WMO/CAS/WWW

SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 3.1 : **Advances and Requirements for Operational Tropical Cyclone Track Prediction**

Rapporteur: T.C. Lee
Hong Kong Observatory
134A Nathan Road, Kowloon,
Hong Kong, China.

Email : tclee@hko.gov.hk
Fax : (852) 2377 3472

Working Group: Wes Browning, Philippe Caroff, Eun-Jeong Cha, Duong Lien Chau, Cuiying Tian, Julian Heming and Alan Radford, Prisco Nilo, Mannoji Nobutak, David Richardson, Ali Shareef, S.K. Subramanian.

3.1.1. **Introduction**

A National Meteorological and Hydrological Service (NMHS) should provide accurate quantitative forecasts of high winds, heavy rain, and storm surge associated with tropical cyclones. Under-warnings of these hazards may result in avoidable loss of lives and damage to properties while over-warnings could cause unnecessary disruption to socio-economic activities. Both affect the credibility of the NMHS. An accurate forecast of tropical cyclone (TC) track and a good knowledge of the wind and rain distribution around the TC are essential in this regard.

In this report, the recent developments in operational TC track prediction techniques and tools (Section 3.1.2) and the improvement in operational TC track forecasts (Section 3.1.3) in the past few years are reviewed. Identified roadblocks in operational TC track prediction are discussed in Section 3.1.4. Opportunities and recommendations are given in Section 3.1.5.

In addition to the inputs of working group members, this report draws on published information as well as TC track forecast verification data available online from the websites of various operational warning centres.

3.1.2. **Recent developments in operational tropical cyclone track prediction techniques and tools**

(a) Improvements in numerical weather prediction (NWP) guidance

With increasing horizontal and vertical resolution, improvement in physical parameterization schemes, and more effective assimilation of satellite observations, the skill of numerical weather prediction (NWP) models in TC track prediction has been improved significantly in the last decade (Heming 2000; Lam 2001; Aberson 2001; Sakai and Yamaguchi 2004; Goerss and Sampson 2004). Some examples are the 5-year mean TC track forecast errors of the Japan Meteorological Agency (JMA) global model for western North Pacific and South China Sea from 1995 to 2005 (Fig. 3.1.1a), 5-year mean TC track forecast errors of the UK Meteorological Office (UKMO) global model for Northern Hemisphere from 1992 to 2005 (Fig. 3.1.1b), and 5-year mean TC track forecast errors of UKMO for Southern Hemisphere from 1992 to 2005 (Fig. 3.1.1c). The forecast errors of these two models for all forecast ranges from 24 hours to 120 hours have decreased over the last decade, with the most dramatic improvements in the longer forecast ranges. The 5-year mean errors of 72-hour forecasts for 2001-2005 are now smaller than those of 48-hour forecasts for 1991-1995. The reductions during 1996-2000 and 2001-2005 were in the range of 10-15 % for 24- and

48-hour forecasts (see Table 3.1.2). Moreover, NWP models are now capable of even predicting sharp turns in the TC tracks. A recent example (Fig. 3.1.2) is the forecast for Typhoon Chanchu in May 2006 that abruptly made a right-angle turn in the South China Sea.

(b) Enhancement in availability and accessibility of NWP products and operational TC forecast information

More NWP products are made easily accessible for NMHSs via either the WMO Global Telecommunication System (GTS) or internet through bilateral or regional arrangements. For example, JMA implemented in 2004 a password-protected "Numerical Tropical Cyclone Prediction Web Site" that displays TC forecast tracks from major NWP centres for access by the Members of the ESCAP/WMO Typhoon Committee (Kyouda 2006). Furthermore, official TC warnings issued by Regional Specialized Meteorological Centres (RSMCs) and NMHSs are available at the Severe Weather Information Centre (SWIC) website (http://severe.worldweather.wmo.int/) of the WMO (Lam 2001).

(c) Developments in multi-model consensus TC track forecasts

Goerss (2000), Lee and Wong (2002), and Jeffries and Fukada (2002) indicate that the TC forecast tracks derived from the multi-model consensus are, on average, more accurate than the forecasts of individual models. The multi-model consensus approach that makes simple averages of the forecast tracks from different centres is a relatively low cost solution for adding values to model TC track forecasts and has been adopted by several warning centres as the primary guidance for TC track forecasts in recent years. Besides simple averaging, other methods such as selective consensus method(Carr et al. 2001), weighted consensus(Weber 2003), and statistical/linear regression schemes (Vijaya Kumar et al. 2003; Zhang 2006) have been developed to reduce the error of the consensus track. Furthermore, a consensus prediction error product has also been developed to provide a measure of confidence in the consensus forecasts (Goerss 2004, 2006). These radii of circular areas indicate the uncertainty at a certain confidence level of the forecast TC positions based on the spread of the consensus each day, rather than being the same radii each day based on historical average errors.

In recent years, the outputs of Ensemble Prediction Systems (EPS) of major NWP centres have been made available to NMHSs (Cheung 2001; Heming et al. 2004; Kyouda 2006). From individual TC track forecasts of EPS, TC strike probability forecasts can be generated for use by forecasters and decision-makers (Regnier and Harr 2006). Two examples of strike probability maps generated by the European Centre for Medium-range Forecasts (ECMWF) ensemble for Hurricane Katrina are given in Fig. 3.1.3. The ensemble track forecasts from 00 UTC 26 August suggest a large uncertainty in the track of Katrina. Once Katrina crossed into the Gulf of Mexico 12 hours later, the uncertainty in the track of Katrina was substantially reduced. The ECMWF strike probability maps are available to all NHMSs via the ECMWF website. As recommended by the IWTC-V, the TC tracks for the individual ensemble members are now distributed on the GTS. One example of how EPS outputs may be used to assist forecasters is in handling bifurcation situations. Under a cooperative research project between HKO and JMA on the utilization of the EPS TC data, Wong (2006) found that the use of actual TC observed positions *a posteriori* for the “conditioning” of strike probability could help forecasters to choose among divergent EPS tracks such as in the case of Songda (Fig. 3.1.4). As verified by the actual track (black line in Fig. 3.1.4), the conditioned strike probability successfully indicated the likelihood of Songda recurving near 30^{o} N, 128^{o} E.

(d) Development of tools for operational TC track forecasting

Several NMHSs have developed integrated, interactive tools to assimilate and display track forecast information and to interpolate model tracks to facilitate the formulation of forecasts and warning strategies by front-line forecasters. Figure 3.1.2 is an example of the Tropical Cyclone Information Processing System (TIPS) operated in Hong Kong, China (Tai and Ginn 2001).

