Observing-Systems Simulation Experiments for Tropical Cyclone Initialization Based on Four-Dimensional Variational Data Assimilation

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1. Introduction

As the conventional observations usually have much less degree of freedom than the model does, the 4-dimensional variational (4D- VAR) data assimilation has become one of the most advanced processes to combine the observational data with the model in a way so that the initial conditions are consistent to the model dynamics and physics. Based on 4D-VAR, a bogus data assimilation (BDA) method has been developed recently by Zou and Xiao (2000) to improve the initial condition for tropical cyclone simulation. Given a specified sea level pressure (SLP) distribution, the BDA process can lead to a better initial typhoon structure. Zou and Xiao (2000) showed that with the better initialization procedure, the simulation of the track and intensity of Hurricane Felix (1995) are also improved.

Xiao et al. (2000) expanded their work by assimilating the wind field data into the model. Using the observed data, such as the minimum SLP, and/or the maximum wind speed and radius of maximum wind speed, and based on the presumed idealized distribution of the SLP and/or 3-dimensional wind field structure, a dynamically consistent initial structure is produced. By comparing the simulation with different data used for BDA, their result indicates that the assimilation of only the pressure field is more effective than the assimilation of only the wind field. However, using a similar approach, Pu and Braun (2001) showed that the assimilation of wind field would be more useful than the assimilation of the pressure field, while assimilating both the wind and pressure fields would provide the best results.

These studies present a useful new direction for tropical cyclone initialization using BDA. Nevertheless, important questions remain to be answered: (1) what are the most critical parameters for BDA; and (2) what can be done to improve the existing BDA procedures. The primary motivation of this study is to clarify and investigate the related questions of the BDA method mentioned above. In this study, we performed a set of Observing-Systems Simulation Experiments (OSSE's) to address the above questions on BDA.

2. Experiment design

We first construct the original reference data by running the Penn State/NCAR mesoscale model (MM5) with relatively simple physics [Grell cumulus parameterization (1993); the Blackadar PBL scheme (1979); the atmospheric radiation scheme of Dudhia (1993); the simple ice microphysics (Dudhia 1989)] in two nests (two-way interactive) at 90- and 30-km resolutions for Typhoon Zane for 72h from 1200 UTC September 27 to 1200 UTC September 30, 1996. In order to allow time for the model to generate realistic hurricane structure, we start the OSSE's at 12h forecast of the original reference data, and runs the MM5 forward model in the single-mesh inner nest for 60h from 0000 UTC September 28 to 1200 UTC September 30. The result of this 60h simulation is regarded as the best initial condition (BIC), and is used as the model's true atmosphere (e.g., "nature" run) for further comparison.

In order to assess the impact of different variables on BDA, we first degraded the quality of the inner-nest reference data by using a successive smoothing operator to create the degraded reference datathat has a quality roughly equivalent to that of a global analysis. Based on the degraded reference data, a 60h simulation [starting at 0000 UTC September 28 (t = 0h for OSSE's) with the same model set-up as the natural run] is carried out to produce a set of data (denoted as FEC) that can be regarded as the lower bound of the simulation, and serves as our control (no assimilation) experiment.

Consistent with the above 60h simulation, the inner-nest domain is selected for data assimilation experiments using the MM5 Adjoint Modeling System (MM5- 4DVAR) as described in Zou et al. (1997). Note that the model physics used in the adjoint system are slightly different from those used in the forward integration model, including the use of Kuo cumulus parameterization and simple bulk-aerodynamic PBL scheme, and no radiation parameterization.

2.1 Data assimilation

(a) Specified axisymmetric typhoon vortex

One important step in the present BDA process is to assume a hypothetic typhoon vortex structure. In this study, we use the vortex structure follows that of Xiao et al. (2000).

(b) Data from BIC

We also select 3-dimensional u, v, t, q, w, p' variables within the domain simulated by BIC as data source for assimilation.

2.2 Experiment design

A series of OSSE's have been conducted to assess the potential impact of different parameters on BDA. By taking different observed data for BDA, each experiment produces its own initial condition and the ensuing 60h simulation to examine the track and intensity of the simulation.

(a) BIC/BIC, FEC/BIC

BIC/FEC (FEC/BIC) represents an experiment similar to BIC (FEC) while taking the new reference data (the original reference data) as the lateral boundary conditions during the model integration. The purpose of these two experiments is to indicate the impact of boundary conditions on the simulation.

