DROPSONDE OBSERVATIONS FOR TYPHOON SURVEILLANCE NEAR THE TAIWAN REGION (DOTSTAR): AN OVERVIEW

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ABSTRACT

DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region) is an international research program conducted by meteorologists in Taiwan partnered with scientists at the Hurricane Research Division (HRD) and the National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA). The experiment is based on successful surveillance missions conducted in the Atlantic with NOAA's Gulfstream-IV jet aircraft. During the experiment, GPS dropwindsondes are released from a jet aircraft flying above 42000 ft in and around tropical cyclones approaching Taiwan to collect critical meteorological data for improving the analysis and the prediction of typhoons.

After one-year of training, development and installation of all the needed software and hardware in the aircraft, the DOTSTAR research team initiated typhoon surveillance in 2003. Two missions (in Typhoons Dujuan and Melor) were conducted successfully,and seven or eight missions are expected to be conducted annually during the 2004 and 2005 typhoon seasons.

The current manuscript provides an overview of the scientific objectives of DOTSTAR including operational plans, organization, data management, and data archiving. Preliminary results of the two missions in the first season in 2003 are presented. The experiment marks the beginning of typhoon surveillance in the western North Pacific and is expected to yield impressive improvements in typhoon research, observations and forecasting.

1. INTRODUCTION

Typhoons are one of the most destructive weather systems in nature, and the most catastrophic weather phenomenon in Taiwan. Ironically the significant rainfall they bring is also a crucial water resource in Taiwan. Taiwan has been affected severely by many typhoons in recent years, and the loss of life and property has been staggering. The typhoons that battered Taiwan in 2001 alone caused 583 deaths, and more than US$ 400 million in agricultural losses, nearly paralyzed the Taipei Rapid Transit System, and did tremendous damage to private and public sectors.

Prompted by their sense of social responsibility, and the National Science Council's (NSC) emphasis on typhoon research, atmospheric science researchers in Taiwan initiated an interagency research project on typhoons in September, 2001. The "National Priority Typhoon Research Project" was formed in July, 2002, and the NSC approved the necessary 3-year funding. One key item of this project involves a field experiment, Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR), which marks the beginning of a new era for the surveillance of tropical cyclones in the western North Pacific using GPS dropwindsondes.

2. OVERVIEW of DOTSTAR

a. Background

Other than satellite observations, there has been an unfortunate lack of observations in TCs in the western North Pacific (NW Pacific), especially since the U.S. discontinued typhoon reconnaissance flights in the region in 1987. As described in Wu and Kuo (1999), the currently available data are not adequate enough to provide accurate initial and boundary conditions for the analyses used by numerical models in TC forecasting. This deficiency puts a huge constraint on the accuracy of the TC forecasts, as well as the general understanding of TCs in the NW Pacific region.

Considering the potential of dropwindsonde data in improving TC forecasting and understanding of their behavior, the DOTSTAR project was launched in 2002. The initiative of DOTSTAR is a collaborative effort between researchers from the National Taiwan

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University (NTU), Central Weather Bureau (CWB), in partnership with scientists at HRD and NCEP, building upon work pioneered at NOAA's HRD to improve track forecasts for TCs (Burpee et al. 1996; Aberson 2003).

The key to DOTSTAR is the use of GPS dropwindsondes released from a jet aircraft flying above 42,000 feet in the environments of TCs that approach Taiwan (Fig. 1). These sensors measure temperature, humidity, pressure, and wind velocity twice each second as they fall to the surface. Information from the surveillance flights is transmitted by a satellite communication aboard the aircraft in real time to the CWB (Fig. 2). To make maximum use of the data, the dropwindsonde data are assimilated in real time into the numerical models of CWB (i.e., the global model, C-GFS), NCEP (i.e., the global model, GFS; and the GFDL hurricane model), the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) (i.e., the global model, NOGAPS; the regional model, COAMPS; and the Navy version of the GFDL hurricane model, GFDN) and the Japanese Meteorological Agency (JMA, beginning in the 2004 season). The data are expected to enable us to forecast storm track and intensity much better than without the additional data.

The typhoon surveillance missions are carried out by an Astra SPX jet from the Aerospace Industrial Development Corporation (AIDC) in Taichung, Taiwan. The aircraft can cruise at abut 750 km h-1 and reaches a maximum height of 45,000 ft. It is the first time during the past 16 years that aircraft have been used in the northwestern Pacific to routinely observe typhoons. Each flight lasts for up to six hours during which time dropwindsondes are released about 150 to 200 km apart, consistent with the spatial resolution of the traditional rawinsonde network. The flight route is designed to obtain observations targeted to the most sensitive region around the TC (i.e., the area with the largest deep-layer-mean wind bred vectors from the NCEP global ensemble forecasting system, Aberson 2003), while modified to meet aircraft and air-control requirements. The project will enable scientists to formulate future airborne observation strategies, facilitate adaptive observations of typhoons, and improve data assimilation capabilities. The project is considered a pioneering step forward in basic research and forecasting of typhoons in the NW Pacific.

b. Objectives

The objectives of the project are:

1) To conduct a pilot study to enhance observations of the atmosphere and to improve the numerical guidance for NW Pacific TCs that may affect the Taiwan area.