3.1.3. **Improvements in operational tropical cyclone track forecasts**

The accuracy of 24-, 48-, and 72-h track forecasts for eight centres from 1990 to 2005 using data provided by working group members and available online (see Table 3.1.1) was reviewed (Figs. 3.1.5a-c). These centres are: Regional Specialized Meteorological Centre-Tokyo (RSMC-Tokyo); Regional Specialized Meteorological Centre-La Reunion (RSMC-La Reunion); National Weather Centre of China Meteorological Administration (CMA); Joint Typhoon Warning Center of U.S. Department of Defense (JTWC); National Hurricane Center of U.S.A. (NHC); Central Pacific Hurricane Center of U.S.A. (CPHC); Vietnam National Center for HydroMeteorological Forecasting (NCHMF); and Hong Kong Observatory (HKO).
A 5-year running mean of the track forecast errors has been used to smooth the interannual variations in track errors and the number of TC forecasts issued by various centers and thus illustrate the long-term trend.

Significant improvements have been achieved by practically all of the centres. In general, the 24-, 48- and 72-hour TC track forecast errors have been reduced to around 150 km, 250 km, and 350 km, respectively, during 2001-2005. Except for CPHC, the reductions in the 5-year mean 24- and 48-hour TC track forecast errors in the two consecutive 5-year periods of 1996-2000 and 2001-2005 were in the range of 10% to 35%. These reductions are commensurate with the trends in the track forecast errors of the JMA global model and the UKMO global model for the same two 5-year periods. Moreover, reductions in errors for some NMHSs and RSMCs are noticeably higher than the 10% to 15% of individual models, which is attributed to the use of the multi-model consensus and the EPS products value to the model TC track forecasts (Goerss 2000; Lee and Wong 2002; Jeffries and Fukada 2002; Goerss et al. 2004; Heming et al. 2006).

3.1.4. **Roadblocks**

In spite of the significant developments and advancements as described in sections 3.1.2 and 3.1.3, a number of roadblocks need to be overcome to improve operational TC track forecasting.

3.1.4.1 Lack of observations

Although the passive microwave and scatterometer data from polar-orbiting satellites (e.g., AMSU, QuikSCAT, SSM/I, etc) in recent years have been made available for better determination of TC position and intensity, the temporal coverage of these satellites still does not meet all of the needs for real-time operations. The lack of observations for determining the position and intensity of a TC accurately over data-sparse areas (especially for weaker TCs with ill-defined structure) still hinders the numerical and operational TC track prediction.

3.1.4.2 Diversity of NWP guidance in forecasting TC track

While the multi-model consensus provides reliable guidance for formulation of TC track forecasts in the majority of cases when the model tracks are in reasonably good agreement, in other occasions the models give very diverse forecasts. This diversity might be due to uncertainties in initial conditions for weaker storms, difficulties in predicting certain synoptic patterns, or model bias. Simple consensus forecasts usually do not work in such cases. While the selective consensus method (Carr et al. 2001) might be used to identify and remove the likely erroneous model or cluster, very large forecast errors could still occur if the wrong model track is removed. These bifurcation cases therefore pose a great challenge to forecasters (Carr and Elsberry 2000; Jeffries and Fukada 2002).

3.1.4.3 Difficulty in forecasting landfalling TCs

It makes a lot of difference to disaster preparedness and prevention for a particular location if the forecast track of a TC is off by tens of kilometres. Current NWP guidance with an average 24-hour track forecast error of about 150 km is not sufficiently accurate for the protection of a city (Lee 2002; Regnier and Harr

2006). More accurate forecasts of the landfall point of a TC as well as the occurrence of gale winds are required.

3.1.4.4 Limited accessibility of NWP products and lack of operational TC track forecasting tools

The TC track forecasts from major NWP centres are not available to all NMHSs. Some NMHSs only have access to the outputs of no more than one or two NWP models. Multi-model consensus tracks that provide better accuracy than individual model forecasts thus cannot be constructed. Those NMHSs already using multi-model consensus method require more NWP products to identify the optimal combination of forecast members (Goerss and Sampson 2004).

Some NMHSs also lack resources and experience to develop interactive graphic tools for assimilating, interpolating, and displaying TC forecast information from advanced centres in an operational environment.

3.1.4.5 Lack of training

Many forecasters and meteorologists lack the appropriate training to make good use of NWP products from advanced centres.

3.1.5. **Opportunities and recommendations**

3.1.5.1 More observations for determining TC position and intensity

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellites are scheduled to be launched in the next few years. This will greatly add to the satellite-derived wind data that can be ingested in NWP models (Velden and Hawkins 2002; Miller et al. 2006). Thus, NWP centres should prepare for the ingestion of these satellite data into their numerical models.

The NMHSs are encouraged to disseminate their weather observation data and radar fix (RADOB) data via GTS or internet as much as possible when a TC is within the coverage of their observation networks.

3.1.5.2 Development and utilization of EPS products

In recent years, post-processing of EPS TC track forecast has been explored by several NMHSs to improve TC track prediction. It is recommended that further studies in this area should be conducted with a view to developing a systematic and optimized approach for operational implementation.

The consensus prediction error product (Goerss 2004, 2006) and outputs of EPS as mentioned in Section 3.1.2(c) can provide forecasters with some measure of the confidence in the TC track forecasts. This confidence measure may also help decision-makers to balance the lead-time versus accuracy trade-off and evaluate investments to reduce lead times or create flexibility in preparations (Regnier and Harr 2006). It is recommended that NMHSs should explore the possibility of integrating the spread information from consensus or the EPS track forecasts with the operational forecast track to also indicate the confidence.

3.1.5.3 Development of mesoscale modeling techniques

High-resolution mesoscale models incorporating local climate features and topography hold promise for improving TC track forecasts near landfall. The UKMO is applying an experimental North American (NA) regional model to investigate the impact of resolution on the forecasts for severe weather events such as hurricanes. This NA model has a domain covering North America, the Gulf of Mexico, and Caribbean Sea and has a horizontal resolution of 0.15^{o} lat. x 0.15^{o} long. (Heming et al. 2006). To meet the need for accurate track and wind/rainfall forecasts for landfalling TCs, the China Meteorological Administration has been developing a new mesoscale model called GRAPES (**G**lobal/**R**egional **A**ssimilation **P**r**E**dication

System) since 2001 (Chen and Xue 2006). A version of GRAPES with a resolution of 0.25^o lat. x 0.25^o long. was experimentally run in 2004 and its outputs have been used for TC track and precipitation forecasts (Fig. 3.1.6). Continuing research efforts are recommended to improve the ability of mesoscale models in simulating the TC landfalling processes.

