OVERVIEW ON THE PROGRESS OF WORKING GROUP ON METEOROLOGY OF ESCAP/WMO TYPHOON COMMITTEE IN THE RECENT 10 YEARS

XIAOTU LEI[1], CLARENCE FONG[2], VICENTE B MALANO[3], CHE GAYAH ISMAIL[4]

[1]*Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China, 200030*
[2]*ESCAP/WMO Typhoon Committee Secretariat, Macao, China*
[3]*Philippine Atmospheric, Geophysical and Astronomical Services Administration, Manila, Philippines*
[4]*Malaysian Meteorological Department, Kuala Lumpur, Malaysia*

ABSTRACT

This paper reviews the major achievements of the Working Group on Meteorology (WGM) of ESCAP/WMO Typhoon Committee since its establishment in 2004, especially in tropical cyclone observational research and scientific experiments, tropical cyclone monitoring and forecasting technologies, seasonal prediction and climate change assessment for the past decade. The progress illustrates the great value of the Committee and WGM in monitoring and forecasting of tropical cyclones in the region and the improvement of disaster prevention and reduction capabilities.

Keywords: tropical cyclone, ESCAP/WMO Typhoon Committee, Working Group on Meteorology, 50th Anniversary

1. Introduction

Tropical cyclone (Hereinafter referred to as TC) ranks the first among the top ten natural disasters in the world. The Northwest Pacific is the most active region for TC activity, and TCs generated in the region account for about one-third of the world's annual average (Chen and Ding, 1979). Countries and regions in Northwest Pacific area are hit by TCs frequently, and it is not uncommon for a single TC to cause direct economic losses of several billion U.S. dollars. The highest mortality associated with a single TC was the Bangladesh cyclone of 12–13 November 1970 with an estimated death toll of 300 000 people (Cerveny et al, 2017). And some of TC's name has been retired due to the seriousness of the disaster (Lei and Zhou, 2012). In order to strengthen the cooperation among countries and regions in the Northwest Pacific area to battle for TCs, Economic and Social Commission for Asia and the Pacific (ESCAP) and World Meteorological Organization (WMO) jointly initiated and established the ESCAP/WMO Typhoon Committee in 1968. The committee has grown from 7 founder Members including China, Hong Kong China, Japan, Republic of Korea, Lao PDR, the Philippines and Thailand since its establishment to 14 Members today (include: Malaysia, Cambodia, Viet Nam, DPR Korea, Macao China, Singapore, and United States).

At the 37th Session of the Typhoon Committee held at Shanghai in November 2004, Members discussed and initiated the reform of the organizational structure of the Committee and decided to set up a Working Group on Meteorology (WGM) chaired by Mr. Wang Bangzhong from China Meteorological Administration (CMA), and vice-chaired by Dr. Nguyen Dai Khanh of the National Hydro-Meteorological Service (NHMS) of Vietnam. In January 2009, at the 41st Session of the Committee held in Chiang Mai, Thailand, it was decided that Dr. Lei Xiaotu from CMA would take over the role of the chair of WGM. The chairpersonship from 2004 is list in table 1.

In the past ten years, with the full support and cooperation of Members, and under the joint efforts of all the experts in the working group, more than 30 priority projects, including Annual Operating Plans (AOPs), Perennial Operating Plans (POPs) and Preliminary Projects (PPs), was organized and implemented annually (ESCAP/WMO TC, 2009-2017). The projects are listed in Table 2 and they cover scientific experiments, key technologies in tropical cyclone monitoring and forecasting, forecasting performance verification, research result conversing to operation and implementation of operational forecasting platform,

Corresponding author: LEI Xiaotu, leixt@typhoon.org.cn

DOI: 10.6057/2019TCRR02.03

Table 1. The chairpersonship of WGM from 2004

Name	Member	Position	Period
Mr. WANG Bangzhong	China	chairperson	2004-2009
Mr. LEI Xiaotu	China	chairperson	2009-
Mr. Nathaniel Cruz	The Philippines	vice-chairperson	2004-2010
Mr. Nathaniel Servando	The Philippines	vice-chairperson	2011-2014
Dr. Vicente Malano	The Philippines	vice-chairperson	2015-
Dr. Nguyen Dai Khanh	Viet Nam	vice-chairperson	2004-2010
Ms. Che Gayah Ismail	Malaysia	vice-chairperson	2011-

seasonal prediction and climate change assessment. These projects played an important role in setting up the strategic plan of the Committee, disaster preparation and reduction for Members in the region, and increasing international influence. This paper briefly outlines the major technological advances in the meteorological component of the Committee in the past 10 years.

2. Typhoon field campaign and scientific experiment

As early as 1982-1983, the ESCAP/WMO Typhoon Committee organized a scientific experiment named "Typhoon Operational Experiment (TOPEX)", which included meteorological and hydrological parts. The meteorological part consisted of intense observations to form a regional tropical cyclone real-time analysis-forecasting-warning system, while the hydrological part utilized on-site flood and storm surge data to evaluate hydrological forecast results and improve relevant model forecasting capabilities. To study the difficulty in operational forecasting of tropical cyclone anomalies such as deflection and looping, the international tropical cyclone community implemented three field campaign and experiments in 1990 at the same time, namely TCM-90, TYPHOON-90, and SPECTURM-90. Among them, SPECTRUM-90 was a scientific experiment initiated by the ESCAP/WMO Typhoon Committee. It aimed to study the movement characteristics and formation mechanism of tropical cyclones in weak steering flow or with turning track. The experiment was carried out by collecting observational data along the track of tropical cyclone to improve the accuracy of the forecast track. A variety of observation methods including satellites, Doppler weather radars, wind profilers, ground observation stations, vessels, buoys, offshore oil platforms, and aircraft dropsonde soundings were used. From August to September 1990, Typhoon Winona (9011), Yancy (9012), Abe (9015), Dot (9017), Ed (9018), Flo (9019), and Gene (9020) were selected as target tropical cyclones for intense observations. Vertical profiles of wind, temperature and humidity were collected, and subsequent scientific research supported an improvement in tropical cyclone track forecasting capabilities. In 2008, WMO launched a 10-year research project "The Observing System Research and Predictability Experiment (THORPEX)". In cooperation with THORPEX Asia Pacific (T-PARC), WGM established "To improve the forecasting skills throughout the Typhoon Committee region" project in 2008 and was led by the Japan Meteorological Agency (JMA). The project showed that the aircraft's soundings reduced the (global) model's prediction error for the 72-hour forecast of the typhoon steering path of Sinlaku (0813) and Jangmi (0815) by about 18% (Aberson, 2011). In 2009, the CMA also successfully implemented the first aircraft dropsonde experiment.

