Typhoon Initialization in a Mesoscale Model — Combination of the Bogused Vortex and the Dropwindsonde Data in DOTSTAR

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Abstract

Issues on the initialization and simulation of tropical cyclones by integrating both the dropwindsonde data and the bogused vortex into a mesoscale model have been studied. A method is proposed to combine the dropwindsonde data with the bogused vortex for the tropical cyclone initialization and to improve the track and intensity prediction. Clear positive impact of this proposed method on both the tropical cyclone track and intensity forecasts in a mesoscale model is demonstrated in three cases of typhoons, Meari (2004), Conson (2004) and Megi (2004). The effectiveness of the proposed method in improving the track and intensity forecasts are also demonstrated in the evaluation of all 10 cases of DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region) missions in 2004. This method provides a useful and practical means to improve the operational tropical cyclones prediction with the dropwindsonde observations.

1. Introduction

Over the past 30 years, persistent and steady progress on the track forecasts of tropical cyclone (TC) have been well demonstrated through the improvement of the numerical models, the data assimilation and bogusing systems, the targeted observations, and the satellite and dropwindsonde data available to the forecast systems (Wu et al. 2007a). In particular, considerable progress has been made in the prediction of TC track with numerical models (e.g., Kurihara et al. 1995). Recent works (e.g., Zhang et al. 2002; Wu et al. 2002, 2003) have also displayed the capability of high-resolution non-hydrostatic mesoscale models to realistically simulate the detailed mesoscale structure of a TC. Wang (2001) demonstrated that a high-resolution model has the ability to simulate many aspects of TCs, including the inner core structure, the inner and outer spiral rain bands, and the vortex Rossby waves within the rapidly rotating eyewall.

As a TC spends most of its lifetime over the tropical ocean, where conventional observations have always been sparsely made, the uncertainty and poor quality in initial conditions can lead to monumental errors in the numerical simulation and prediction of TCs. For example, Kurihara et al. (1995) have shown that a better prediction could be achieved by the use of improved initialization procedures that better represent the initial environment, as well as the vortex-scale, flow and mass fields. Wu et al. (2000) showed that numerical simulations of typhoon track and intensity tended to have some systematic biases, which also varied with different initial conditions. Recently, a more advanced TC initialization called bogus data assimilation was proposed (Zou and Xiao 2000) based on the four-dimensional variational data assimilation. Further studies indicated that the bogus data assimilation can improve the TC forecasting and simulation (Zou and Xiao 2000; Pu and Braun 2001; Park and Zou 2004; Wu et al. 2006). These researches clearly pointed out that the improved initial condition is a crucial step toward improving the simulation and prediction of TCs.

Starting from 2003, the research program of "Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region" (DOTSTAR) marks the beginning of an era of tropical cyclones surveillance and targeted observations in the western North Pacific using GPS dropwindsondes (Wu et al. 2005, 2007a, b). Built upon work pioneered by Hurricane Research Division (HRD) to improve tropical cyclone track forecasts, DOTSTAR is a collaboration between researchers from the National Taiwan University and the Central Weather Bureau of Taiwan, in partnership with scientists at HRD, Ncational Centers for Environmental Prediction (NCEP), Japan Meteorological Agency (JMA), and Naval Research Laboratory of U.S. Navy. Three operational global and two regional models were used to evaluate the impact of the dropwindsonde data from DOTSTAR on TC track forecasting (Wu et al. 2007a). Based on the results of 10 missions conducted in 2004, the use of the dropwindsonde data from DOTSTAR on average improve by 22% the 72-h ensemble track forecast of three global models, i.e., the Global Forecasting System (GFS) of NCEP, the Navy Operational Global

Atmospheric Prediction System (NOGAPS) of the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the JMA Global Spectral Model.

Nevertheless, Aberson (2002 and 2003) found very small changes in track forecasts with the Geophysical Fluid Dynamics laboratory (GFDL) hurricane model after the use of the dropwindsodne data. Wu et al. (2007a) also showed that the average improvement of the dropwindsonde data made by DOTSTAR to the 72-h typhoon track prediction in the GFDL hurricane models is an insignificant 3 %. This is likely due to the fact that in the initialization of the GFDL hurricane model, the bogused vortex is added into the initial analysis from NCEP GFS which already contains the dropwindsonde data information. Therefore, the bogused vortex would swamp the dropwindsonde data when they are not consistent to each other. The above results are consistent with Tuleya and Lord (1997) where they showed that the bogusing system retarded the positive impact of dropwindsonde for as long as two days. Wu et al. (2007a) suggested that an optimal way of appropriately combining the dropwindsonde data with the bogused vortex in the mesoscale model needs to be developed in order to further boost the effectiveness of the dropwindsonde data.