3.1.5.4 Availability of tropical cyclone forecast information and tools

The JMA "Numerical Tropical Cyclone Prediction Web Site" that displays in graphical form TC forecast tracks provided by major NWP centres is extremely useful to Typhoon Committee Members (RSMC-Tokyo 2003; Kyouda 2006). This website is an encouraging example for sharing NWP products among NMHSs. It is recommended that similar initiatives be developed for other TC basins and related forecasting tools and references be made available to NMHSs.

To facilitate timely and convenient access to NWP products by NMHSs, it is recommended that the NWP centres disseminate TC track forecasts and EPS products in a standardized digital / alphanumeric format via GTS and internet.

The NWP and operational TC track forecasts developed in the past few years are very useful for NMHSs to identify optimal combinations of forecast tracks for the multi-model consensus and for researchers to develop new TC track forecasting techniques and tools. It is recommended that a feasibility study be made for setting up a unified database for archiving and sharing of NWP and operational TC track and intensity forecasts.

3.1.5.5 Collaboration and Training

It is recommended that more training events for forecasters be organized on the use of multi-model consensus and EPS products in operational TC track forecasting.

Opportunities should be created for interaction between researchers and forecasters, such as through regional or international meetings, seminars and workshops on Operational Tropical Cyclone Forecasting. These events would enable: (i) NMHSs to provide feedback on the usefulness of the NWP models; (ii) forecasters to share experiences on operational TC forecasting (e.g. forecasting tools, procedures, etc.) and thus help model developers and researchers to better understand the needs and difficulties of the NMHSs; and (iii) the identification of research needs and how research results could be adopted for operational use.

3.1.6 **Summary**

Considerable progress has been made in operational TC track forecasting in the past decade. The 5-year mean of the 24-, 48- and 72-hour forecast errors of the eight RSMCs/NMHSs studied have been reduced to around 150 km, 250 km, and 350 km, respectively, during 2001-2005, roughly 10% to 35% less than those during 1996-2000. Such improvements are attributed to the improved TC track forecasting guidance from NWP models and the use of the multi-model consensus forecasts and EPS products. However, more reliable objective forecasting techniques have yet to be developed to handle divergent track scenarios and to improve short-range forecasting of the landfall point. In this respect, methods for further post-processing of EPS track forecasts have to be developed.

More TC track guidance from NWP centres should be made available to forecasters. Steps should be taken to ensure timely and convenient access to NWP model forecast tracks in a standardized format by all NMHSs. Moreover, forecasters in many NMHSs require software tools and appropriate training to fully utilize the improved NWP-based TC forecast information in the operational environment.

References

Aberson, S. D., 2001: The ensemble of tropical cyclone track forecasting models in the North Atlantic Basin (1976-2000). *Bull. Amer. Meteor. Soc.,* **82** , 1895-1904.

Bell, G. J., 1979: Operational forecasting of tropical cyclones: past, present and future. *Aust. Meteor. Mag*., **27**, 249-258.

Carr, L. E., III, and R. L. Elsberry, 2001: Beta test of the systematic approach expert system prototype as a tropical cyclone track forecasting aid. *Wea. Forecasting,* **16**, 355-368.

Carr, L. E., III, and R. L. Elsberry, 2000: Dynamical tropical cyclone track forecasting errors. Part I: Tropical region error sources. *Wea. Forecasting,* **15**, 641-661.

Chen, D., and J. Xue, 2006: Introduction of Chinese new generation of numerical prediction model system: GRAPES. *Internal communication of China Meteorological Administration*.

Cheung, K. K. W., 2001: A review of ensemble forecasting techniques with a focus on tropical cyclone forecasting. *Meteorol. Appl.* **8**, 315-332.

Goerss, J. S., 2000: Tropical cyclone track forecasts using an ensemble of dynamical models. *Mon. Wea. Rev.*, **128**, 1187-1193.

Goerss, J. S., 2004: Estimation of tropical cyclone track forecast uncertainty. Preprints, 26th Conference on Hurricanes and Tropical Meteorology, Miami, FL, Amer. Meteor. Soc., 152-153.

Goerss, J. S. and C. R. Sampson, 2004: A history of western North Pacific tropical cyclone track forecast skill. *Weather and Forecasting*, **19**, 633-638.

Goerss, J. S., 2006: Prediction of tropical cyclone track forecast error for Hurricane Katrina, Rita and Wilma. 27th Conference on Hurricanes and Tropical Meteorology, Monterey, CA, Amer. Meteor. Soc.

Goerss, J.S., and T. F. Hogan, 2006: Impact of satellite observations and forecast model improvements on tropical cyclone track forecasts. 27th Conference on Hurricanes and Tropical Meteorology, Monterey, CA, 23-28 April 2006.

Heming, J., 2000: Tropical cyclone forecasting – the last decade. *NWP Gazette*, June, 4-5.

Heming, J.T., S. Robinson, C. Woolcock, and K. Mylne, 2004: Tropical cyclone ensemble product development and verification at the Met Office. 26th Conference on Hurricanes and Tropical Meteorology, Miami Beach, FL, Amer. Meteor. Soc., 158-159.

Heming, J.T., and G. Greed, 2006: Katrina, Rita and Wilma: Met Office model forecasts. 27th Conference on Hurricanes and Tropical Meteorology, Monterey, CA, Amer. Meteor. Soc.

Jeffries, R.A., and E. J. Fukada, 2002: Consensus approach to track forecasting. Proceedings of the Fifth WMO International Workshop on Tropical Cyclone (Topic 3.2), Cairns, Australia 3-12 December 2002.

Kyouda, M., 2006: Report on applications of EPS for severe weather forecasting. WMO Commission of Basic Systems, OPAG DPFS, Expert meeting on Ensemble Prediction Systems, Exeter,UK. 6-10 February 2006.

Lam, C.C., 2001: Performance of the ECMWF model in forecasting the tracks of tropical cyclones in the

South China Sea and parts of the western North Pacific. *Meteorological Applications*, **8**, 339-344.