With advances in technologies such as satellites and numerical models, typhoon track forecast accuracy has increased significantly, but improvement in intensity forecast was slow (Chen and Yu et al, 2013; Elsberry and Lambert et al, 2007). In view of this, CMA, in conjunction with the Hong Kong Observatory (HKO), proposed the implementation of the scientific trial "Experiment of Typhoon Intensity Change in Coastal Area" (EXOTICCA) for tropical cyclones in the Asia-Pacific offshore region at the 45th Session of the Committee held at Hong Kong in 2013 (ESCAP/WMO TC, 2013). The proposal was approved next year at the 46th Session held in Thailand (ESCAP/WMO TC, 2014) and at the 47th session head at Thailand in 2015, the Committee decided that China and Hong Kong China should jointly implement the project (ESCAP/WMO TC, 2015). Subsequently, a project organization committee composed by some of the Typhoon Committee Advisory Working Group (AWG) and participating Member representatives was set up. The Deputy Director of CMA, Ms. Jiao Meiyan was appointed as the chair and Mr. Lai Sau-tak of HKO was appointed as the vice-chair. The first meeting of the organizing committee was held at Shanghai in 2015. At the same time, the Project Scientific Steering Committee was established and directed by Chen Lianshou, from Chinese Academy of Meteorological Sciences, and the deputy director from the US senior hurricane observation researcher Peter Black. Dr. Lei Xiaotu from the Shanghai Typhoon Institute (STI) of CMA and Mr. Wong Wai-kin from HKO were appointed as Project Chief Scientists (ESCAP/WMO TC, 2016; Lei and Wong et al, 2017). Since the implementation of the EXOTICCA project, significant progress in tropical cyclone detection technology, field campaign, structure and intensity change characteristics in offshore area, especially the wind shear in tropical cyclone condi-

TABLE 2. The priority projects of WGM from 2008 to 2017

No.	Title	Coordinator Member	Beginning	Remark/Status
Experiment				
1	Improvement of tropical cyclone forecasting skill of TC Members	JMA	2009	Related T-PARC, end in 2009
2	Contribution for the experiment on typhoon intensity change in coastal area (EXOTICCA)	CMA	2014	On going
Monitoring and Forecast				
3	To increase the forecast accuracy of TC affected by the interaction between monsoon and tropical cyclone	JMA	2008	End in 2009
4	To evaluated new grade of new tropical cyclone standards	RSMC	2008	End in 2009
5	To provide the forecasting guideline for typhoon-related disaster risk management in urban area	WMO	2008	End in 2008
	Improvement of warning services for urban areas (coastal areas)	JMA	2009	End in 2009
	Improvement of storm surge forecasting skill for coastal areas and warning services for urban area (UFRM)	JMA	2010	End in 2010
	Storm surge watch scheme for UFRM	JMA	2011	End in 2011
	Storm surge watch scheme	JMA	2014	On going
6	Typhoon early warning system	CMA, RSMC	2010	End in 2011
7	Exchange of radar data	TMD, JMA	2010	End in 2010
	Development of regional radar network	TMD, JMA	2011	On going
8	Verification of landfall typhoon forecast	CMA	2010	End in 2010
	Verification of tropical cyclone operational forecast	CMA	2012	On going
9	QPE/QPF for UFRM	JMA	2011	End in 2014
10	Ensemble forecast	JMA, CMA	2011	End in 2011
	Enhanced use of ensemble forecast	JMA	2012	On going
11	South China Sea typhoon forecast	CMA	2012	End in 2012
	Improvement of South China Sea typhoon forecast	CMA	2013	End in 2013
	Improve the performances and impacts of South China Sea typhoon model	CMA	2017	On going
12	Contribution to SSOP	Members	2013	End in 2013
	Contribution to the development of SSOP manual and SSOP training	Members	2014	End in 2015
13	Harmonization of tropical cyclone intensity analysis	JMA, CMA, HKO	2013	End in 2017
14	Harmonization of timing of upgrade of TD to TS by various warning centers	HKO (taskforce)	2013	End in 2013
	Available data used in operational tropical cyclone analysis	CMA	2015	On going
15	Improvement of severe weather forecasting and interaction with user communities	Viet Nam	2013	End in 2013
	Implementing roles of RFSC-HaNoi in SWFDP for South East Asia	Viet Nam	2016	End in 2017
16	High resolution tropical cyclone model (HTCM)	CMA	2014	End in 2014
	High resolution tropical cyclone model based on GRAPES (G-TCM)	CAM	2015	End in 2016
17	Development of tropical cyclone forecasting competency	RSMC	2015	End in 2017
Platform and communication system				
18	To effectively use the updated communication system	Members	2008	End in 2009
19	To establish consultation mechanism among the member as well as RSMC	RSMC-Tokyo	2008	End in 2009
20	To improve the information processing system of each Member	HKO, KMA	2008	End in 2008
	Development of typhoon information processing system (TIPS)	HKO, KMA	2009	End in 2009
	Typhoon information processing system (TIPS)	HKO, KMA	2010	End in 2010
	Transfer of the typhoon information processing system technology	HKO, KMA	2011	End in 2011
	Transfer of the technology of the Typhoon Analysis and Prediction System (TAPS)	KMA	2013	End in 2013
	Transfer of the technology of the typhoon operation system (TOS)	KMA	2017	On going
21	Improvement of communication system in the TC area	CMA, KMA	2009	End in 2010
22	Promotion of discussions among forecasters of TC Members during the approach of tropical cyclones	CMA	2009	End in 2010