2) To evaluate how the dropwindsonde data influence model track predictions, and study the optimal (targeted) observation strategies for improving forecasts.

3) To validate/calibrate remote sensing data (such as the satellite- and radar-derived products) around typhoons and help explore typhoon dynamics, such as the storm's asymmetric structure, the boundary-layer structure, and the typhoon-ocean interaction.

4) To improve data assimilation.

c. Organization

The Principal Investigator (PI) and director of DOTSTAR is the first author of this paper, and the second to fourth authors serve as CO-PIs. The organization of DOTSTAR falls into two working groups. The observation team is in charge of the aircraft surveillance, including the creation of flight tracks, the release of dropwindsondes, the data communication, the processing of data by the Airborne Vertical Atmosphere Profiling System (AVAPS), the transmission of the data to the CWB through the satellite phone, and then to NCEP, FNMOC, and JMA, and the on-board data debugging/analysis and coding. The analysis and research team is in charge of the receipt, analysis, and simulation/assimilation of the dropwindsonde data, assessment of the influence of the dropwindsonde data on typhoon forecasts, and all other follow-up research.

During the 2002 hurricane season, four researchers from Taiwan worked with HRD scientists during operational surveillance missions, learning the operational and scientific aspects of aircraft use to sample the hurricane environment. A number of essential tasks were completed before the typhoon season in 2003. First, the whole aircraft platform, dropwindsonde equipment and the onboard data receiving, analysis, and transmitting system and programs were successfully set up at AIDC. Second, the system for the realtime analysis and assimilation of dropwindsonde data at CWB, as well as at NCEP and FNMOC was completed. Third, three test flights and testing of the data flow and assimilation, were successfully performed from May to June, 2003.

With all the above preparation work completed in June, 2003, the DOTSTAR team was ready to conduct surveillance missions.

3. PRELIMINARY RESULTS

Starting during the 2003 TC season, the ASTRA jet was ready to fly missions in and around TCs in the NW Pacific near Taiwan. About 8 surveillance missions were expected for the first season. Nevertheless, because of the uncertainty of the TC track prediction and the constraints due to the two-day in-advance requirement for submitting flight plans to the air traffic control agencies controlling different air spaces, only two missions were executed.[1]

On 1 September, 2003, the first DOTSTAR mission was successfully completed around Typhoon Dujuan, with 11 dropwindsondes released (Fig. 3). On 2 November, 2003, the second mission was conducted around Typhoon Melor, with 15 dropwindsondes released (Fig. 4) and the ASTRA flew directly over the center of Melor. Note that a rather symmetric flight track was flown around the periphery of Dujuan, whereas in Melor, the aircraft passed over the center of the typhoon and did not completely surround it with dropwindsonde data. The descriptions of the two missions, along with the preliminary results are described as below.

a. Typhoon Dujuan

1) Synopsis

After a two-month wait, the first DOTSTAR mission was launched around Typhoon Dujuan between 0430 and 0800 UTC 1 September, commencing a new milestone for typhoon observations and research in the NW Pacific. After taking off from Taichung at 0430 UTC, the aircraft followed the northwestern edge of the peripheral circulation of Typhoon Dujuan at an altitude of 41,000 ft, and released its first dropwindsonde at 0520 UTC. The aircraft released a total of 11 dropwindsondes at intervals of about 200 km and at 200-250-km radius from the storm center (Fig. 3). The CWB began receiving data at 0630 UTC, and finished receiving all the dropwindsonde data before the plane landed in Taichung at 0800 UTC. The CWB used the Internet to transmit data in real time to NCEP, and then FNMOC, enabling all these centers to assimilate the dropwindsonde data into their 0600 UTC assimilation cycles.

2) Analysis of the dropwindsonde data

The wind fields (Fig. 5) from the dropwindsonde data show that the cyclonic circulation was asymmetric (partly because the aircraft did not fly around the storm at a constant radius from the center) and extended from 925 hPa (with a maximum wind of about 40 m s^{-1} in Fig. 5a) to 200 hPa (with a maximum of 25 m s^{-1} in Fig. 5c). The data revealed that Typhoon Dujuan was stronger and more coherent vertically than had been analyzed without the dropwindsonde data at CWB (not shown), as well as at the Joint Typhoon Warning Center (JTWC). This is the first time ever that this type of valuable information was available to the forecasters at CWB in realtime. The data also led to a better estimation of Dujuan's 250-km radius of gale-force wind, larger than the value of 220 km estimated from satellite imagery at some operational centers with no knowledge of the dropwindsonde data. This information is particularly important for issuing warnings for impacts from the wind field as Dujuan approached land.