Lam, C. Y., 2001: Tropical cyclone forecasting: Linkage between theory and practice. WMO Workshop on Typhoon Forecasting Research, Jeju,Korea, 25-28 September 2001.

Lam, H. K., 2001: The World Meteorological Organization pilot websites: "Severe Weather Information Centre" and "World Weather Information Service," 34th Session of the ESCAP/WMO Typhoon Committee.

Lee, T. C., and M. S. Wong, 2002: The use of multiple-model ensemble techniques for tropical cyclone track forecast at the Hong Kong Observatory. WMO Technical Conference on Data Processing and Forecasting Systems, Cairns, Australia, 2-3 Dec. 2002.

Lee, T.C., 2002: Effective warning. Proceedings of the Fifth WMO International Workshop on Tropical Cyclones (Topic 5.3), Cairns, Australia, 3-12 December 2002.

Miller, S.D., J. D. Hawkins, J. Kent, F. J. Turk, T. F. Lee, A. P. Kuciaskas, K. Richardson, R. Wade, and C. Hoffman, 2006: NextSat: Previewing NPOESS/VIIRS imagery capabilities. *Bull. Amer. Meteor. Soc.*, **87**, 433-446.

Regnier, E. and P. Harr, 2006: Information forecasting for hurricane preparation. 27th Conference on Hurricanes and Tropical Meteorology, Monterey, CA, Amer. Meteor. Soc.

Weber, H.C., 2003: Hurricane track prediction using a statistical ensemble of numerical models. *Monthly Weather Review*, **131**, 749-769.

Sakai, R., and M. Yamaguchi, 2005: The WGNE Intercomparison of tropical cyclone track forecasts by operational global models. *WGNE "Blue Book"*, available at http://www.cmc.ec.gc.ca/rpn/wgne/

Tai, S.C., and W. L. Ginn, 2001: Tropical cyclone processing systems (TIPS) of the Hong Kong Observatory, *Eighth Workshop on Meteorological Operational Systems,* ECMWF, 12-16 Nov 2001.

Tsuyuki, T., R. Sakai, and H. Mino, 2002: The WGNE intercomparison typhoon track forecasts from operational global models for 1991-2000. *WMO Bulletin*, **51**, 253-257.

Velden, C.S., and J. D. Hawkins, 2002: The increasing role of weather satellites in tropical cyclone analysis and forecasting. Proceedings of the Fifth WMO International Workshop on Tropical Cyclones (Topic 0.3), Cairns, Australia, 3-12 December 2002.

Kumar, T. S. V., T. N. Krishnamurti, M. Fiorino, and M. Nagata, 2003: Multimodel superensemble forecasting of tropical cyclones in the Pacific. *Mon. Wea. Rev.,* **131**, pp. 574–583.

WMO, 2005: Thirty-first status report on the implementation of the WMO Tropical Cyclone Programme.

Wong, M.C., 2006: Weather-related disaster risks and risk reduction. WWRP/THORPEX Scientific Conference on "Improving the Global Predictability of High Impact Weather including a review of Southern Hemisphere Plans," Capetown, South Africa, 13-15 February 2006.

Zhang, S. F., S. Z. Gao, and Y. Li, 2005: Application of consensus method on the forecast of tropical cyclones in 2004. *Internal communication of China Meteorological Administration*.

Table 3.1.1 Summary of operational TC track forecasts by warning centres, in various basins, and periods reviewed in this report

Warning Centre	TC Basin	Period
Joint Typhoon Warning Center of U.S. Department of Defense (JTWC)	Western North Pacific & South China Sea, North Indian Ocean (NIO), and Southern Hemisphere (SH)	1985-2005
National Hurricane Center of USA (NHC)	Eastern Pacific (EPC) Atlantic	1989-2005
Central Pacific Hurricane Center of USA (CPHC)	Central Pacific	1990-2005
National Weather Centre of China Meteorological Administration (CMA)	Western North Pacific & South China Sea	1991-2005
Regional Specialized Meteorological Centre – Tokyo (RSMC-Tokyo)	Western North Pacific & South China Sea	1996-2005
Regional Specialized Meteorological Centre- La Reunion (RSMC- La Reunion) *for TCs with Dvorak current intensity >=3.0*	Southwest Indian Ocean	1990/91-2004/05
Hong Kong Observatory (HKO)	Western North Pacific & South China Sea	1985-2005
Vietnam National Center for HydroMeteorological Forecasting (NCHMF)	South China Sea	1996-2005

Table 3.1.2 Summary of 5-year mean TC track forecast errors (km) for 1996-2000 and 2001-2005 (Total number of forecasts in brackets)

Centres	24-hour Forecast			48-hour Forecast		
	5-Year Mean (1996-2000)	5-Year Mean (2001-2005)	Improvement (%)	5-Year Mean (1996-2000)	5-Year Mean (2001-2005)	Improvement (%)
HKO	182 (514)	131 (617)	28	356 (334)	232 (416)	35
CMA	165 (1040)	133 (1908)	20	318 (802)	228 (1551)	28
RSMC-Tokyo	154 (1839)	128 (2289)	17	288 (1394)	232 (1820)	19
NHC-EPC	131 (1227)	111 (1152)	15	240 (940)	190 (877)	21
NHC-Atlantic	144 (1405)	119 (1743)	17	258 (1168)	219 (1410)	15
JTWC-WNP	184 (3174)	128 (3161)	31	321 (2513)	220 (2597)	31
JTWC-NIO	208 (285)	139 (228)	33	380 (186)	252 (168)	34
JTWC-SH	196 (1737)	144 (1028)	27	382 (1414)	251 (810)	34
CPHC	135 (135)	140 (173)	-4	273 (93)	251 (117)	8
NCHMF	169 (289)	143 (232)	15	---	---	---
RSMC-La Reunion	172 (689)	155 (848)	10	332 (516)	291 (836)	12
NWP Models						
UKMO-NH*	146 (2080)	132 (2431)	9	254 (1556)	227 (1886)	11
UKMO-SH**	178 (1125)	161 (767)	9	301 (831)	267 (568)	11
JMA#	169 (633)	145 (740)	14	268 (515)	229 (611)	15

* forecasts for TCs in Northern Hemisphere / ** forecasts for TCs in Southern Hemisphere
# forecasts for TCs in western North Pacific and South China Sea
Percentage of improvement = 100% x (Mean Error (1996-2000) – Mean Error (2001-2005)) / Mean Error (1996-2000)

(Note : Colour version of the Figures are available on the CD version)