Continued

Table 2. The priority projects of WGM from 2008 to 2017

No.	Title	Coordinator Member	Beginning	Remark/Status
23	Improvement of warning information dissemination	HKO	2009	End in 2010
24	Web-based typhoon forum	CMA, RSMC	2010	End in 2010
	Web-based typhoon forum	CMA, TSC	2016	On going
25	Effective warning	Members	2011	End in 2012
26	Publication of Typhoon Cyclone Research and Review	CMA	2011	On going
27	Training attachment to HKO on QPE/QPF	HKO	2014	End in 2015
28	Collaborative Discussion (CoDi) platform on tropical cyclone analysis and forecast	CMA, HKO	2017	On going
Seasonal prediction and Climate change				
29	To assess the frequency and intensity change of tropical cyclone	HKO, CMA	2008	End in 2008
	Assessment of the impact of climate change on tropical cyclone frequency and intensity variation	HKO, CMA	2009	End in 2009
	Assessment of impact of climate change on tropical cyclone in TC region	Macao (expert team)	2010	1st report issued in 2010
	2nd assessment report on the impact of climate change on tropical cyclone track and impact areas in TC region	Macao (expert team)	2011	2nd report issued in 2013
	Assessment report on the impact of climate change on tropical cyclone in TC region	Macao (expert team)	2013	On going (For 3rd report)
30	Development of typhoon seasonal prediction system	KMA	2013	On going

tions, and the conversions between wind speeds at different time intervals, were achieved and listed below.

2.1 Development of new sounding technologies

A new tropical cyclone dropsonde sounding system using rocket (missiles) was developed and the world's first test was implemented in October 2015. In the core zone of the super typhoon Mujigae (1523) (about typhoon center in the area of 80 km far and 12 km high), four sounding dropsondes were released and observation data such as wind, temperature, pressure and humidity were successfully obtained with high quality (Lei and Zhao et al, 2017). The experiment also showed that the rocket (missiles) was relatively fast (about 6 minutes from takeoff to landing) and is an effective means of acquiring direct observation data in different regions of the tropical cyclone and at the same time which can be used in forecast-based target sensitivity observations.

2.2 Collaborative field observation

This include the use of wind chasing vehicles, low-altitude drones, surveillance flight and challenger jet, buoy arrays, and wind profilers, microwave radiometers, GPS automatic radiosondes, and disdrometers. During 2014-2016, more than 20 target tropical cyclones were observed[1)]. Vertical soundings and wind profiles for the boundary layer and data from disdrometers were obtained for Fungwong (1416), Chan-hom (1509), Soudelor (1513), Mujigae (1522), Nepartak (1601), Meranti (1614), Megi (1617), and Sarika (1621). Sea-surface wind, surface flow and air-sea flux data before and after passage of buoy arrays were obtained for Rammasun (1409) and Kalmaegi (1415). Unmanned aircraft detection data at the boundary layer (400 meters low altitude) for the tropical cyclone landing process were obtained for Chan-hom (1509). Dropsonde data from rockets (missiles) for tropical cyclone intensity and inner core structure were obtained for Mujigae (1522). And aircraft observation data were obtained for Linfa (1501), Mujigae (1522), Nida (1604) and Dianmu (1608).

2.3 Application demonstration research

Based on field campaign data, the changes in the boundary layer structure (including the height of the boundary layer, etc.) during the landing process of target tropical cyclones such as "Meranti", "Sarika", and "Megi" and the characteristics of turbulence flux and counter gradient transport in surface layer was observed and studied, with focus on the change of wind shear before and after landfall. The wind speed conversion relationship at different times was revised and the results were applied in CMA's best track analysis and the improvement in Dvorak analysis in operation. In addition, the value of field campaign data, in addition to improving the understanding of the tropical cyclone landfall process and modifying the corresponding parameterization scheme to improve the forecasting ability of the model, the project also conducted numerical experiments on direct assimilation of field campaign data to mod-

1) Lei X.T., Wong W.K., Zhou B.K.,etc., The progress of experiment on typhoon intensity change in coast area.

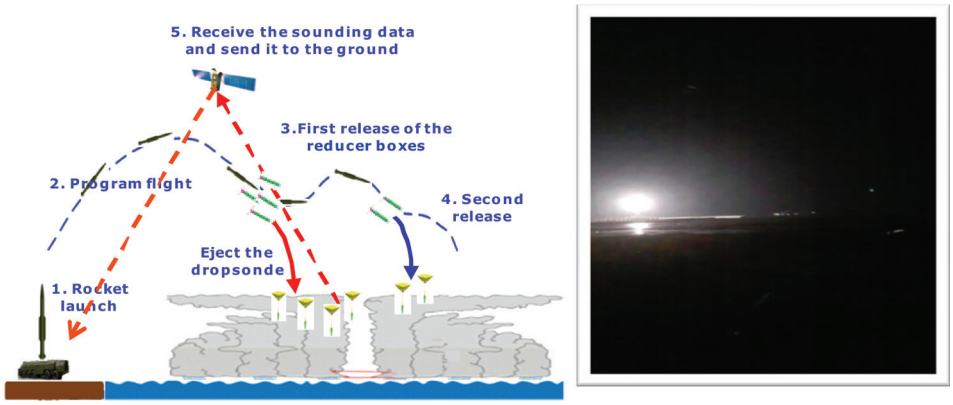

FIG. 1. Process of rocket dropsonde system launch (left) and pilot for Mujigae (1522) on 11pm of 3 Oct. 2015