Although Dujuan did not make landfall on Taiwan, strong winds and heavy rain that it brought caused extensive damage in southern Taiwan, testifying to the large extent of the typhoon's wind field. Dujuan continued to develop throughout 2 September, and ultimately caused widespread destruction in Hong Kong, Macao, and Shantou in China's Guangdong Province.

3) Impact of the data on the numerical models

Due to the lack of observations around TCs, TC structure generally is not well represented in global analyses without the use of synthetic data. For Dujuan, the cyclonic winds in the middle and upper troposphere are much stronger in the model initial conditions when the dropwindsonde are assimilated (Fig. 6). In particular, the closed circulation at high levels associated with Dujuan is not analyzed by CWB's Global Forecasting System (C-GFS) (Fig. 6b) without the dropwindsonde data. Nevertheless, after assimilating the dropwindsonde data, the wind velocities are improved distinctly (Fig. 6a). The circulation center of C-GFS is located about 1 degree to the south of the actual location by the assimilation of the dropwindsonde data, likely due to both the poor first guess (the C-GFS did not perform the vortex relocation as in NCEP GFS) and insufficient model resolution.

Figure 7a (7b; 7c) shows the differences in the initial deep-layer-mean (925-250 hPa) wind fields of the C-GFS (NCEP GFS; FNMOC NOGAPS) with and without assimilating the dropwindsonde data. The region with the largest difference is collocated well with the location of the dropwindsondes, with the maximum value of about 7 m s^{-1} for GFS, 3 m s^{-1} for GFS and 7 m s^{-1} for NOGAPS. Due to some technical problems, only three of the eleven dropwindsondes were assimilated into NCEP GFS in realtime.[2] The difference of the deep-layer-mean wind in GFS is in good agreement with Aberson (2003), though it is not clear why the the C-GFS (NOGAPS) has much larger differences and larger impact regions to the south (southeast) of the data locations.

The comparison of the model runs of Dujuan

[1] This drawback will be improved upon in subsequent seasons, as a better and more flexible flight operation application procedure to the air-control agencies in the Philippines and Japan has been set up.

[2] This problem has been fixed though a rerun incorporating all 11 dropwindsondes has not been completed, mainly due to the heavy operational load at NCEP.

with and without the dropwindsonde data show that the NCEP GFS forecasts are improved by 32% to 81% between 6 and 30 h (Table 1 and Fig. 8) and by less than 10% beyond 36h. The average improvement from 6 to 48 h is 35% (note that only three dropwindsondes were assimilated). Some improvement of about 25% (not shown) between 6-24-h can also be identified in the NCEP GFS initialized at 1200 UTC 1 September (i.e., the dropwindsonde information were carried into the next assimilation cycle through the 6-h forecasts from 0600 UTC 1 September).

However, no impact on the NCEP GFDL hurricane model track forecast is found (not shown). The GFDL model does not assimilate the dropwindsonde data directly, but uses the initial fields from the NCEP GFS. It is possible that the GFDL synthetic vortex removed the dropwindsonde information from the NCEP GFS in this case. On the other hand, the impact of the dropwindsonde data from all eleven dropwindsondes on NOGAPS forecast (Table 1) is completely different from that of the NCEP GFS. The impact on track forecasts is negative during the first 24h, then positive at 36 and 48h. Follow-up analyses on the physical features leading to such improvement in the NCEP GFS and degradation in NOGAPS are ongoing through use of potential vorticity diagnosis (Wu et al. 2003, 2004). It is hoped that such analyses may provide insight into how the inclusion of the dropwindsonde data affects the performance of each model.

b. Typhoon Melor

1) Synopsis

The observations for Typhoon Melor were obtained between 0400 and 0700 UTC 2 November, as Melor crossed Luzon and headed northward toward the southern tip of Taiwan. During this mission, the jet departed from Taichung at 0400 UTC, rounded northern Taiwan, and flew south along the east coast of Taiwan. The aircraft released the first GPS dropwindsonde near Green Island, passed the southern tip of Taiwan, and dropped several more dropwindsondes as it continued on a southerly course. Flying at 41,000 feet, the aircraft successfully overflew the center of Typhoon Melor and gathered important data on the structure of the typhoon near its eye (Fig. 9). The aircraft immediately turned toward the west upon arriving at the northern tip of Luzon. After rounding the western edge of the typhoon (this flight pattern was required due to the air control issues) and releasing more dropwindsondes, the aircraft flew back to the southwestern tip of Taiwan, released its 15th and final dropwindsonde, and returned to Taichung at 0700 UTC.

The analysis of the dropwindsonde data

The detailed structure of Melor can be depicted along the leg (drops 3 to 7, Fig. 4) when the aircraft flew directly over the center. Note that the apparent warm core exists in the center (Fig. 9), with the saturated equivalent potential temperature higher than that of the surroundings by about 5-10 degrees. Figure 9 shows that Melor has a rather large eye with the radius of about 100 km, about the size estimated from the satellite imagery (Fig. 4). The axis of the maximum wind speed tilts outward with height, with a maximum measured wind speed of 24 m s^{-1} at 900-hPa near the 6th dropwindsonde. Note that this is also the first time that this type of detailed inner structure of TCs in the NW Pacific is available in real time at CWB.