In short, it has been shown that either the bogusing of the initial storm vortex (Kurihara et al. 1998) or the assimilation of the dropwindsonde data (Aberson 2004; Wu et al. 2007a) alone can improve the track forecast of the typhoons. However, as noted above, when both issues are taken into account, how to optimally combine the bogused vortex with the dropwindsonde data becomes a critical problem worthy of further study. Therefore, to maximize the use of the dropwindsonde data in the storm environment while inserting a suitable vortex into the numerical model, in this paper we investigate a method to appropriately combine the dropwindsonde data with the bogused vortex during the initialization procedure.

The proposed new method is presented and is experimented in three typhoon cases where the dropwindsonde data show very positive impact. The detailed methodology of combining the dropwindsonde data and the bogused vortex, along with the designed experiments, are described in section 2. Results on the track and intensity forecast and the implications from these experiments are discussed in section 3. The conclusion is shown in section 4.

2. Methodology and experiment design

A single domain with 15-km resolution (301 x 301 grid points; 23 sigma vertical levels) of the latest version (V3.7.2) of the Penn State/NCAR nonhydrostatic mesoscale model (MM5) is adopted to examine the role of the dropwindsonde data and the bogused vortex on the TC forecasts. The model physics include the mixed-phase microphysics scheme (Reisner et al. 1998), the Grell cumulus parameterization scheme (Grell 1993), the MRF planetary boundary layer scheme (Hong and Pan 1996), and the cloud-radiation interaction scheme (Dudhia 1993). The detailed descriptions of the model can be obtained from Grell et al. (1995). Typhoons Meari, Conson and Megi (2004) (Fig. 1), in which cases the global models (such as the NCEP GFS and the FNMOC NOGAPS) show rather positive impact on the 72-h track prediction when 17, 16 and 16 dropwindsonde data corresponding to each storm are assimilated (Wu et al. 2007a). The model's initial and lateral boundary conditions and sea surface temperature are obtained from the denial runs (without using the dropwindsonde data) of the NCEP GFS model.

As practiced in the surveillance observations of the Atlantic TCs using the G-IV aircraft (Aberson and Franklin 1999; Aberson 2004), the DOTSTAR makes the dropwindsonde observations at the targeted areas surrounding the TC (generally more than 300 km away from the storm center). Such kind of special observations on the TC environment in DOTSTAR has shown positive impact on the track forecasts in global models (Wu et al. 2007a). However, since DOTSTAR does not conduct observations in the inner core of the storm, the dropwindsonde data may somewhat improve the analysis of the storm's outer circulation (at about 300-km radius), yet provides very limited impact on the analysis of the inner-core storm structure. Therefore, the impact of the dropwindsonde data to the typhoon intensity prediction is usually limited, and not as effective as that from the implanted bogused vortex (Kurihara et al. 1995).

The purpose of this work is to design a method to suitably combine the dropwindsonde data (in the storm environment) with the implanted bogused vortex (in the inner few hundred-km core of the storm), and to improve both the track and intensity predictions.

To avoid the interference of the dropwindsonde data with the bogused vortex, the strategy is to first bogus the vortex based on the analysis from Joint Typhoon Warning Center (JTWC) (such as the storm location, maximum surface wind, minimum central sea-level pressure, and the radius of the maximum surface wind) within the 200-300-km ring outside which the dropwindsondes are generally deployed. After the bogused vortex is implanted in the model, the 3-dimensional variational data assimilation (3D-VAR) procedure of MM5 (Barker 2004) is used to assimilate the dropwindsonde data obtained from DOTSTAR.