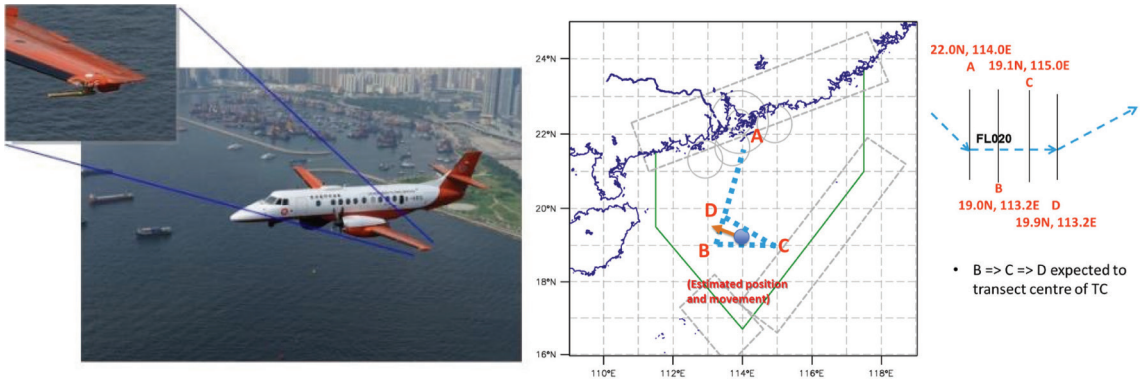

FIG. 2. The reconnaissance flight of Hong Kong China and the scheme for Mujigae (1522)

els. There are positive contributions to the simulation and forecast of tropical cyclone track and intensity (ESCAP/WMO TC, 2017).

Senior scientists such as Peter Black of the United States and Zhang Jun of the Hurricane Research Division (HRD) participated in the international cooperation in the field of observational data quality control and diagnostic analysis (financed by the National Natural Science Foundation of China and the Ministry of Science and International Cooperation of China). Thailand, Viet Nam, the Philippines, and Malaysia have sent experts to participate in the demonstration application research of field campaign data.

3. Key technologies for tropical cyclone monitoring and forecasting

In the past ten years, WGM has made remarkable progress in key technologies such as radar network, satellite typhoon monitoring and typhoon numerical forecasting by undertaking the WMO demonstration project, setting up and conducting continuous special research annually. These include:

3.1 Southeast Asia radar network and tropical cyclone quantitative precipitation estimation

Quantitative precipitation estimation and forecast (QPE/QPF) is a difficult point in operation and is the main technical bottleneck restricting the accuracy of hydrological forecasting. To cope with the implementation of the Urban Flood Risk Management System (UFRM) under tropical cyclone conditions adopted by the Typhoon Committee, WGM implemented the "QPE/QPF for UFRM" project in 2010 and was led by the WMO Regional Specialized Meteorological Center (RSMC)-Tokyo. The project researched and collated the technical progress made by Members in tropical cyclone QPE/QPF, formed a corresponding technical booklet, and provided training to pilot cities selected by the Committee. In addition, because of various reasons, radar models in Thailand and the Philippines are not the same (even within their territory), causing problems such as uniformity of radar network application. As a result, WGM established the project in 2011 to achieve the splicing and sharing of radar data of different types in Southeast Asia, and to develop tropical cyclone QPE technology based on

different types of radar puzzles. Thailand took the lead and JMA provided technical support, with Malaysia, Viet Nam, Philippines and Lao PDR joining the project in succession. The project first realized the seamless puzzle of multi-type radars in Thailand. Then the scope of the puzzles was extended to Malaysia and will be further expanded to Viet Nam and the Philippines. In addition, the project also established a tropical cyclone QPE system based on the radar puzzles, and has already invested in quasi-operational applications, effectively improving the monitoring capabilities of offshore and landing tropical cyclones (especially precipitation) in Southeast Asia.

3.2 *Timeliness of typhoon numbering and application of multi-source direct observation data in tropical cyclone intensity analysis*

As the South China Sea area is small compared with Northwest Pacific, a tropical cyclone can land within 2-3 days after genesis. Sometimes the tropical cyclone will land less than 1 day after being numbered (upgraded from tropical depression to tropical storm), which will result in passive time reduction for flood prevention in coastal countries and regions. In view of this, CMA raised the issue of "strengthening the numbering of the typhoon in the South China Sea" in 2011. During the subsequent successive sessions and seminars, WGM conducted thematic discussions and set up "Ad hoc" and "Taskforce" expert groups successively, with members from China, Hong Kong China, Japan, the Philippines, Republic of Korea and Viet Nam. In 2012, the Ad hoc Group of Experts conducted a more detailed study on cases of discrepancies in the warning intensity of tropical cyclones in the South China Sea between China and Japan (especially associated with the upgrade from tropical depression to tropical storm). In 2014, the Taskforce expert group held a special discussion in Hong Kong China and concluded that early issuance of the warning bulletins by RSMC-Tokyo would greatly facilitate the warning operation of other countries and that more effective exchange of observational data over the South China Sea (e.g. offshore oil platform and buoy data) should be made among the centres, with the exchange of metadata of the observations also necessary for data quality assessment. The study also found that when using the Dvorak technique to determine the intensity of tropical cyclones in operation, even with the same satellite image, different analysis results could be obtained by different centres. To further investigate into this issue, WGM established the "Harmonization of tropical cyclone intensity analysis" project in 2013 to systematically compare and analyze the intensity data from CMA, RSMC-Tokyo, Joint Typhoon Warning Center (JTWC) of USA, and HKO to find out the reasons for the differences in Dvorak intensity estimates for tropical cyclones.