3) The impact of the dropwindsonde data to numerical models

The track forecasts for Typhoon Melor shows one of the greatest challenges for numerical models in the typhoon season of 2003, as most models predicted that Melor would head into the South China Sea after passing through Luzon. However, Melor turned northward toward Taiwan (Fig. 10). For this case, the NCEP GFS model forecasts show negative impact with the dropwindsonde data (Fig. 10 and Table 2). Significant degradations (about 50% in the first 24 h, Table 2) are seen from 6 to 36 h. This result is in agreement with Aberson (2003) who showed that the sampling of the entire target feature is needed to improve the forecasts, otherwise degradation is probable.

The initial results of DOTSTAR indicate a golden opportunity for improving the track prediction of typhoons in the western North-Pacific (near Taiwan). More dropwindsondes will be released into the periphery of typhoons near Taiwan during the typhoon seasons of 2004 and 2005. As the number of observations increases, we expect to see a more statistically significant evaluation of the impact of these dropwindsondes on TC track predictions. While it will take careful assessment of the results of this project to show whether the dropwindsonde data can be used to improve typhoon forecasting, it is likely that these valuable data will lead to major breakthroughs in typhoon research.

Meanwhile, by flying over a typhoon eye for the first time, the mission for Melor also laid the groundwork for future observations of TC's inner core structure. The pilots from AIDC are scheduled to visit NOAA/AOC during the spring of 2004 to gain experience in flying in the storm (hurricane) core. These exchanges should be quite positive for future DOTSTAR missions. Meanwhile, work is ongoing to compare the data collected by the mission with satellite data and data from the Doppler radar station at Kenting (Lee et al. 2000), which is located near the southern tip of Taiwan. This may shed new light on the study of TC structure, rainbands, and circulation.

4. SUMMARY AND FUTURE PLANS

In light of the heavy damage done by typhoons to Taiwan each year, the NSC of Taiwan places a great premium on typhoon research, and therefore has appropriated US$ 1 million for the "National Priority Typhoon Research Project" each year for three years (from August 1, 2002 to July 31, 2005), especially for the field experiment, "Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR)". DOTSTAR is an international research program conducted by meteorologists in Taiwan, partnered with scientists at NOAA HRD and NCEP. This project marks the beginning of a new era for aircraft surveillance of typhoons in the western North Pacific.

Built upon work pioneered at NOAA's HRD, the key to the project is the use of airborne sensors, dropwindsondes, which are released from jet aircraft flying above 42,000 feet in the environment of a tropical cyclone. These sensors gather temperature, humidity, pressure, and wind velocity information every half second as they fall to the surface. Information from the surveillance flights is transmitted in near realtime to the CWB of Taiwan, as well as to NCEP and FNMOC. Starting in the 2004 season, the data are also scheduled to be transmitted to JMA in real time. The data are assimilated operationally into the numerical models of CWB, NCEP (GFS/GFDL) and FNMOC (NOGAPS/COAMPS/GFDN). DOTSTAR is expected to provide valuable data that can help increase the accuracy of TC analyses and track forecasts, to assess the impact of the data on numerical models, to evaluate the strategies for adaptive observations, to validate/calibrate remotely sensed data, and to improve our understanding of TC dynamics.

On September 1, 2003, the first DOTSTAR mission was successfully completed around Typhoon Dujuan. On November 2, the second mission was launched, and the aircraft flew over the center of Typhoon Melor. Preliminary results have shown that these observations have provided helpful data for the analysis, prediction and understanding of both Dujuan and Melor.

We are expecting to undertake at least 8 surveillance missions in both 2004 and 2005. Instead of using the previous targeting strategy, where the dropwindsondes are released at locations in which the "spread" (or standard deviation) of an ensemble forecast from NCEP GFS is large at the observation time, we plan to examine the new targeting strategy based on the Ensemble Transform Kalman Filter (Majumdar et al. (2002), which predicts the signal variance (reduction in forecast error variance) for all feasible deployments of targeted observation, or the NOGAPS singular vector analysis (Melinda Peng, personal communication 2004).

. The research group maintains close communication and exchanges important scientific ideas with HRD/NOAA, while gaining helpful technical experience. As the DOTSTAR research team continues to harvest important data and gain valuable experience, we believe that future typhoon observations will reach full maturity, enabling significant progress in both academic research and typhoon forecasting. For example, because the NW Pacific is the region with the most frequent and intense TCs worldwide, with the very high vertical-resolution observations from the dropwindsondes, DOTSTAR offers a very good opportunity for the detailed measurement of the boundary layer wind and air-sea exchange coefficient at high wind conditions (Powell et al. 2003), which are also one critical element for improving our understanding of the TC intensity change (Emanuel 1999; Wang and Wu 2003). Many of the wind and moisture data in the entire troposphere can also prove to be a unique dataset for the validation and calibration of many remotely sensed data for TCs in the NW Pacific region.