To assess the impact of the dropwindsonde data, as well as the bogused vortex, four different experiments, with and without the dropwindsonde in addition to with and without the bogused vortex (Table 1), are designed. The experiment BNDN represents a forecast in which the initial and boundary conditions are directly interpolated from the denial runs (without using the dropwindsonde data) of the NCEP GFS model, i.e., no bogused vortex is implanted and no dropwindsonde data are assimilated into the model; the experiment BNDY is the same as BNDN, except that the dropwindsonde data are assimilated. The two sets of experiments, BYDN and

BYDY, are similar to BNDN and BNDY, respectively, except that the bogused vortex is implanted in the storm core region at the initial time. As described in the previous paragraph, in the BYDY experiments, the bogused vortex is implanted in the initial storm center first, and then the dropwindsonde data are assimilated into the model based on the 3D-VAR.

The detailed descriptions below discuss the way that the bogused vortex is implanted and the way that dropwindsonde data are assimilated to the model:

a. Implanting the bogused vortex in the inner core region

Due to the lack of observations in the storm region and the limited horizontal resolution for the global analyses available on the reachable public domain (e.g., the ftp site of the NCEP GFS products) in realtime, the global analyses generally do not well resolve the detailed structure of TCs. Therefore, the storm intensity in global analyses is often underestimated. For this reason, when these global analyses are used to drive the mesoscale or hurricane models, a bogused vortex spun up from a separate simulation or prediction is generally adopted in the initialization process in order to obtain a more reasonable initial storm structure (Kurihara et al. 1995; Wu et al. 2002). In the method proposed here, a Rankine vortex using the bogusing scheme of Low-Nam and Davis (2001) with the strength analyzed from the JTWC is implanted 6 h prior to the model's initial time. This simple scheme for bogusing tropical cyclones is part of the MM5 system, which can extract the weak and broad vortices from the global analysis and implant an axisymmetric nonlinear balanced Rankine vortex (according to the actual storm position and the radius of maximum wind and the maximum sustained wind to initialize the model.

Taking Typhoon Meari as an example, the DOTSTAR mission for Meari was conducted at 1200 UTC 25 September, 2006. Since the maximum sustained wind of Meari was estimated at 57 m s-1 (110 knots) by JTWC at 1200 UTC 25 September, 2006, the Rankine vortex, with a 60-km radius of maximum wind and a 65 m s-1 maximum wind was first created at 0600 UTC. Then the 6-h model integration is performed to produce a spun-up asymmetric vortex at 1200 UTC. Following Wu et al. (2002) for obtaining a model-consistent and asymmetric vortex structure, this study replaces the model's three dimensional control variables (pressure perturbation, horizontal and vertical winds, temperature, and water vapor) in the storm core region with the above spun-up vortex as the new initial condition at 1200 UTC for Meari.

Since the dropwindsondes are generally deployed outside the circle 300 to 400 km away from the storm center, to avoid the conflict of the bogused vortex information with the dropwindsonde data, the replacement domain is typically chosen to be inside the region where dropwindsonde data are available. By doing so, the observed dropwindsonde data would not be seriously contaminated by the artificially-bogused vortex. Note that for the case of Meari, as shown in Figs. 1 and 2c, the dropwindsonde data are generally taken at least about 400 km away from the storm center. Therefore, the circular region with a radius of 400 km (R2) is selected for vortex replacement. Specifically, inside the inner 200-km radius (R1, shown as the solid circle in Fig. 2c), the model data are completely replaced by the spun-up vortex, while a linear transition zone between the 200- and 400-km radius is used to smoothly blend the spun-up vortex with the original global analysis.

For the case of Conson, the DOTSTAR mission was conducted at 1200 UTC 8 June, 2004. Since Conson was located close to Luzon at the time of the flight mission, to avoid releasing the dropwindsondes over the landmass of Luzon, the dropwindsondes were deployed at the location about 150 to 200 km from the storm center. Therefore, the implantation of the bogused vortex is within the 150 km-radius region (i.e., R1 = 75 km and R2 = 150 km). And for the Megi case, the R1 and R2 are the same as those of Meari, which are 200 and 400 km, respectively.

b. Assimilating the dropwindsonde data after the bogused vortex implanted

The MM5-3DVAR system was used to assess the impact of the dropwindsonde data on this study. The system is designed for the use in real-time applications and is available to the data assimilation community for general research. Its configuration is based on an incremental formulation, producing a multivariate incremental analysis for pressure, wind, temperature, and relative humidity in the model space. The background error covariance matrix allows for a separate definition of the vertical and horizontal correlation functions. The climatological background error covariances and statistical regression coefficients are estimated via the National Meteorological Center (NMC) method of averaged forecast differences (Parrish and Derber 1992). A detailed description and application of the MM5-3DVAR system can be found in Barker et al. (2004).