(b) BIC_V, BIC_P, BIC_VP, BIC_V1, BIC_V3

These five experiments are performed by replacing the FEC data within the whole domain by the data from BIC, and then rerun the forward model for 60h (note that for all sensitivity experiments the degraded reference data are used as the lateral boundary conditions). The purpose of these experiments is to investigate the impact of different parameters on the storm initialization, as well as the subsequent forecast, through a direct data-replacing process.

BIC_V (BIC_ P; BIC_VP) represents a simulation started with an initial condition after the u and v (p'; u, v, and p') of FEC have been replaced by those from BIC; In BIC_V1 only the lowest-level (σ = 0.98) u and v of BIC is used to mimic the situation when only the surface wind is observed (such as from the QuickSCAT data); BIC_V3 is similar to BIC_V1 while the u, v of BIC in three levels (σ = 0.98, 0.625, 0.225) are used to simulate the impact of the data that may be obtained from the surface (QuickSCAT) and satellite cloud-drift wind at three different levels.

(c) DA_BIC_V, DA_BIC_P, DA_BIC_VP, DA_BIC_ALL, DA_BIC_V1, DA_BIC_V3

The experiments are similar to the above experiments (b) except that the five experiments are performed by assimilating different data from BIC into the control experiment (FEC) through the BDA with a 30-minute assimilation window to create the new initial condition, and then runs the forward model for 60h. The comparison of results from experiments (b) and (c) can indicate the relative strength of BDA and direct data replacement. For DA_BIC_ALL, all the variables (u, v, t, q, w, and p') in BIC are assimilated.

(d) DA_SPC_VP, DA_SPC_V, DA_SPC_P

These three experiments assimilate a specified meteorological field of an axisymmetric vortex using BDA. DA_SPC_VP (DA_SPC_V; DA_SPC_P) assimilates the 3-dimensional axisymmetric u, v and p' data (u and v; p') defined in Xiao et al. (2000). The comparison between these experiments with experiments (c) will highlight the difference between the axisymmetric and asymmetric initial vortex and their impact on storm simulation.

(e) DA_R_V, DA_R_P, DA_R_VP, DA_R_ALL

These three experiments are similar to experiments in (c), except that only the BIC data within a 600-km circular area surrounding the storm are assimilated through BDA (i.e., the BIC data in the inner 300-km area are used; no BIC data are considered outside the 600-km circle; a linear transition zone is present between 300- and 600-km radius). Such experiments tend to show the relative importance of data within the storm core as compared to data in the storm environment.

3. Results

3.1 Initial vortex structure

Figure 1 shows the west-east cross section, cutting through the storm center, of the potential vorticity (PV; solid line), wind speed (shaded) and temperature (dotted line) of the initial vortex. A much weaker initial vortex is represented by the FEC (Fig. 1a) as compared to the one in BIC (Fig. 1b), where high PV and warm potential temperature air is present in the storm core surrounded by an eyewall with a maximum wind of about 55 m/s on the east flank.

When a specified vortex (DA_SPC_VP) is assimilated (Fig. 1c), a hurricane-like vortex structure is produced, though the specification of an axisymmetric storm structure cannot well represent the asymmetric feature in the storm. Such incorrect specification of initial vortex turns out to affect the storm track, as will be shown in the next section. When the wind and pressure data from the core region of BIC (DA_R_VP) are both assimilated to FEC through BDA, an asymmetric vortex structure (Fig. 1d) consistent with (though not identical to) that of BIC (Fig. 1b) is produced. The slight difference from BIC results from the fact the assimilation process tries to minimize the cost function that contains both the background (i.e., the FEC data) and observation terms. As the background information is also taken into consideration (though at a rather weaker weighting), the assimilated results cannot be identical to the observations used.

If only the pressure field from BIC (DA_R_P) is assimilated, the maximum lower-level wind (Fig. 1e) cannot be recovered. It is not clear why another wind maximum occurs at about 400 mb. On the other hand, by assimilating only the wind field from BIC (DA_R_V), most of the vortex structure (Fig. 1f) similar to DA_R_VP is recovered. This result indicates that the wind field is a relatively more crucial parameter to assimilate as far as the recovery of the initial storm structure is concerned.

When only the 3-level wind field from BIC (BIC_V3) is used to replace FEC, the result (Fig. 1g) shows an inconsistent vortex structure. If BDA is adopted to assimilate the 3-level wind field (DA_BIC_V3), a more vertically coherent vortex (Fig. 1h) shows up with the warm core in the middle layer and the high PV air and strong cyclonic flow in the middle and upper layer. The result indicates that the data assimilation procedure combines the data with the model more effectively than direct replacement, while the three-level wind field is not enough to recover the overall storm structure.