It is hoped that DOTSTAR will shed light on typhoon dynamics, enhance typhoon track forecasting accuracy, place Taiwan at the forefront of international typhoon research, and make a significant contribution to the study of typhoons in the northwestern Pacific and East Asia region.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. Hung-Duen Yang, Director of the Division of Natural Sciences of National Science Council of Taiwan, for his strong support of the DOTSTAR program. Special thanks go to Dr. Ching-Yen Tsay, Dr. Shaw Liu, Mr. Hsinn-Liang Shieh (and CWB), and Dr. Frank Marks (and Hurricane Research Division) for their help and advice. Helpful discussions with Drs. Hugh Willoughby, Kerry Emanuel, Yoshio Kurihara, Russ Elsberry, T. N. Krishnamurti, Greg Holland, Kuo-Nan Liou, Michael Montgomery, Simon Chang, C-P Chang, Bill Kuo, Wen-Chau Lee, Yuqing Wang, Lou Lee, George Chen, Gen-Rong Liu, Ben Jou, Chung-Hsin Sui, and Hung-Chi Kuo are appreciated. We particularly thank the nice contribution from all the team members of the DOTSTAR project and the collaborators at AIDC, especially from Chia-Hsiang Tsao, Li-Shyong Yin and Ying-Hao Chen, who were on board of both surveillance flight missions in Dujuan and Melor. Important help from the Japanese Civil Aviation Bureau and the Meteorological Research Institute (MRI)/JMA (Dr. Tetsuo Nakazawa), Air Transportation Office of Philippines, NCEP (Drs. Hua-Lu Pan and Naomi Surgi), GFDL (Morris Bender) and FNMOC (Drs. Mary Alice Rennick and Brain Strahl) are also appreciated. Another special thanks to Dennis Keyser of NCEP/EMC for enabling the GFS rerun of the Melor mission and for help in debugging communications. Thanks also goes to Russ Treadon and Mark Iredell of NCEP/EMC and Timothy Marchok of GFDL for help in running the NCEP models, and to Dr. Stephen Lord and the staff of the NCEP Central Computing Facility who enabled the runs to proceed in real time. The research is supported by Grant NSC 91-2119-M-002-032 and NSC 92-2119-M-002-009-AP1.

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Table 1. Forecast track errors (in km) from the NCEP GFS and FNMOC NOGAPS models (initialized at 0600 UTC 1 September) with and without the dropwindsonde data, and the relative improvement (%).

Forecast time **(h)**	6	12	18	24	30	36	42	48
GFS (3drop) (km)	15	15	33	53	118	204	260	268
GFS (nodrop) (km)	22	81	108	123	176	199	272	295
GFS Improvement (%)	32%	81%	69%	57%	33%	-3%	4%	9%
NOGAPS (alldrop) (km)		68		141		178		102
NOGAPS (nodrop) (km)		63		103		190		206
NOGAPS Improvement (%)		-8%		-37%		6%		50%

Table 2. Forecast track errors (in km) from the NCEP GFS model (initialized at 0600 UTC 2 November) with and without the dropwindsonde data, and the relative improvement (%).

Forecast time (h)	6	12	18	24	30	36
GFS (alldrop) (km)	79	139	223	348	469	641
GFS (nodrop) (km)	53	91	137	252	400	610
GFS Improvement (%)	-49%	-53%	-63%	-38%	-17%	-5%

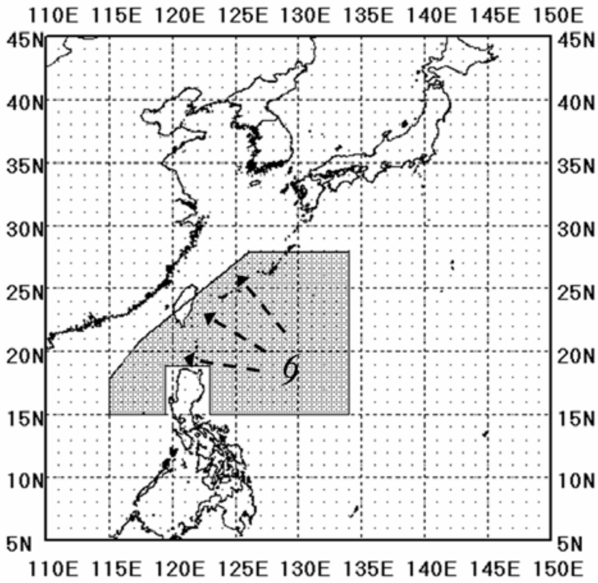

Fig. 1. The area (shaded) for proposed typhoon surveillance in DOTSTAR.