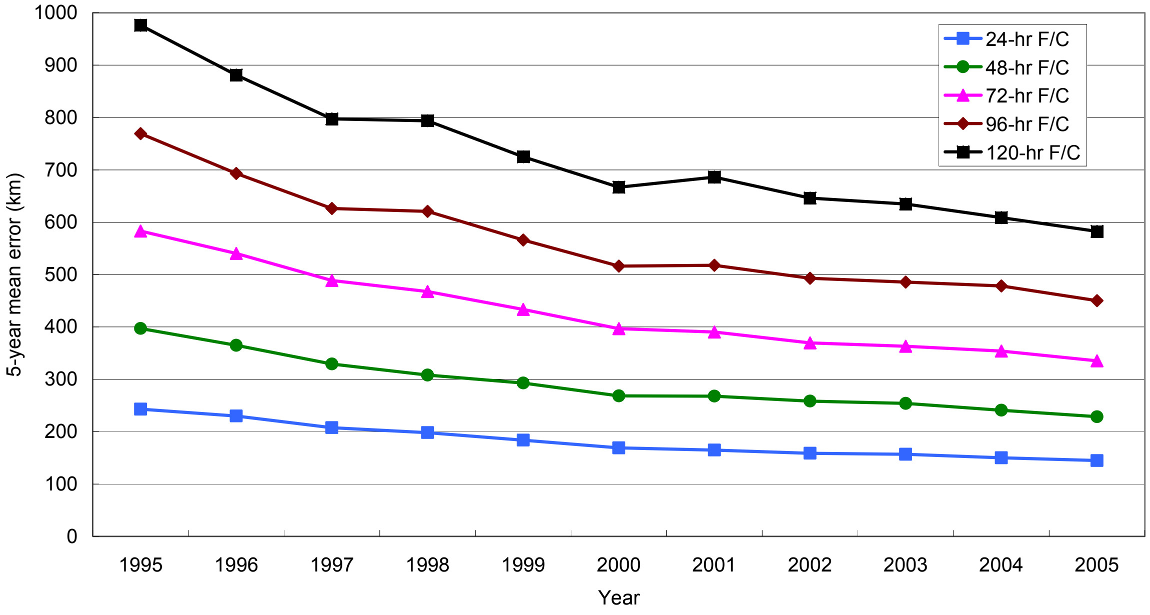

Figure 3.1.1(a) 5-year running mean tropical cyclone forecast errors of JMA global model for western North Pacific and South China Sea from 1995 to 2005 (Data Source : RSMC-Tokyo)

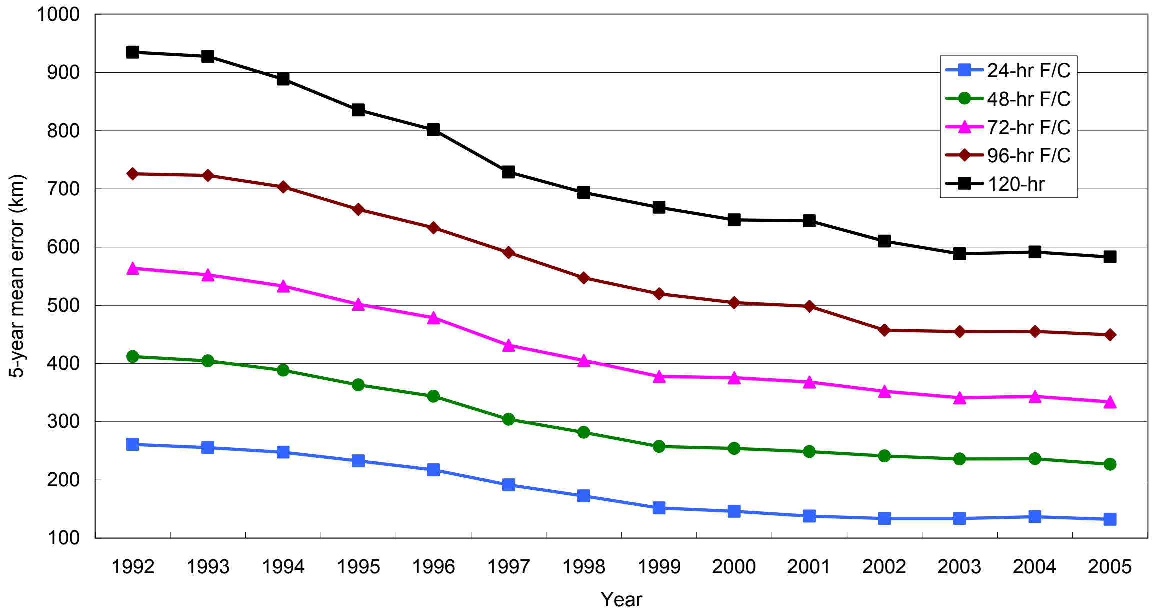

Figure 3.1.1(b) 5-year running mean tropical cyclone track forecast errors of UKMO global model for Northern Henisphere from 1992 to 2005 (Data Source : UKMO)