3.2 Results of the simulations

(a) FEC, BIC, BIC/BIC, FEC/BIC

The track of BIC (Fig. 2a) indicates that the storm moves northward in the first 6h, turns north-northwestward until 24h, then stays nearly stationary and loops for 12h before it finally turns eastward. The minimum SLP of BIC (Fig. 2b) remains between 968 and 962 mb during the 60h integration, with the maximum wind (Fig. 2c) ranging between 43 and 49 m/s. The track of FEC (Fig.2a) is very different from BIC. Compared to BIC, the track error of FEC is 215, 150, and 123 km, for 24, 48 and 60h, respectively.

The initial minimum SLP of FEC is 995mb (Fig. 2b), with maximum velocity of 17 m/s, which is much weaker than the storm intensity in BIC. The results indicate that the initial vortex structure and the track and intensity simulation of FEC is very different from those in BIC. Meanwhile, the simulation of BIC (FEC) and BIC/FEC (FEC/BIC) are very much alike (figures not shown), indicating that the impact from the boundary is rather small in this case, and can be ignored.

(b) DA_R_P, DA_R_V, DA_R_VP

Except for the first 6h simulation of DA_R_P, the simulation of tracks (Fig. 2a), minimum central SLP (Fig. 2b) and maximum wind (Fig. 2c) in DA_R_V and DA_R_VP and DA_R_ALL are similar. Compared to BIC, the track error of DA_R_P (DA_R_V; DA_R_VP) is 131 (90; 90), 79 (103; 77) and 103 (150; 102) km, for 24, 48 and 60h, respectively. Comparison experiments shown in Figs. 2a, b and c indicate that the assimilation of wind field within the storm core region can more or less recover the major structure of the initial vortex, as well as the follow-up track and intensity simulation.

For DA_R_V, even though the minimum central SLP is too high at the initial time, then it adjusts to a more reasonable value after a few hours of integration. On the other hand, when only the pressure field is assimilated (DA_R_P), the initial velocity field is totally off the line, and the minimum central SLP fills immediately after the integration starts. We believe that the above finding is related to the geostrophic adjustment process in the tropics, in which the mass field is adjusted to the velocity field. The above result also indicates that DA_R_P is dynamically imbalanced initially, and more adjustment takes place in the first 6h of integration. This improper initial vortex does result in larger track errors of DA_R_P in the first 12h. Even though the track and intensity simulation of DA_R_V at later periods is not very different from that of DA_R_P, it still does not rule out the possibility that for some cases the uncertainty in the initial vortex structure may affect the later track forecast more seriously. Nevertheless, as far as the initial vortex structure is concerned (see Figs. 2b and c), the above result appears partially consistent with Pu and Braun (2001) and shows that information from the velocity field is more important than the pressure field. (c) DA_R_VP, DA_SPC_VP

With the specified axisymmetric initial vortex, the track (Fig. 3a) of DA_SPC_VP is too slow as compared to both BIC and DA_R_VP. Compared to BIC, the track error of DA_SPC_VP is 167, 46 and 60 km, for 24, 48 and 60h, respectively. The results suggest that the 24h forecast track error will increase due to the incorrect specification of an axisymmetric vortex. In other words, the accurate information on the asymmetric vortex of a tropical cyclone is important for its track simulation (Kurihara et al., 1995)

(d) DA_R_VP, DA_BIC_VP

The track (Fig. 3b) of DA_BIC_VP is nearly identical to that of BIC, thus indicating that the assimilation of the wind and pressure fields from BIC into FEC can recover the major information controlling the storm track. On the other hand, when only the wind and pressure fields near the storm core area from BIC are assimilated (DA_R_VP), slightly different track from that of DA_BIC_VP is produced, and the difference increases in the later integration period. Over all, compared to BIC, the track error of DA_BIC_VP is 60, 15 and 52 km, for 24, 48 and 60h, respectively. The above result suggests that the environmental wind and mass information also plays important role in determining the track evolution.