The MM5-3DVAR system is used to assimilate the dropwindsonde data in our experiments, e.g. BNDY and BYDY. Note that in BYDY (BNDY), the dropwindsonde data are assimilated into the model's analysis field from the NCEP GFS where the bogused vortex has (has not) been implanted.

3. Results

a. The dropwindsonde data and the bogused vortex impact on the initial analyses

To assess the impact of the dropwindsonde data and the bogused vortex on the model's initial analysis, the difference of the 850-200-hPa deep-layer mean (DLM) (as in Aberson 2002) wind between the model analysis and the observed dropwindsonde data for Typhoon Meari at 1200 UTC 25 September, 2004 are examined (Fig. 2). Regarding the impact of the dropwindsonde data, the comparison of the DLM wind difference in experiments BNDN and BNDY (Figs. 2a, b) shows that when the dropwindsonde data are assimilated into the model, the analysis DLM wind agrees much better with the observed value from the dropwindsonde. In other words, the maximum DLM wind difference decreases from 5.6 to 1.5 m s-1, and the root mean square error (RMSE) among the 17 dropwindsonde soundings and the corresponding analyses interpolated to the sounding locations from the grid points is also reduced from 2.6 to 0.8 m s-1. The above result clearly indicates that the MM5-3DVAR efficiently assimilates the dropwindsonde data into the model, thus positively enhancing the impact of the dropwindsonde data from DOTSTAR. This result is rather consistent with that shown in NCEP GFS model (Wu et al. 2007a).

As to the impact from the implantation of the bogused vortex, as shown in experiment BYDN (Fig. 2c), the inner core structure becomes more intense as compared to the BNDN, i.e., the maximum DLM wind increases from 20 m s-1 (without bogusing) to 55 m s-1 (with bogusing)

Note that as compared to the DLM wind from the dropwindsondes which are located at about 350-400 km from the storm center, the RMSE difference between the BYDN and the dropwindsonde soundings is about 2.3 m s-1. This result indicates that the outer circulation of Meari is still not very accurate, despite that its inner core intensity is better represented by the bogused vortex. When the dropwindsonde data are assimilated after the implantation of the bogused vortex (i.e., BYDY, as in Fig. 2d), not only is a reasonably-represented inner-core structure shown, but also a better analyzed outer circulation is obtained, with the RMSE of the DLM wind difference of 0.8 m s-1.

b. Track evaluation

The best track from JTWC and all 72-h model tracks from the above four experiments initialized at 1200 UTC 25 September, 2004 and the model track position errors verified against the best track of JTWC are shown in Fig. 3. For the experiment without the implantation of the bogused vortex and without the assimilation of the dropwindsonde data (BNDN), the model overpredict the westward movement of Meari in the first 12 h and has a southward track bias during 12-24 h. This significant bias in the first 24-h results in a weak interaction of Meari with the approaching upper mid-latitude trough, and thus leading to an unrealistic track making landfalling in Taiwan at about 36 h. When the dropwindsonde data are assimilated into the model without the bogused vortex (BNDY), despite somewhat smaller westward bias in the first 24h, Meari recurves to the north at about 30 h. Therefore, the track error is reduced to 125, 290, and 574 km for 24, 48, and 72 h, respectively, as compared to that of 392, 706, and 1263 km in the BNDN experiment. This result of significant track error reduction due to the use of the dropwindsonde data has also been demonstrated in NCEP GFS model (Wu et al. 2007a).