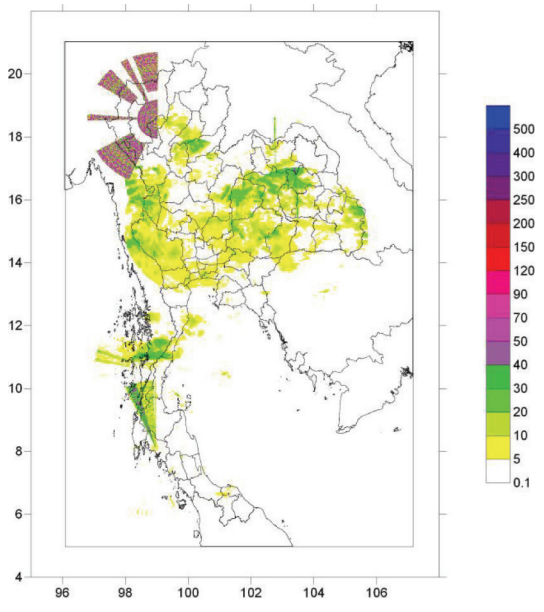

Fig. 3. Radar network in Thailand and the radar QPE on 18 JUL 2014 23:45 UTC

On the other hand, with the development of coastal and marine economies in various countries and regions, multi-source direct observation data such as island meteorological observation stations and marine buoys, offshore oil platforms, gradient observation towers, ship navigation, and flight exploration scientific experiments were becoming increasingly abundant. However, the current operational tropical cyclone intensity analysis (including RSMC-Tokyo) still relied heavily on satellite-based Dvorak technology, and a large number of direct multi-source observations were not available in real-time from the WMO GTS system. Therefore, WGM established a pre-research project on the application of multi-source direct observation data in tropical cyclone intensity analysis. It was led by CMA and aimed to study the possibilities, techniques and operational procedures to utilize the data provided by Members in determining the intensity of tropical cyclones. So far, the CMA has compiled a total of 223 ground-based observing stations (including radars) available in the South China Sea area. Through analysis of individual cases of 18 tropical cyclones between 2013 and 2016, CMA has demonstrated that the various types of direct ground-based observations for tropical cyclone intensity and structural analysis was very effective, and initial operational procedures for utilizing these data in tropical cyclone structural and intensity change analysis were designed. After further improvement, the Typhoon Operation Manual (TOM) of ESCAP/WMO Typhoon Committee will be revised.

In addition, Members have made great progress in meteorological satellite technologies in recent years, such as the launch of high-resolution meteorological satellites including Himawari-8/9, FY-2F/4, and GOES-16 and CYGNSS, which have enhanced the monitoring and forecasting capa-

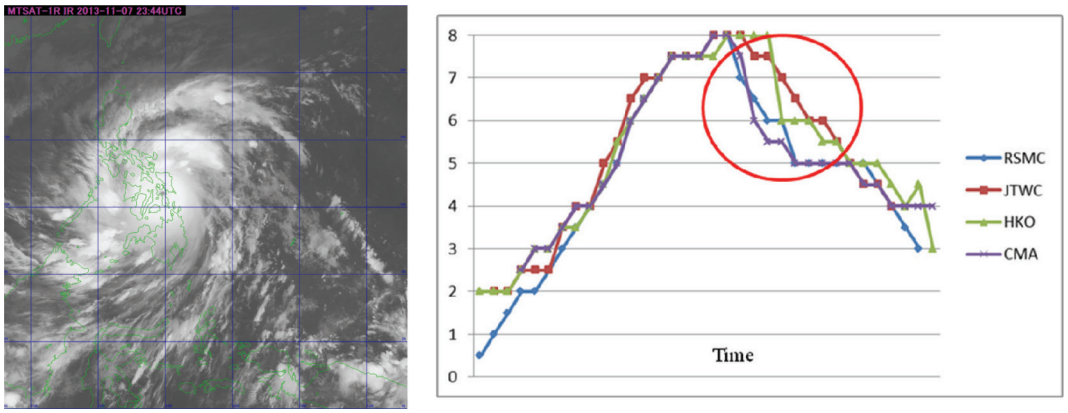

FIG. 4. Large difference among RSMC-Tokyo, CMA, HKO and JTWC in CI numbers are found after Haiyan(1330) made landfall in the Philippines on 23UTC 7 November 2013

bilities of tropical cyclones. As a result, WGM established a preliminary project on strengthening the application of high-resolution satellite data in 2018. It was led by the JMA and was focused on Himawari-8/9 initially, but would be extended to other high-resolution satellite data applications in the future.

3.3 Development and improvement of the South China Sea Typhoon numerical model system

In recent years, the development of tropical cyclone numerical models in various countries and regions has progressed significantly. In particular, H-WRF in the United States and GRAPES-TCM in CMA have played an indispensable and important contribution to the prevention and reduction of disasters by tropical cyclones. There are many islands in the South China Sea, and the underlying surface conditions are complex. The proportion of unusual typhoon activity is also high and hence monitoring and forecasting is difficult. WGM has strengthened and established AOP on the development of the typhoon model in the South China Sea since 2012, led by the Guangzhou Tropical Ocean Meteorology Research Institute of CMA. The project is based on the regional tropical ocean meteorology model (TRAMS) developed by Guangzhou Tropical Ocean Meteorology Research Institute and combined with the tropical cyclone scientific experimental and the field campaign observation data in the South China Sea region. The model nonlinearity and convective precipitation calculation were carried out under strong wind conditions, and the parameterization of sea surface and tropical cyclone boundary layer processes could be improved. The horizontal resolution of the model has been increased from the initial 36km