(e) DA_BIC_V, DA_BIC_V1, DA_BIC_V3

Fig. 3c shows the tracks from DA_BIC_V, DA_BIC_V1 and DA_BIC_V3. The comparison highlights the impact from the near-surface wind (DA_BIC_V1) and wind at three different levels (DA_BIC_V3) that may be obtained from satellite-derived cloud-drift wind or QuickSCAT. Compared to BIC, the track error of DA_BIC_V (DA_BIC_V1; DA_BIC_V3) is 83 (167; 146), 54 (104; 123) and 87 (74; 49) km, for 24, 48 and 60h, respectively. The above results indicate that by only improving wind fields at single or certain level(s) can improve the track forecast (such as compared to that of FEC), but its performance is still far from the case when a full vertically resolved wind field is recovered.

4. Summary

Issues on the initialization and simulation of tropical cyclones have been studied here based on OSSE's. In particular, experiments have been carried out to assess (1) what the most critical parameters are for BDA; and (2) what can be done to improve the current BDA procedures. Highlights of our findings are:

- The assimilation of wind field is more effective than the assimilation of pressure field.
- The assimilation of an axisymmetric vortex tends to misrepresent the actual storm and leads to a large track prediction error. This suggests that the inclusion of the asymmetric component of the tropical cyclone vortexis important for vortex initialization.
- Direct replacement of BIC data to FEC may result a vertically incoherent iintial vortex, while BDA is able to recover a more balanced initial vortex structure.
- Assimilation of wind at individual level(s) only slightly improves the initial vortex structure and its track simulation. This suggests that for a better representation of the tropical cyclone and a better storm simulation, comprehensive and more vertical levels of observed data are needed.
- Both the improvement on the initial vortex structure and the environmental wind and mass information affects the track evolution, suggesting the need for near storm, as well as storm environment, observations in order to improve the track simulation.

Over all, this is just a preliminary OSSE study to evaluate the uncertainty of the initial structure of a tropical cyclone and its impact on the storm simulation. It remains to be investigated whether the above findings can be generalized. Therefore, in the future, we will stretch such OSSEs and perform more case studies by assimilating different special observed data (e.g., SSMI-PW; GPS/MET; dropsonde;and radar data, etc...). Such work should provide valuable information on the impact of each data type. Meanwhile, sensitivity tests based on the adjoint system (Zou et al. 1997) will also be performed in the future to identify the most sensitive region and variables that affect the tropical cyclone evolution in numerical models. The results from these studies will provide guidance for developing an optimal observation strategies for typhoons.

Acknowledgement: We thank Yong-Run Guo and Wei Huang at MMM Division of NCAR for their assistance in using the MM5 4DVAR system for this study.

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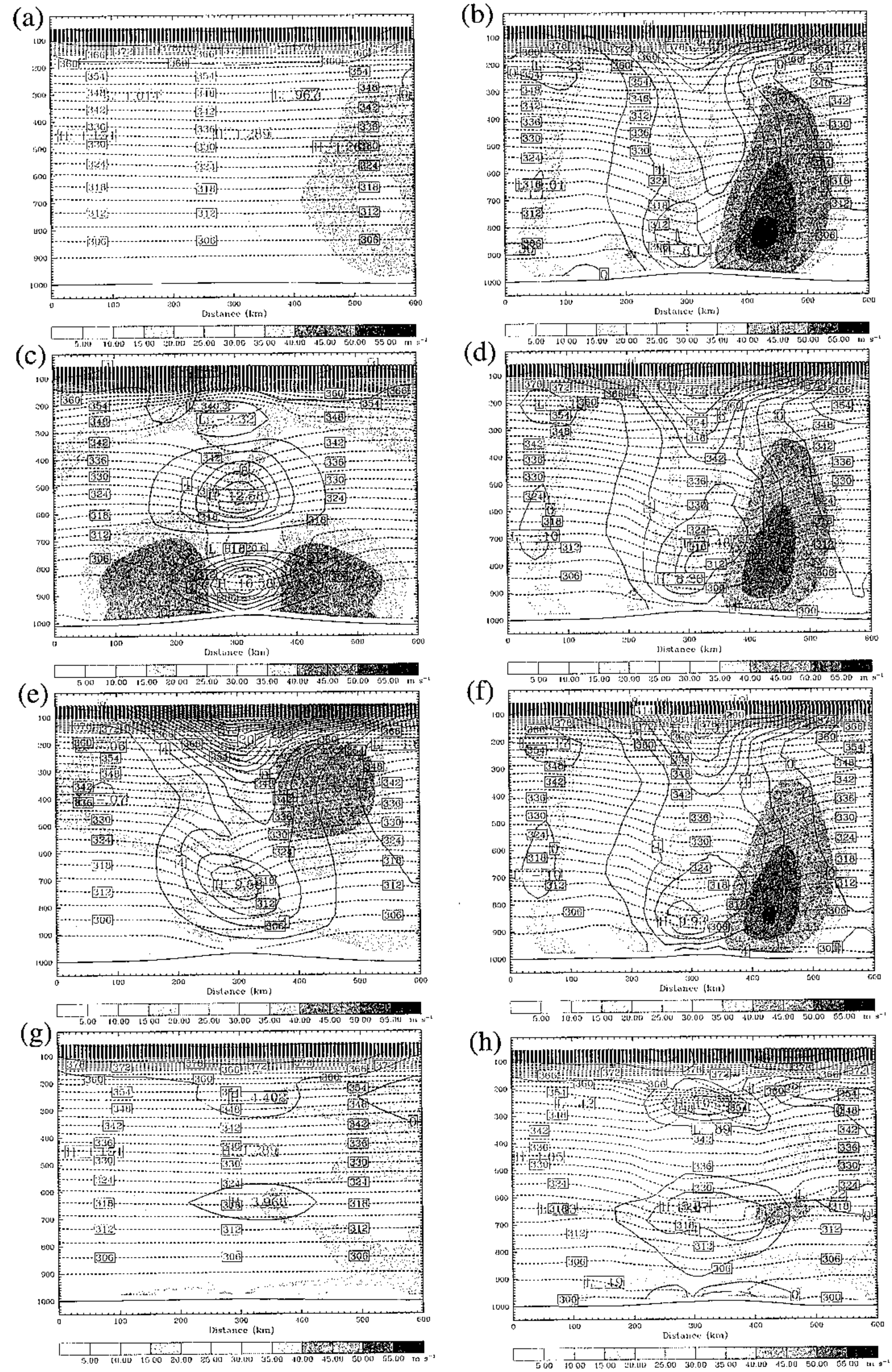