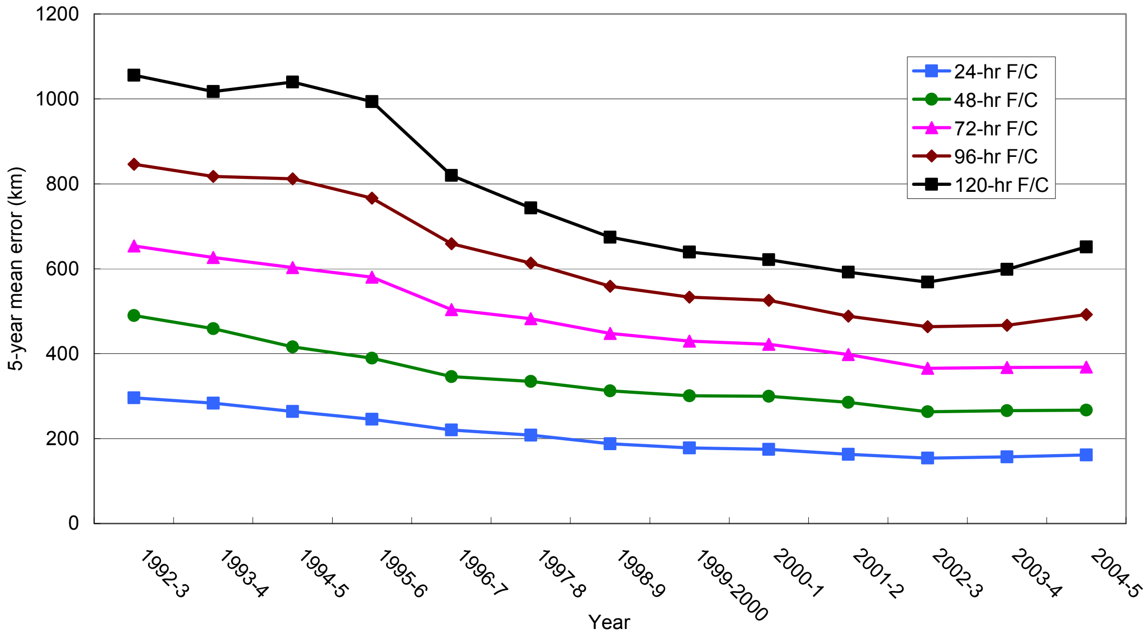

Figure 3.1.1(c) 5-year running mean tropical cyclone track forecast errors of UKMO global model for Southern Hemisphere from 1992/3 to 2004/5 (Data Source : UKMO)

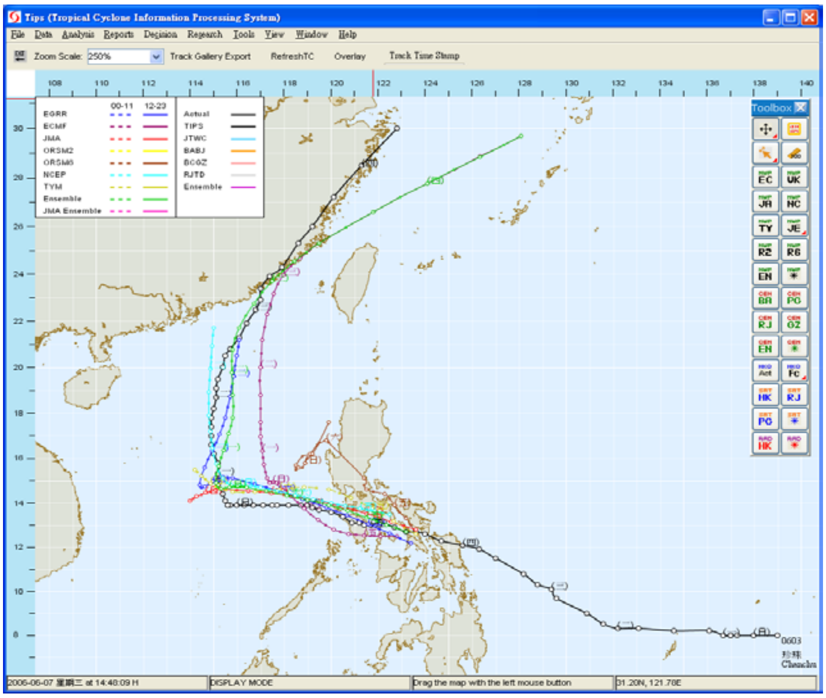

Fig. 3.1.2 The HKO display of the forecast tracks of Typhoon Chanchu based on NWP model forecasts from 00 UTC on 12 May 2006. The observed track of Typhoon Chanchu is also plotted (in black) for reference.

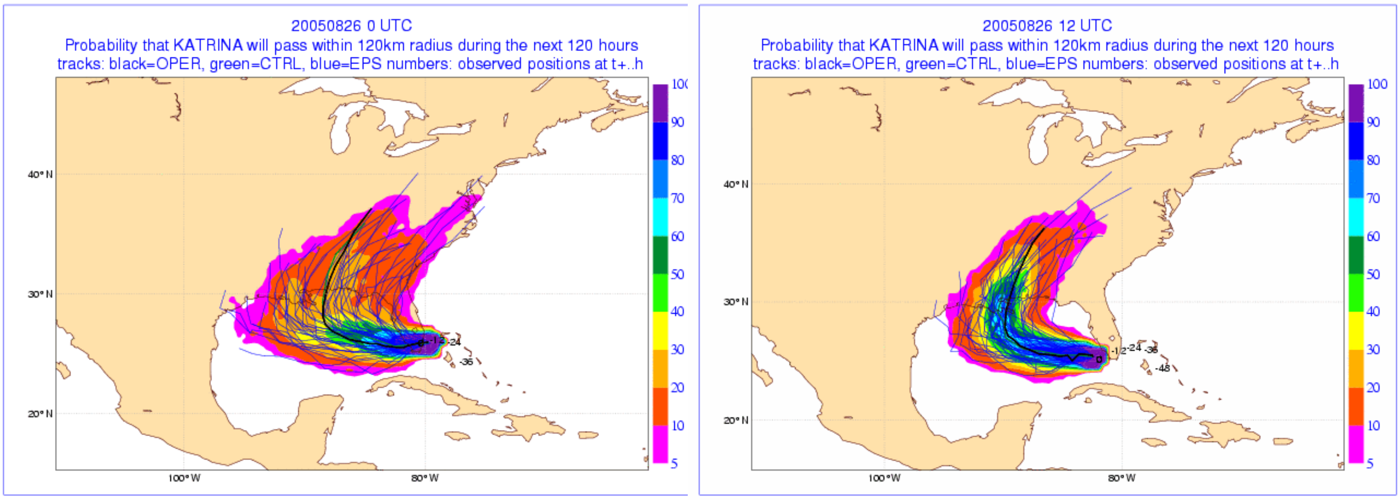

Fig. 3.1.3 ECMWF strike probability maps for Hurricane Katrina for EPS forecasts initialized on 26 August at 00 UTC (left) and 12 UTC (right).