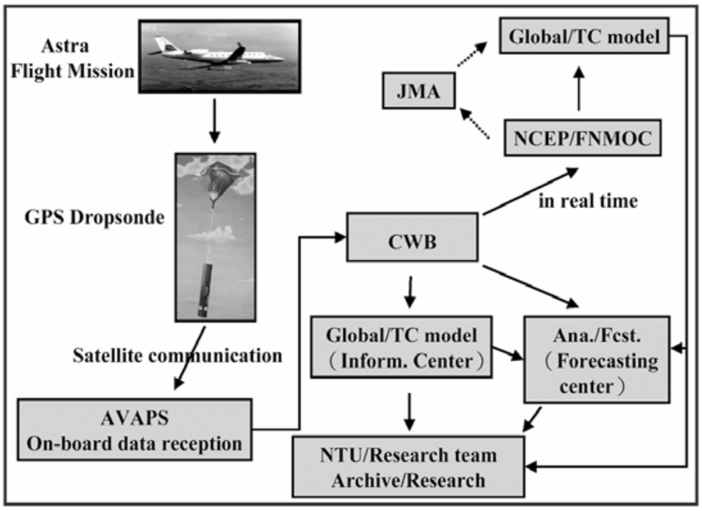

Fig. 2. Data flow chart for the aircraft data.

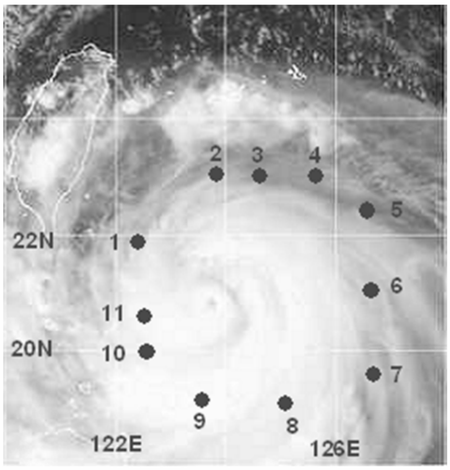

Fig. 3. GMS-5 Visible Imagery at 0525 UTC 1 September 2003, and the dropwindsonde locations (solid dots) for Typhoon Dujuan, 0430 – 0800 UTC 1 September 2003. The numbers indicate the sequence of the dropwindsondes released.

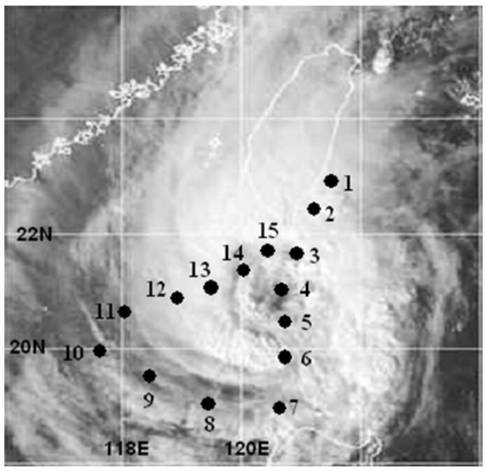

Fig. 4. The GMS-5 Visible Imagery at 0625 UTC 2 November 2003, and the dropwindsonde locations (solid dots) for Typhoon Melor, 0400 – 0700 UTC 2 November, 2003. The numbers indicate the sequence of the dropwindsondes released.

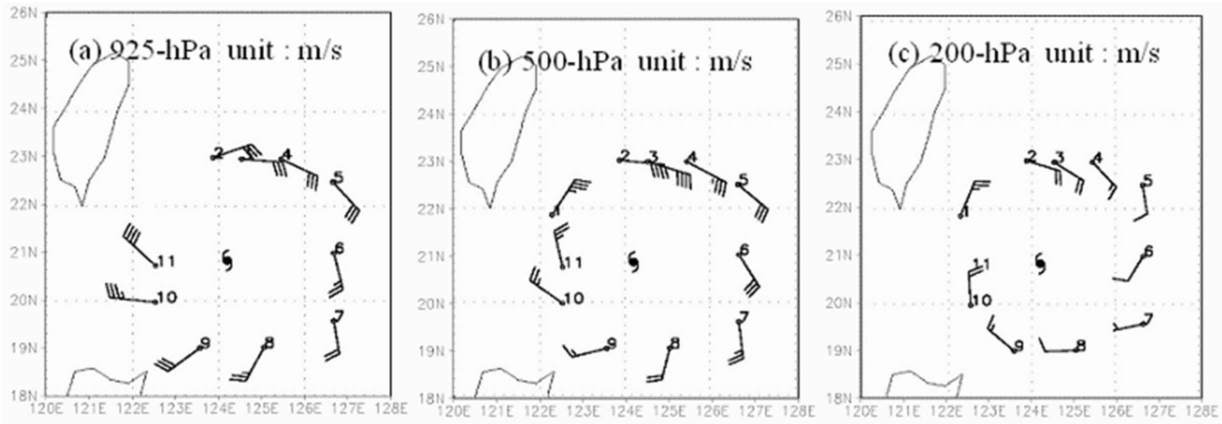

Fig. 5. The wind fields (one full wind barb represents 10 m s^{-1}) from the dropwindsonde data for Typhoon Dujuan at 0600 UTC 1 September 2003, at (a) 925 hPa, (b) 500 hPa, and (c) 200 hPa.