Fig. 1. West-east cross section, cutting through the storm center, of potential vorticity (PVU; solid line), wind speed (m/s; shaded) and potential temperature (K; dotted line) of initial vortex structure: (a) FEC; (b) BIC; (c) DA_SPC_VP; (d) DA_R_VP; (e)DA_R_P; (f) DA_R_V; (g) BIC_V3; (h) DA_BIC_V3

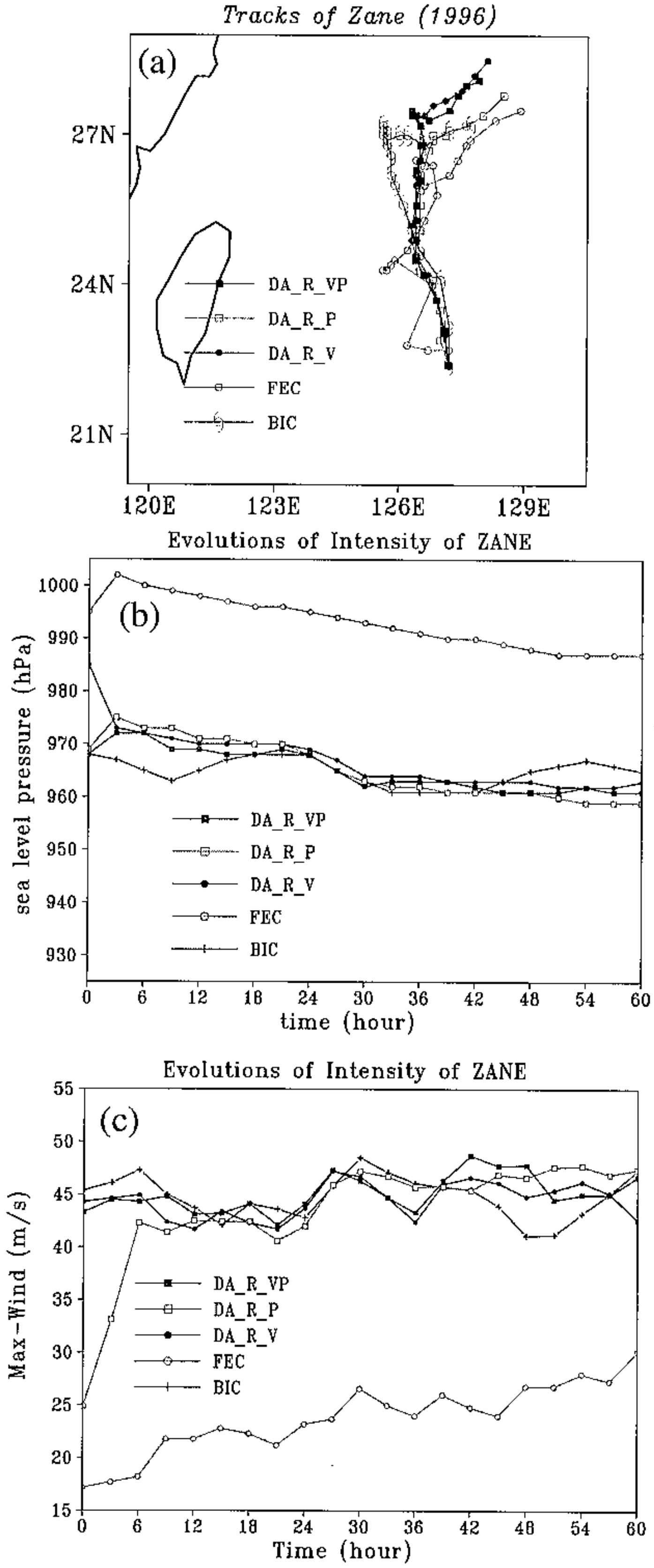