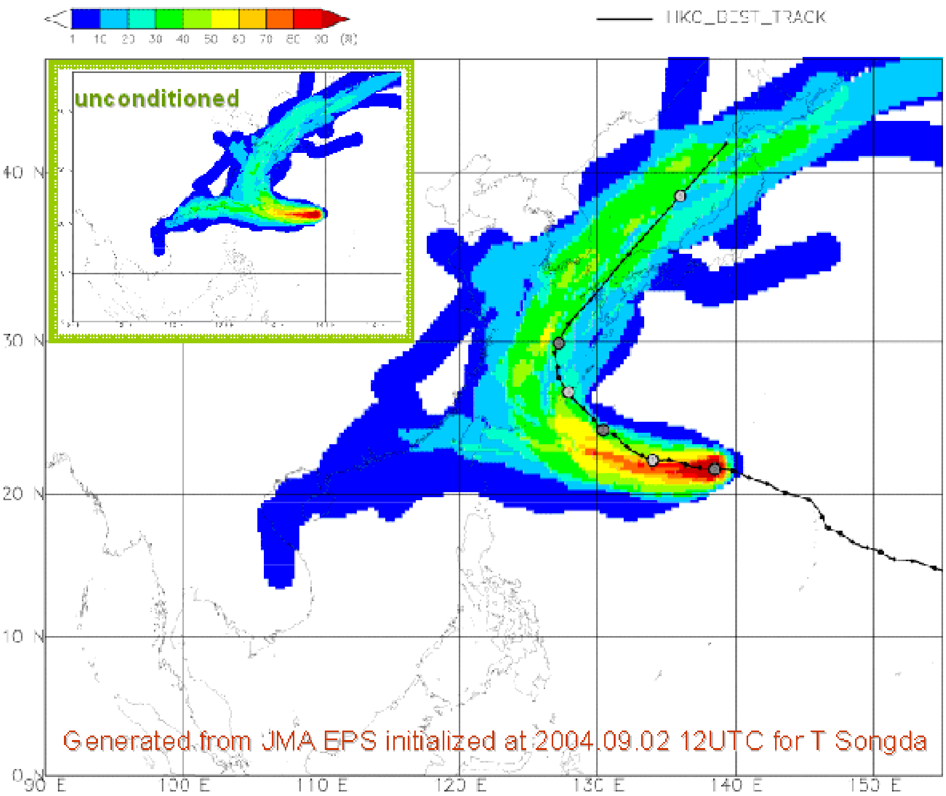

Fig. 3.1.4 Conditioned and unconditioned (inset) strike probability maps for Typhoon Songda in September 2004 (Wong 2006)..

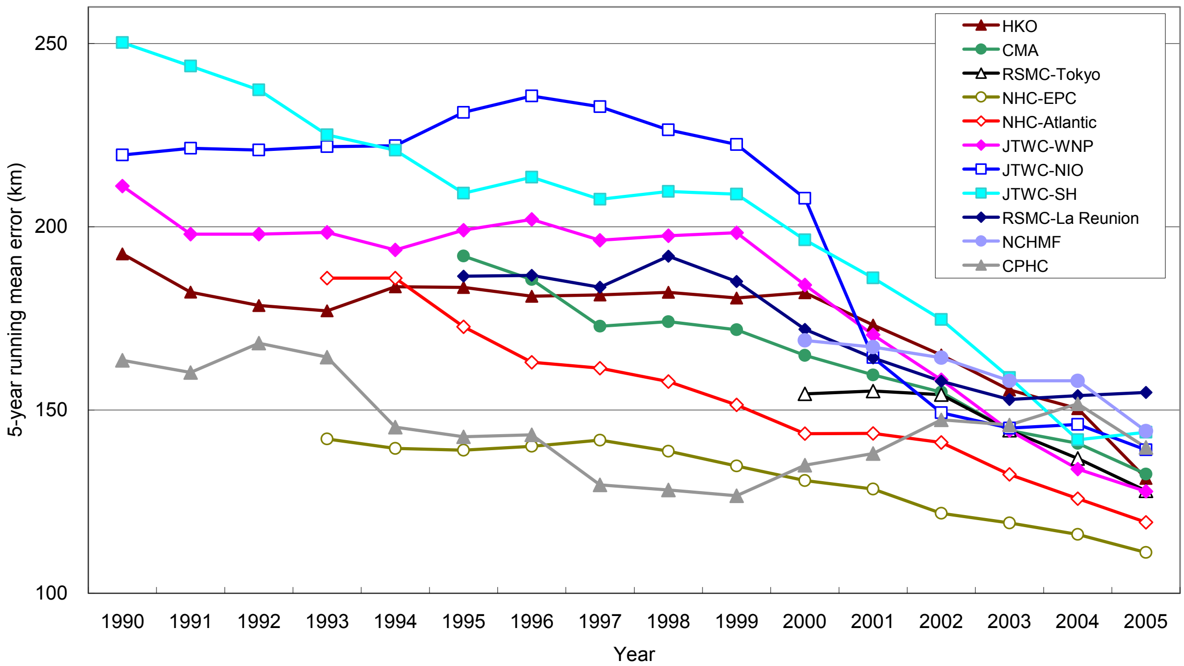

Figure 3.1.5(a) 5-year running mean error of 24-hour tropical cyclone track forecasts by different operational tropical cyclone warning centres (1990-2005)

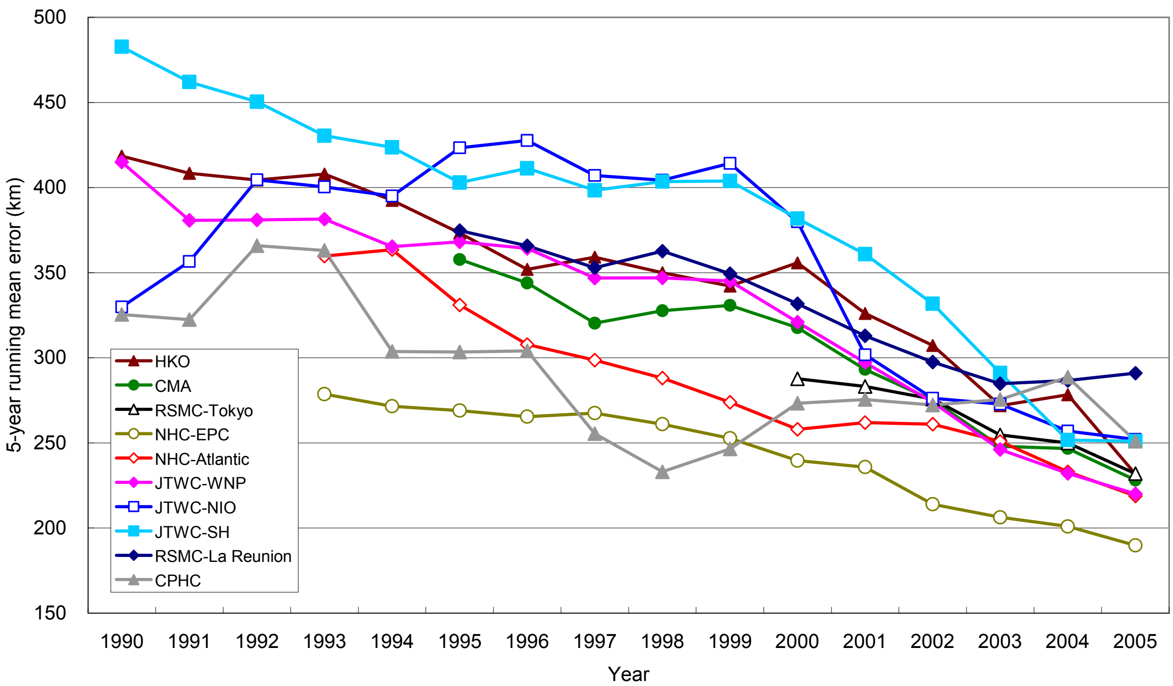

Figure 3.1.5(b) 5-year running mean error of 48-hour tropical cyclone track forecasts by different operational tropical cyclone warning centres (1990-2005)