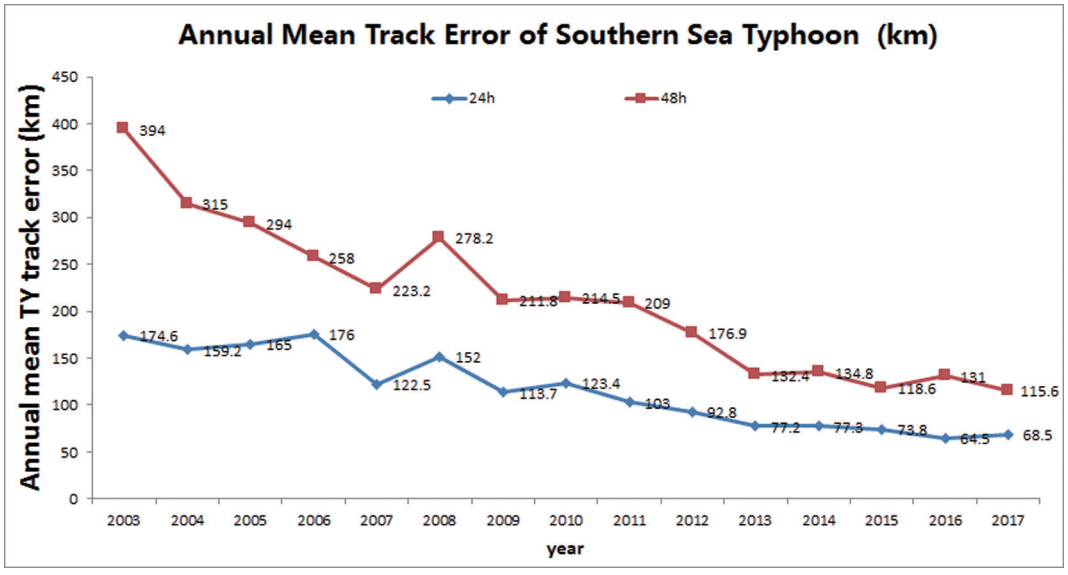

FIG. 5. The track forecast error of TRAMS model

to the current 9km, which has significantly improved the prediction capability of the tropical cyclone in the South China Sea, and the 24 hour mean error of the tropical cyclone track forecast has dropped to about 70km (about 30% less than 10 years ago). The model products have been used by the Members of the Committee in real time through the English website.

In addition, in conjunction with the WMO Severe Weather Forecasting Forecast Demonstration Project (WMO-SWFDP), WGM launched a project entitled Implementing roles of RFSC-HaiNoi in SWFDP for Southeast Asia in 2011, led by Viet Nam. The project developed an objective prediction method for tropical cyclone track and intensity based on the interpretation of multi-source numerical forecast products, which achieved the sharing of products and promoted the development and application of key technologies in the Southeast Asia numerical forecast model.

3.4 Research and development of tropical cyclone ensemble forecast technologies

With the development of global ensemble forecasting systems and especially the sharing of THORPEX Interactive Grand Global Ensemble (TIGGE) data, ensemble and super ensemble forecasting technologies have attracted attention in the weather forecast. The 2nd International Workshop on Tropical Cyclone Landfalling Processes (IWTCLP-2) was held in Shanghai China in 2009 to discuss the tropical cyclone ensemble forecast based on TIGGE. Subsequently, WMO World Weather Research Programme (WWRP) and Tropical Cyclone Programme (TCP) jointly established a tropical cyclone ensemble forecast demonstration project in 2010 (WMO-TCEFP), and the Typhoon Landfall Forecast Demonstration Project (WMO-TLFDP) aimed at improving the capability of forecasting landing tropical cyclone. To strengthen the application of TIGGE in tropical cyclone forecasting (especially for genesis), WGM's 2010 project entitled "Enhanced use of ensemble forecast" was led by Japan. The project investigated and improved the typhoon vortex identification technology in the global model, evaluated the ability of the TIGGE model to generate tropical cyclone forecasts, and developed a preliminary typhoon generation and intensity forecasting method based on TIGGE data. In addition, based on WMO-TLFDP, CMA developed techniques for selecting the members in the ensemble forecasts through the method of determining ensemble weights by their early errors (Du and Qi et al, 2016), and obtained significant outcomes in operational applications.

3.5 The construction of storm surge forecasting system

As we all know, in addition to heavy downpours, storm surges are also the main cause of tropical cyclone disasters in coastal areas. In view of this, WGM has established the Storm surge watch scheme in 2010. The RSMC-Tokyo developed and established a storm surge ensemble forecasting system based on tropical cyclone track and intensity uncertainties to achieve a fine fixed-point forecast for tidal level and tidal time, and system has been operational. The figure 6 shows the sample of storm surge distribution maps and time series charts at station caused by tropical cyclone.

By the end of 2017, storm surge forecast products for a total of 77 locations from 10 Members of the Committee have been exported. In addition, the project also studied the performance evaluation methods of the storm surge forecasting system, and the results have been included in the annual reports on activities of RSMC-Tokyo since 2015.

4. Tropical cyclone forecast performance evaluation and achievement transformation platform

4.1 Tropical cyclone forecast performance verification

With the increase in scientific and technological support for tropical cyclone forecasting, the number of products available for operational use has increased but each product has different performance. It always causes serious

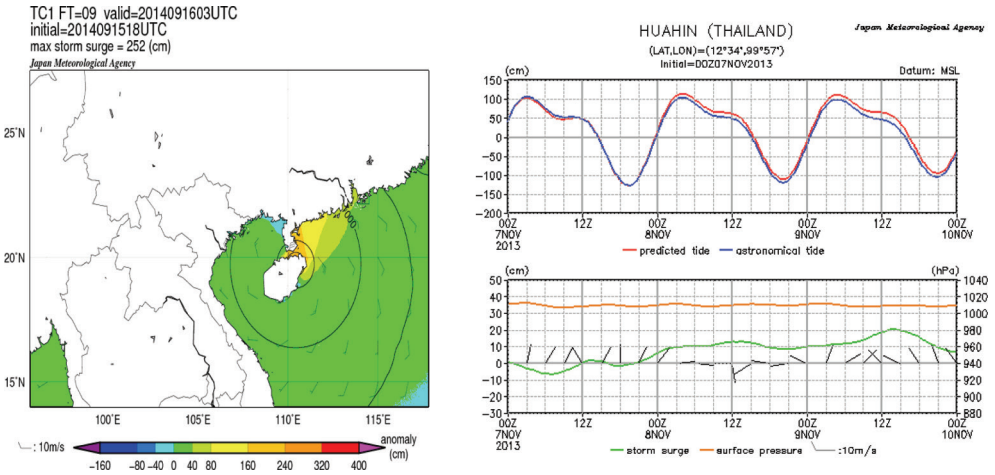

Fig. 6. The sample of storm surge distribution maps (left) and storm surge time series charts (right)