Fig. 2. (a) Tracks of experiments BIC, FEC, DA_R_V, DA_R_P, and DA_R_VP for every 3h; (b) minimum central sea surface pressure; (c) maximum wind at lowest level (sigma=0.98).

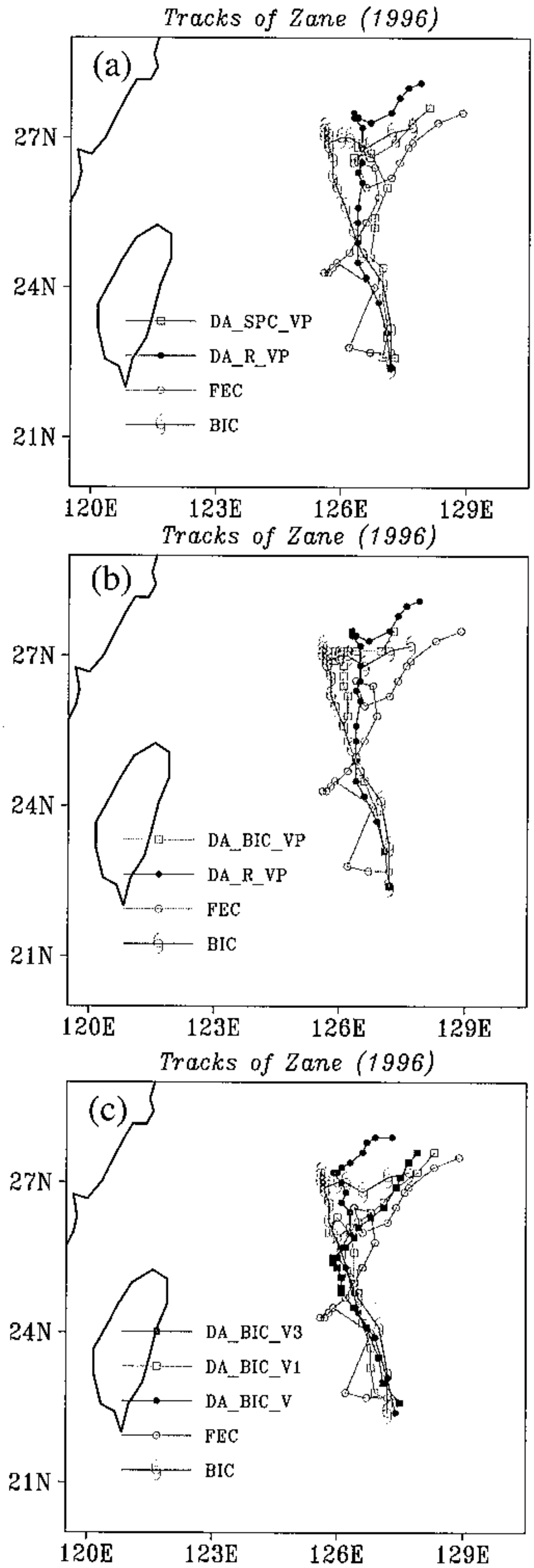

Fig. 3. Tracks of experiments for every 3h: (a) BIC, FEC, DA_R_VP, and DA_SPC_VP; (b) BIC, FEC, DA_R_VP, and DA_BIC_VP; (c) BIC, FEC, DA_BIC_V, DA_BIC_V1, and DA_BIC_V3.