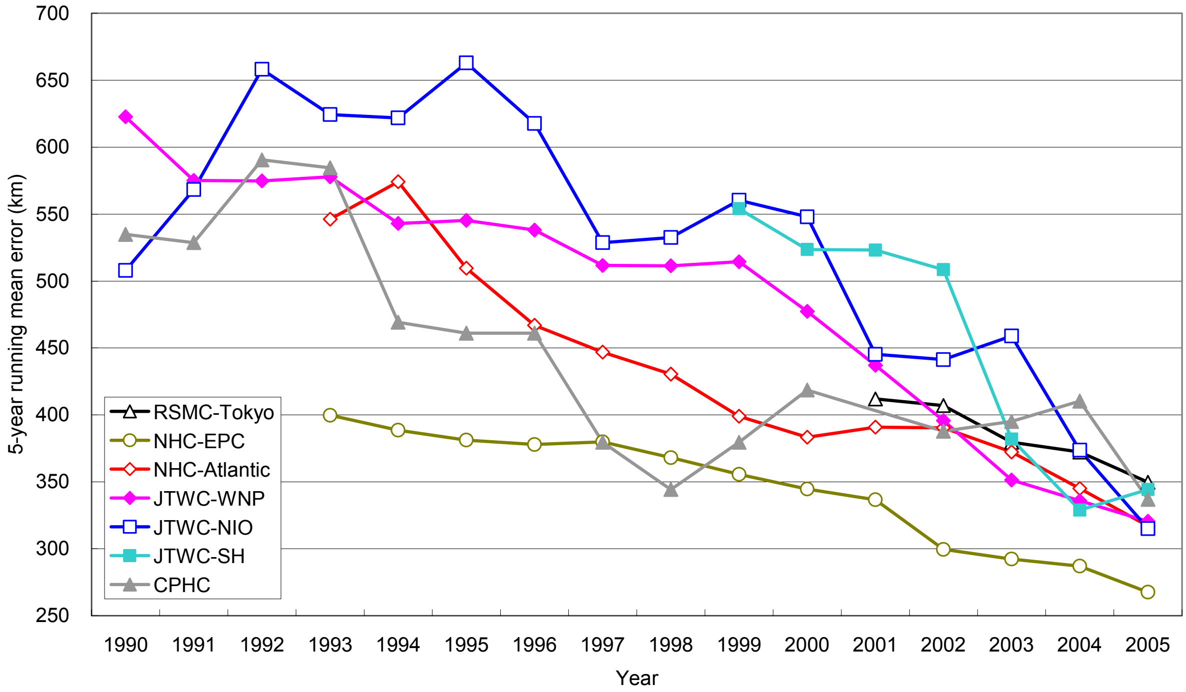

Figure 3.1.5(c) 5-year running mean error of 72-hour tropical cyclone track forecasts by different operational tropical cyclone warning centres (1990-2005)

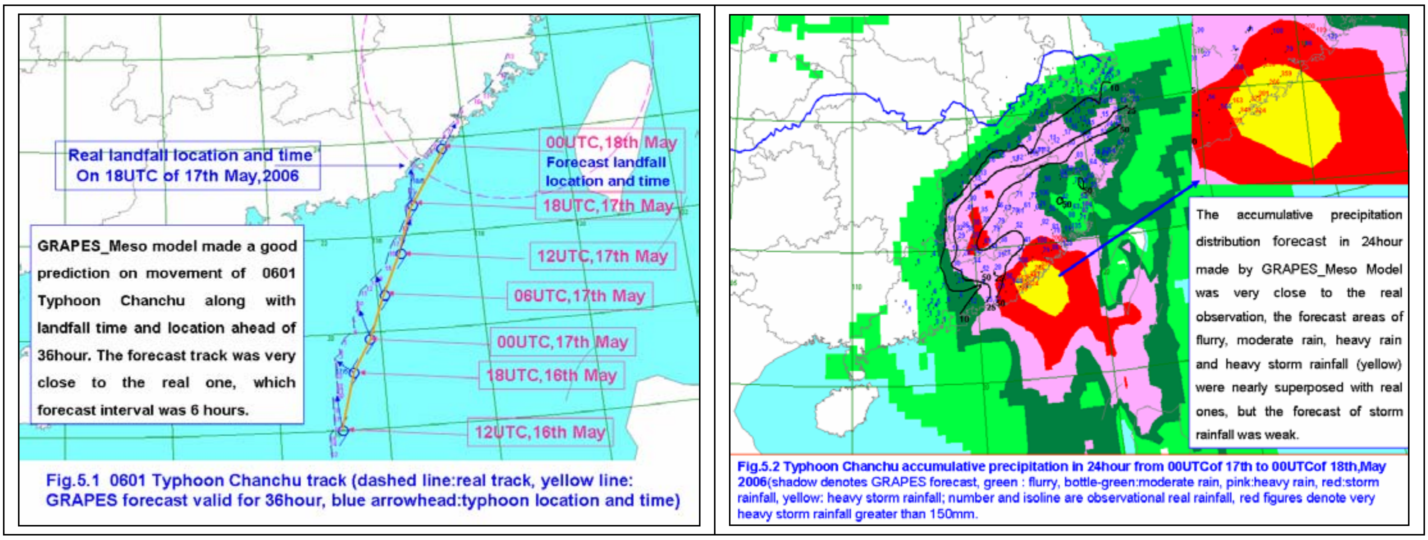

Fig. 3.1.6 Track (left) and precipitation (right) forecasts for Typhoon Chanchu in May 2006 by the GRAPES, of CMA.