Next, regarding the experiments with the implantation of the bogused vortex (BYDN and BYDY), it is clearly shown that in the case of Meari the tracks are greatly improved (especially on the forecast of the recurvature of Meari) when the bogused vortex is added into the model no matter whether or not the dropwindsonde data are used. Meanwhile, when both the bogused vortex is implanted and the dropwindsonde data are assimilated (BYDY), the model is very close to the best track, with the track error of 70, 22, and 134 km at 24, 48, and 72 h, respectively. Results from the above dramatic improvement of the model track indicate that the implantation of the bogused vortex plays a more significant factor than the dropwindsonde data does in improving the track of Meari. However, the combination of both the dropwindsonde data and the bogused vortex to the model leads to the best track forecast for Meari. In all, the above study shows that the proposed method in assimilating the dropwindsonde data after the implantation of the bogused vortex provides a very effective tool to improve the initialization of the TC model and its follow-up forecasts.

c. Intensity evolution

The 72-h intensity forecasts from the above four experiments as compared to the intensity analysis from JTWC of Meari is shown in Fig. 4. First, as compared to the intensity evolution with the JTWC analysis, the intensity in both BNDN and BNDY runs are underestimated by more than 40 hPa in the first 36 h. The intensity in BNDN experiment is still largely underestimated after 36 h while the model storm incorrectly makes landfall in Taiwan at 42 h. On the other hand, after 36 h the BNDY experiment gradually intensifies and matches the analysis of 976 hPa at 72 h by JTWC. In other words, comparison of BNDN and BNDY shows that BNDY has a better intensity prediction at later time due to the improved track (without the unrealistic landfall).

Note that the analysis from the operational global model (such as NCEP GFS) tends to underestimate the storm intensity, as shown in the NCEP global tropospheric final analyses (NFNL) in Fig. 4. Thus when using the global analysis to initialize the mesoscale model (such as MM5 and WRF), the unrepresentatively weak TC intensity at initial time will lead to the under-prediction of the model intensity. When the bogused vortex is implanted to the model (BYDN and BYDY), the problem with the initially-underestimated intensity is relieved, i.e., the overall intensity error in both experiments is reduced to about 20 hPa, an 50% error reduction as compared to those forecasts without bogusing. The improvement on storm intensity forecast allows us to use these numerical models to gain more insight into the dynamics of the inner core (Zhang et al. 2002; Wang 2001; Wu et al. 2003) and the associated rainfall and flooding forecast and simulation when TC makes landfall (Wu et al. 2002).

d. Evaluation of all DOTSTAR cases of the year 2004

Wu et al. (2007a) have shown that the average 6-72-h track error from the operational global model of

NCEP can be reduced by 14% when the dropwindsonde data are assimilated. To understand the overall impact of the above-proposed method, same experiments (i.e., BNDN, BNDY, BYDN, and BYDY) are conducted for all ten DOTSTAR cases of the year 2004.

Figure 5 shows the comparison of the average track errors verified against the best track of JTWC from each experiment. It can be shown that the average 6-72-h track error is reduced by about 30% either with the dropwindsonde data assimilated or with the bogused vortex implanted. When both the dropwindsonde data and bogused vortex are used in the newly-proposed method, the average track error is reduced by 40%. Statistical examination by the paired test with one-sided distribution (Larsen and Marx 1981) for BNDN and BYDY indicates that the track improvement at 6, 42, 48, 60 and 66 h are statistically significant at the 90% confidence level.

Meanwhile, for all ten cases, the evolution of the average intensity error (in terms of the minimal sea level pressure) is also evaluated for forecasts with and without the bogused vortex. For the experiments without the bogused vortex (i.e., BNDN, BNDY), the average intensity error is gradually reduced from 45 hPa initially to 15 hPa at 72 h, since the model vortex is gradually spun up with time. However, for the bogused implanted experiments (i.e., BYDN, BYDY), the average intensity error increases from 15 hPa initially to 25 hPa at 72h, which still under-predicts the storm intensity (Fig. 6). This might be because the current forecast with the 15-km resolution is not fine enough to resolve the realistic typhoon intensity. Nevertheless, it is clear that the average intensity error can be reduced by at least 20 hPa at the first 48 h forecast period. Overall, the statistical examination for BNDN and BYDY shows that improvement of the intensity forecast by the proposed method is statistically significant at the 90% confidence level in the first 48 h.

In all, the substantial track and intensity improvement from the above 10 cases demonstrates the benefit of the proposed method of combining the dropwindsonde data and the bogused vortex to improving the TC forecast in the mesoscale model.