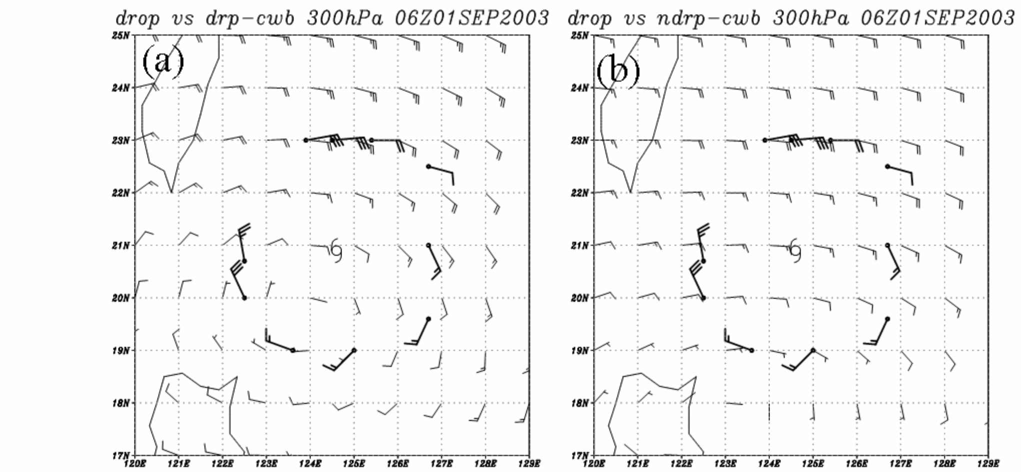

Fig. 6. The initial 300-hPa wind fields (one full wind barb represents 10 m s^{-1}) of CWB's GFS (a) with assimilation of the dropwindsonde data, and (b) without assimilation of the dropwindsonde data. The 300-hPa winds from the dropwindsonde observations are shown in bold.

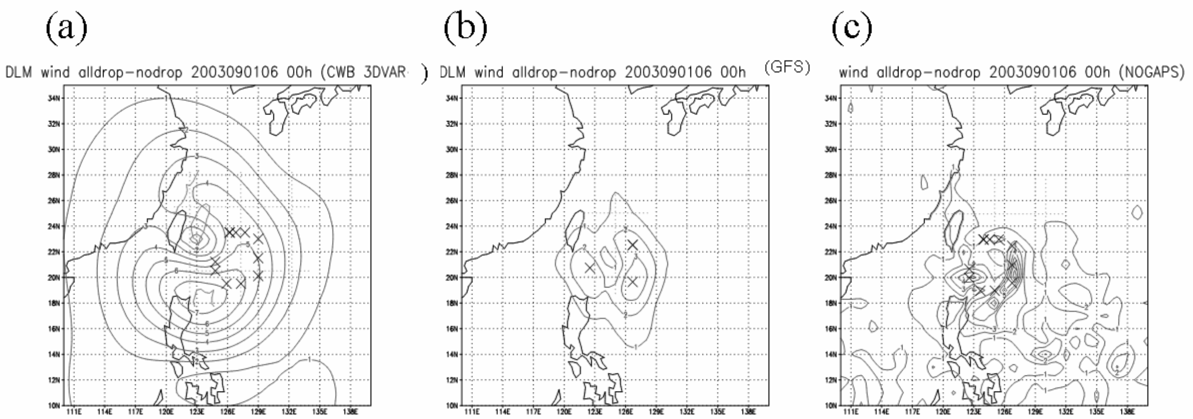

Fig. 7. The difference of the initial deep-layer-mean (925-250-hPa) wind in the model with and without assimilation of the dropwindsonde data in (a) NCEP GFS, and (b) FNMOC NOGAPS models. The contour interval is 1 m s^{-1}. The X's show the locations of the dropwindsonde data being assimilated.

