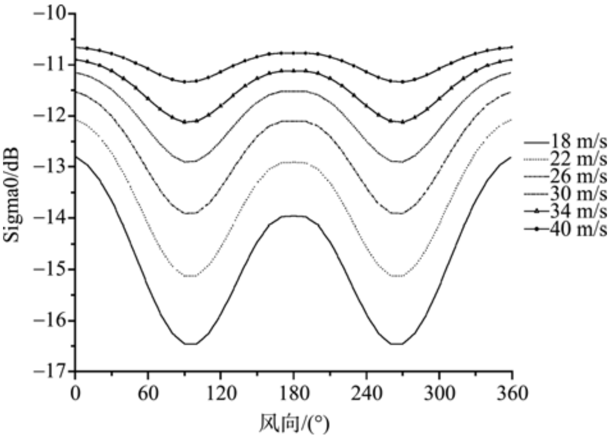

图 9 NN-T-GMF 中 σ_0 与风向的关系

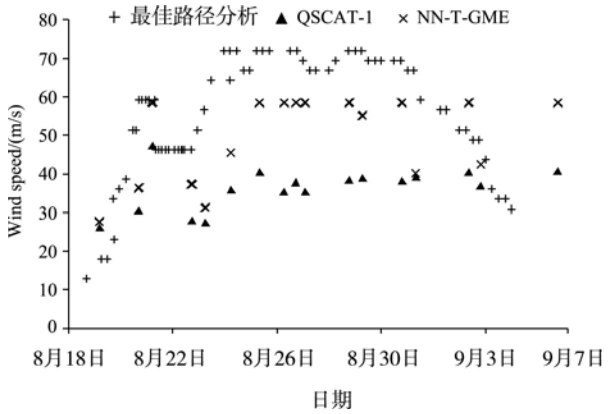

图 10 采用 NN-T-GMF 改进后的台风强度发展(2006 年)

因为在反演过程中，并未考虑降雨对风速反演带来的影响，要得到更为精确的强度监测结果，需要对降雨对后向散射系数信号的影响做进一步校正。

6 结 论

本文通过分析 QuikSCAT 对台风的观测结果，

得出了台风在 QuikSCAT 观测时刻的强度和台风中心的位置。其中台风强度取 QuikSCAT 观测结果反演所得风速的最大值，而对台风中心的确定则利用台风自身的结构特征，分别采用搜索 QuikSCAT 反演风向的涡旋中心，风速或后向散射系数在台风中心处局部最小点作为台风中心所在的位置。在风矢量反演过程中，本文借助 Holland 的台风模式，修正了风矢量反演过程中由于降雨等因素引起的风向误差，提高了台风中心定位的准确性，同时利用大风模型 NN-T-GMF 替代 QSCAT-1 模型，校正了由于地球物理模型在大风条件下精度降低所带来的误差。本文将这种方法应用到对台风路径，强度监测当中，利用 QuikSCAT 对台风的连续观测资料，得出了 Ioke 和 Kaemi 的强度发展和路径，结果与 NHC 通过最佳路径分析得到的结果进行比较，两者基本一致。结果表明：尽管存在一定误差，QuikSCAT 可以有效监测海上台风路径和强度发展，可为进一步推断台风的发展和移动趋势提供帮助。考虑到陆地对散射计回波的污染，这种方法在近岸将会受到一定限制。同时，为提高对台风强度监测的准确性，在进一步的分析中需要考虑降雨对回波强度的影响。

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