4. Conclusions

A suitable two-step method of combing the dropwindsonde data and bogused vortex has been proposed to improve the initialization and prediction of TCs in the mesoscale numerical model for the DOTSTAR cases over the western North Pacific. First, limited area of the bogused vortex spun up from the previous (6-h) model forecast is implanted in the model at the best-track location and inside of the area where the dropwindsondes are deployed, thus creating an initial condition containing a reasonably-represented TC vortex. Second, the dropwindsonde data are assimilated to the above bogused field by the MM5-3DVAR system. The above two steps would make constructive use of information on both the observed dropwindsonde and the bogused vortex while avoiding their interference.

The proposed method is also applied to all 10 cases of DOTSTAR missions of the year 2004. The results show that the average track and intensity error can be reduced by 40% and 30%, respectively, when both the bogused vortex and the dropwindsonde data are used.

The study outlined above indicates that the proposed method has the potential to improve both of the track and intensity forecast while making use of both the dropwindsonde data and the bogused vortex in the model. Work is ongoing for all real-time cases of the future DOTSTAR program using the newly-developed WRF (Weather and Research Forecasting, Skamarock et al. 2005) model. Moreover, note that more consistency between the bogused vortex and dropwindsonde data may likely be achieved by integrating the bogus data assimilation (BDA) technique (Zou and Xiao 2000; Pu and Braun 2001; Park and Zou 2004; Wu et al. 2006) with the dropwindsonde data by the 4D-VAR system, though this would require much higher computational, cost, which is the reason why we propose the current simple bogused-vortex implementation method for realtime application. Following Wu et al. (2006), we have started to work on this BDA issue and plan to show the new results in the follow-up paper in the future. With the potential to improve the track and intensity forecasts of TCs, this method also provides an opportunity to explore the typhoon dynamics (such as the eyewall and typhoon-terrain interaction problems) of the real-case storms.

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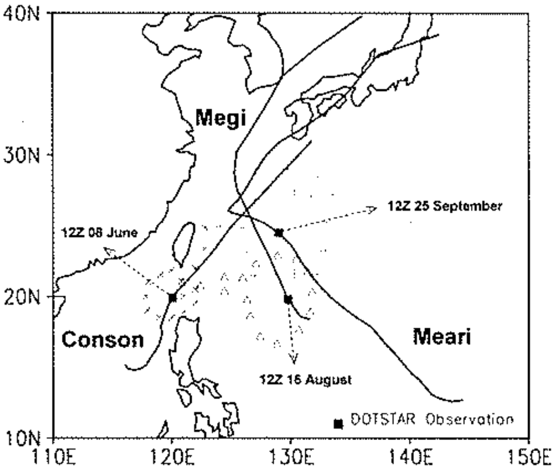


Figure 1. The JTWC best track (indicated with the typhoon symbol for every 12 h) and the deployed locations of the dropwindsondes for Typhoon Conson (denoted as x), Megi (denoted as Δ) and Megi (denoted as +). The symbols, "■" , indicate the center locations of Conson, Megi and Meari during the DOTSTAR observations at 1200 UTC 8 June, 1200 UTC 16 August and 1200 UTC 25 September, 2004, individually.

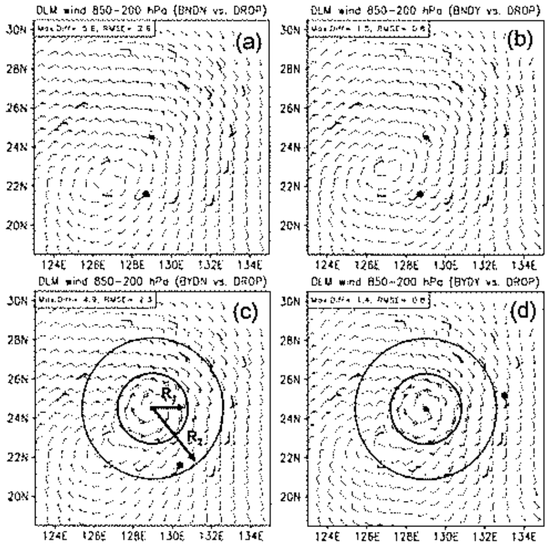
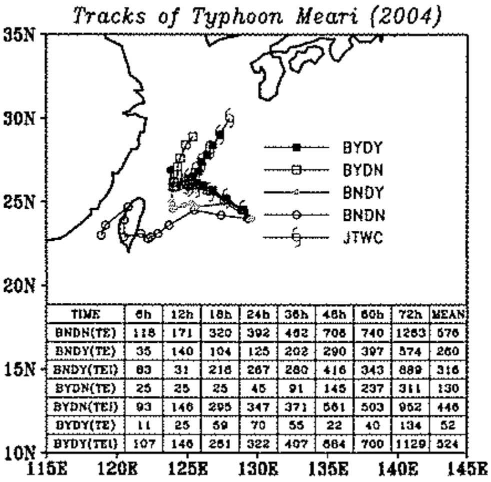