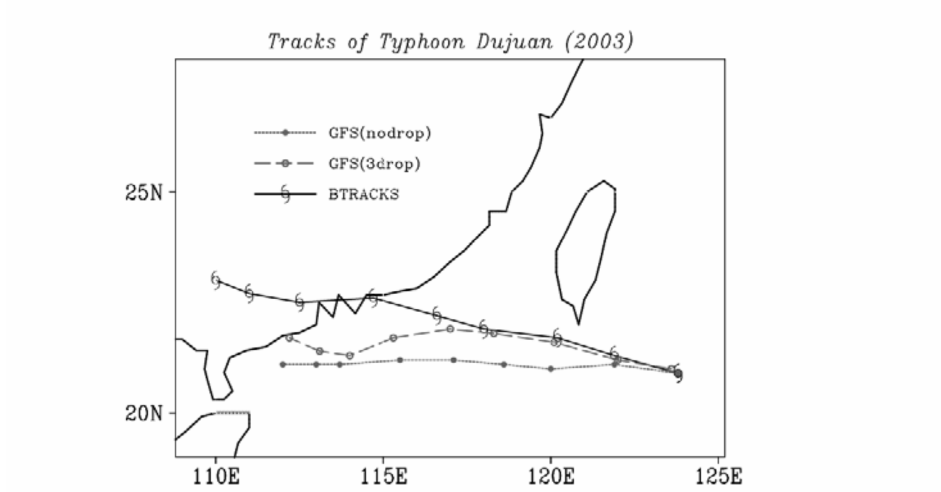

Fig. 8. The best track (BTRACKS) and the corresponding 48-h model forecast tracks of Typhoon Dujuan from the NCEP GFS (initialized at 0600 UTC 1 September) with the assimilation of the dropwindsonde data [GFS(3drop), in circles for every 6 h] and without assimilation of the dropwindsonde data [GFS(nodrop), in dots for every 6 h].

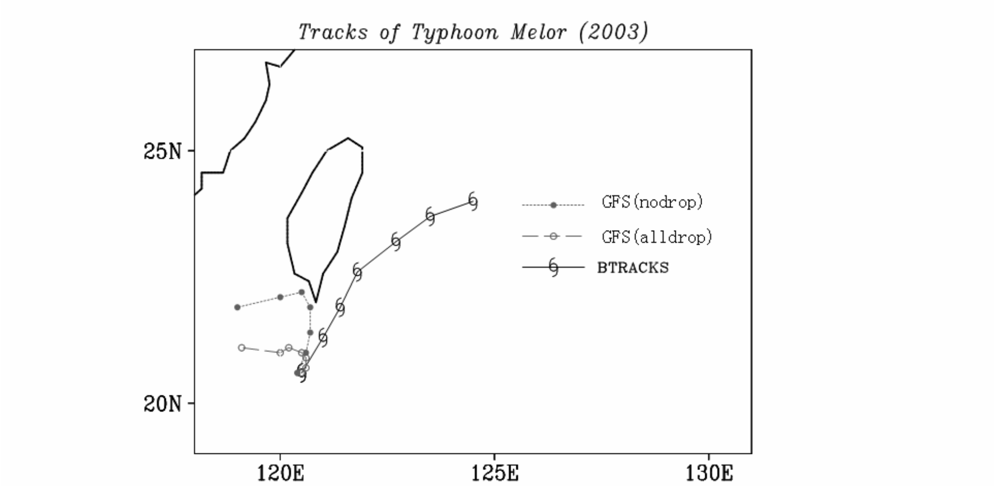

Fig. 9. The vertical cross section of wind speed (with a contour interval of 3 m s^{-1}; one full wind barb represents 10 m s -1) and the saturated equivalent potential temperature (shaded) from the third to the seventh drops (from the north to the south, as shown in Fig. 5) of Typhoon Melor.

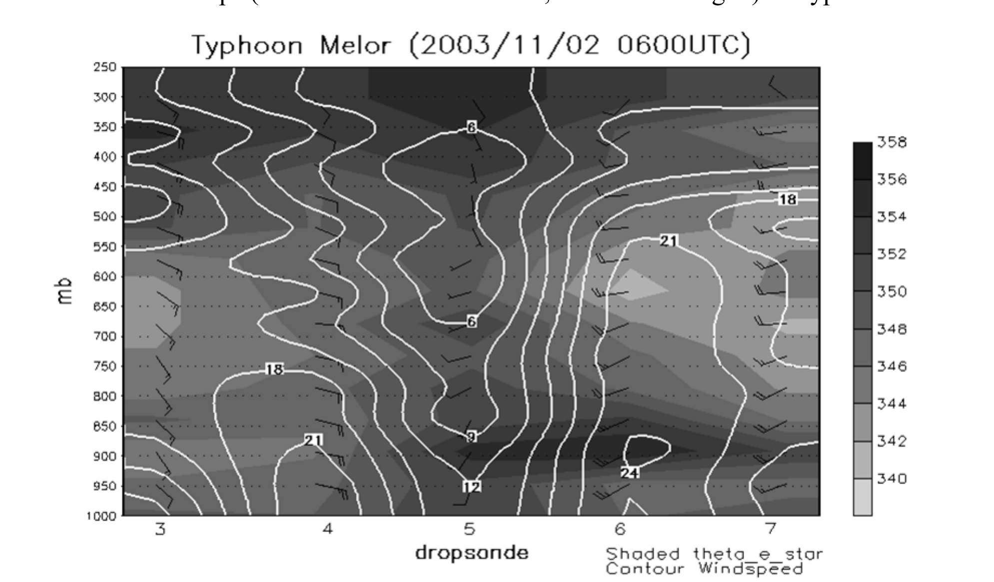

Fig. 10. The best track (BTRACKS) and the corresponding 48-h model forecast tracks of Typhoon Melor from the NCEP GFS (initialized at 0600 UTC 2 November) with assimilation of the dropwindsonde [GFS(alldrop), in circles for every 6 h] data and without assimilation of the dropwindsonde data [GFS(nodrop), in dots for every 6 h].