interference for forecasters and policy makers to judge and choose within limited time in operational situation. Therefore, understanding the performance and systematic errors of different methods and their products will have important operational value. On the other hand, through forecast performance verification, developers can target to improve and conduct further research and development, continue to promote the application, which will facilitate the discovery of new issues in the development in tropical cyclone science. In view of this, WGM has established a verification of tropical cyclone operational forecast project since 2010 and is led by STI of CMA. In combination with the WMO-TLFDP, the project collaborated with the WMO Expert Group on Forecast Assessment to study and establish a complete tropical cyclone forecasting performance evaluation system. The evaluation indicators and technologies were included in WMO related technical manuals (JWGFVR, 2013). On this basis, the performance of various tropical cyclone subjective and objective forecasting methods in the Northwest Pacific (including the South China Sea) region is evaluated and shared in real-time through the WMO-TLFDP website. The annual report of the verification results has been submitted to the annual meeting of ESCAP/WMO Typhoon Committee since 2013 and has become an important reference for the Committee to formulate a strategic plan and annual priority work plan.

4.2 Implementation of operational platform

WGM also focus on the implementation of operational platform. Since 2009, the "Transfer of the typhoon information processing system technology (TAPS)" and "Web-based typhoon forum" have been established. They were led by Korea Meteorological Administration (KMA) and STI of CMA respectively. Among them, the TAPS system was developed by KMA and includes functional modules such as query of tropical cyclone monitoring data, diagnostic analysis and forecasting product, etc. It is a platform for operational monitoring and forecasting as well as skill training for tropical cyclone forecasters. The English version of the TAPS platform was also implemented and provided 2 man-month training for Members of the Committee every year. In addition, other Members of the Committee have also established similar platforms, such as CMA's Meteorological Information Comprehensive Analysis and Processing System (MICAPS) system and the HKO's Typhoon Information Processing System (TIPS) system, both serve as a vehicle to provide training to Members with appropriate skills each year. The Web-based typhoon forum was established by the STI of CMA based on the Internet and aimed to establish a real-time communication for typhoon monitoring and sharing of forecasting information among Members of the Committee. In the forum users can find real-time information exchange, historical information retrieval and real-time discussion on operational issues. Since the launch of the forum, a total of 65 representatives from 11 Members of the Committee have signed up. A link was established in the website of the Typhoon Committee in 2017 and the forum is open to the public. To further improve and expand the real-time communication channels among members, HKO and CMA have jointly established the mobile Internet-based typhoon information real-time exchange platform (CoDi platform) in 2017 for tropical cyclone analysis and forecast and the web-based typhoon forum was merged with CoDi since 2018.

4.3 Establishment of international academic journal

As we all know, tropical cyclone ranks first among the top ten natural disasters in the world. To promote scientific research and operational technology development in various related fields of tropical cyclone in a more comprehensive and timely manner, and to promote the transformation of scientific and technological achievements and the prevention of Asia-Pacific and global typhoon disasters, STI of CMA worked closely with Typhoon Committee Secretariat for more than two years and established the international academic journal of ESCAP/WMO Typhoon Committee in 2012 - Tropical Cyclone Research and Review (TCRR). The journal is a quarterly journal (International Journal No. 2225-6032) with editorial office located at STI of CMA, and it has maintained the high standards of international first-rate journals with internationalization of editorial committees, reviewers, and authors from worldwide. To date, it has published more than 100 high-level tropical cyclone special research papers and the papers are well received by WMO, ESCAP and the international tropical cyclone community. The number of authors and readers are still increasing, especially for countries such as the United States and Australia (the number of full-text downloads in the United States exceeded 50% of the total).

There is also a visiting editor fellowship for the journal which is jointly funded by Typhoon Committee and the STI of CMA. The visiting editor will be selected from among the experts nominated by the Members of Typhoon Committee and he/she will visit and stay in the editorial office for one week in STI of CMA to undertake corresponding editorial work. So far experts from Republic of Korea, Thailand, Philippines, United States, Viet Nam, and Lao PDR joined the fellowship.

Since its establishment, the TCRR has received great attention from literature agencies. In 2017, the Editorial Office signed the TCRR Promotion Cooperation Agreement with China Keai Company. Moreover, the China Knowledge Network (CNKI)'s accepted to archive all articles into their full-text journal database. And in 2017, TCRR became the source journal for the Emerging Sources Citation Index (ESCI). To commemorate the 50th anniversary of the establishment of the Typhoon Committee, TCRR published a series of special issue in 2018. The first special issue was released at the 50th Session of the Committee held in Viet Nam in February 2018.

5. Typhoon seasonal prediction and climate change assessment

5.1 Typhoon seasonal prediction

Seasonal forecasts such as tropical cyclone genesis and landing (or influence) frequency are of great significance for annual budgets and material budgets for preventing and reducing disasters by tropical cyclone. American scientist, Bill Gray studied the technical method of using the Sahara desert precipitation to predict the seasonal frequency and annual frequency of Atlantic hurricanes in the early 1990s and put it into practical use. In 2012, WGM set up a special project on tropical cyclone seasonal prediction, which was led by KMA. For computing the seasonal forecast of tropical cyclone frequency in the Northwest Pacific, the project used a few methods, including multiple linear regression model (MLR), "FSU/COAPS 3D original equation global spectral model ensembles at a resolution of T126L27", as well as statistical-dynamic forecasting methods, and seasonal predictions for June-August and September-November have been released through the project website and shared by Members since 2013. In addition, STI of CMA carried out research on seasonal prediction methods for tropical cyclone in the 1990s, and successively established multiple types of statistical forecasting and statistical-dynamic forecasting methods and produced operational products for the government to formulate an annual plan for preventing and reducing typhoon disasters.