Figure 2. Comparison of the deep-layer-mean (850-200-hPa; DLM) wind between the dropwindsonde soundings (thick black wind barb) and the model analysis (black wind barb, interpolated to the location of each sounding) for experiment (a) BNDN, (b) BNDY, (c) BYDN and (d) BYDY. The bold bullet represents the location where the largest DLM wind difference appears. The numbers drawn on the upper left corner of each panel show the value of the largest DLM wind difference and the root mean square error (RMSE) among all sounding locations.



TIME	6h	12h	18h	24h	36h	48h	60h	72h	MEAN
BNDN(TE)	118	171	320	392	462	706	740	1263	576
BNDY(TE)	35	140	104	125	202	290	397	574	260
BNDY(TEI)	83	31	216	267	280	416	343	689	316
BYDN(TE)	25	25	25	45	91	145	237	311	130
BYDN(TEI)	93	146	295	347	371	561	503	952	446
BYDY(TE)	11	25	59	70	55	22	40	134	52
BYDY(TEI)	107	146	261	322	407	684	700	1129	524

Figure 3. The JTWC best track (typhoon symbols) and the forecast tracks of Typhoon Meari from model experiments initialized at 1200 UTC 25 September, 2004. Model track errors (indicated as TE, in km) verified against the JTWC best track and the track error improvement (indicated TEI, in km) relative to the BNDN experiment are shown in the bottom table of the figure.

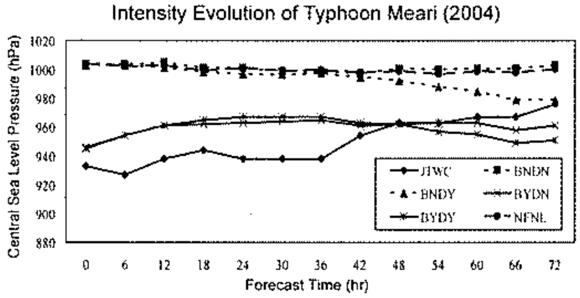


Figure 4. Time series of the intensity (in hPa) of Meari from the JTWC analysis and from all model experiments initialized at 1200 UTC 25 September 2004.

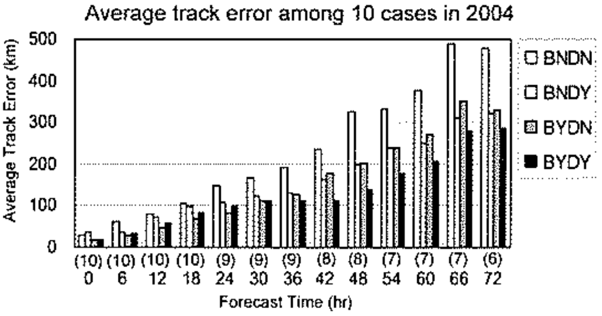


Figure 5. The overall average track errors relative to JTWC analysis in 10 evaluation cases of 2004 (unit: km). The numbers along the bottom axis are the number of the cases at each forecast time.

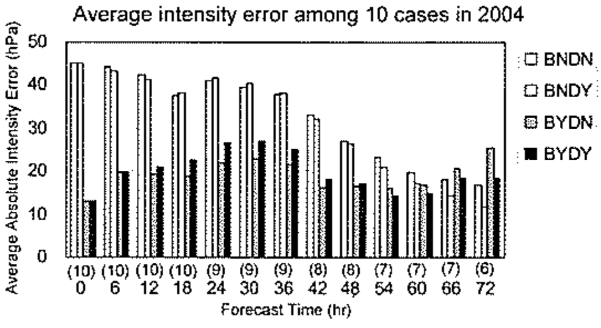


Figure 6. As in Fig. 5, but for the evaluation of the average error of absolute central sea-level pressure error (unit: hPa)