5.2 Tropical cyclone climate change assessment

With the influence of the Intergovernmental Panel on Climate Change (IPCC) assessment report, whether tropical cyclone will increase as a result of global climate change has become a hot topic of international concern. This is a complicated subject with on-going research and discussion by the scientific community. As an official body of the international collaboration on the mitigation of impacts of tropical cyclones in the Asia-Pacific Region, ESCAP / WMO Typhoon Committee attaches great importance to the impact of climate change on tropical cyclones. In view of this, WGM established the "Assessment report on the impact of climate change on tropical cyclone in Typhoon Committee region" project in 2009, and organized a team composed of scientists from China, Hong Kong China, Japan, Republic of Korea and United States (with team leader from Hong Kong China for the 1st report, China for the 2nd and 3rd report, and coordinator from Macao China). Since the establishment of the project, the first and second assessment reports were issued in 2010 and 2013, respectively, under the name of ESCAP/WMO Typhoon Committee. Besides reviewing relevant research publications, the expert team examined the TC frequency trends from datasets available from several different centers for western North Pacific. Moreover, in response to the Typhoon Committee's request, the expert team surveyed each of the Typhoon Committee Member concerning the climatology and observed trend behavior of TC activity and related impacts in their respective countries. The main conclusions have been published in TCRR and cited by the IPCC-AR5, which has greatly increased the influence of the Typhoon Committee and WMO (Lee and Knutson et al, 2012; Ying and Knutson et al, 2012). The preparation of the third assessment report (TC-AR3) started in 2014. The expert team has drawn up plans for the preparation of the report and collected scientific research papers in related fields, and finished the draft at present. The final TC-AR3 report is expected to be released in around 2019-2020.

6. Summary and future plan

The ESCAP/WMO Typhoon Committee was established in 1968 to set up a platform for technical cooperation and sharing among Members of the Committee. The WGM was established in 2004 and has made important contributions to the improvement of tropical cyclone monitoring, forecasting and early-warning capabilities in the Committee region. In the past 10 years, new technologies for tropical cyclone monitoring were developed such as rocket dropsonde soundings, and sensitivity-based observations based on forecasts became possible. Scientific experiments on tropical cyclone intensity changes were organized and research on multi-source observations and tropical cyclone structure and intensity change has been conducted. These have promoted the development of operational tropical cyclone intensity analysis. There is significant improvement in high-resolution tropical cyclone models and ensemble forecasts, and establishment of operational platforms have promoted the application of results for operation as well as training. Track forecast errors of tropical cyclone for Members of the Committee have generally reduced by more than 30% compared with 10 years ago, and seasonal prediction and genesis forecast extended the valuable lead-time for tropical cyclone prevention and disaster reduction. The publishing of tropical cyclone climate change assessment report and international academic journal have greatly increased the international influence of the Committee. In the future, WGM will pay more attention to:

(1) Intensify the field campaign on tropical cyclone in the Committee region, jointly carry out a special scientific experiment on the challenging (hard to forecast) but important issues. For example the structure and intensity changes of landfalling tropical cyclone in the Committee region.

(2) Develop high resolution tropical cyclone model and reinforce the forecast ability of intensity, wind (gale) and quantitative precipitation.

(3) Reinforce the research of techniques for medium and long range forecasting, evaluate and recommend the seasonal prediction techniques of tropical cyclone.

(4) Strengthen the cooperation with Working Group on Hydrology (WGH) and Working Group on Disaster Risk Reduction (WGDRR) towards evaluation of tropical cyclone impact and risk management. Enhance the col-

laboration with Training and Research Coordination Group (TRCG) towards the exchange of latest developments and techniques related to tropical cyclone research and operational forecast, as well as the effectiveness of tropical cyclone early warning system.

(5) Improve the quality and influence of the Committee journal--Tropical Cyclone Research and Review.

Acknowledgements

The authors would like to express special thanks to all the focal points and coordinators of the priority projects of WGM, for their great contribution and kind collaboration, and also sincere appreciation to all Members of the Committee, particularly CMA and RSMC-Tokyo, for their strong support for WGM.

References

Aberson S D., 2011: The impact of dropwindsonde data from the THORPEX pacific area regional campaign and the NOAA hurricane field program on tropical cyclone forecasts in the global forecast system. *Mon Weather Rev*, **139**, 2689–2703.

Cerveny et al., 2017: WMO Assessment of Weather and Climate Mortality Extremes: Lightning, Tropical Cyclones, Tornadoes, and Hail, Weather, Climate, and Society. Published online, DOI: 10.1175/WCAS-D-16-0120.1.

Chen L. S., Ding Y. H., 1979: Introduction to typhoon in the Western Pacific. Science Press, Beijing China.

Chen G. M., H. Yu, Q. Cao, Z. H. Zeng, 2013: The performance of global models in TC track forecasting over the western North Pacific from 2010 to 2012. *Tropical Cyclone Res. Rev.*, **2(3)**, 149-158.

Du Y.G., Qi L.B., Cao X.G., 2016: Selective ensemble-mean technique for tropical cyclone track forecast by using time-lagged ensemble and multi-centre ensemble in the western North Pacific., *Q.J.R. Meteorol.Soc.*, **142**, 2452-2462.

Elsberry, R.L., T.D.B. Lambert, and M.A. Boothe, 2007: Accuracy of Atlantic and Eastern North Pacific tropical cyclone intensity forecast guidance. *Weather Forecasting*, **22**, 747-762.

ESCAP/WMO TC, 2009: The 41st ESCAP/WMO Typhoon Committee Session Report, Chiangmai, Thailand, 19-24 January.

ESCAP/WMO TC, 2010: The 42nd ESCAP/WMO Typhoon Committee Session Report, Singapore, 25-29 January.

ESCAP/WMO TC, 2011: The 43rd ESCAP/WMO Typhoon Committee Session Report, Jeju, Republic of Korea, 17-22 January.

ESCAP/WMO TC, 2012: The 44th ESCAP/WMO Typhoon Committee Session Report, Hangzhou, China, 6-11 February.

ESCAP/WMO TC, 2013: The 45th ESCAP/WMO Typhoon Committee Session Report, Hong Kong, China, 29 January -01 February.

ESCAP/WMO TC, 2014: The 46th ESCAP/WMO Typhoon Committee Session Report, Bangkok, Thailand, 10-13 February.

ESCAP/WMO TC, 2015: The 3rd Joint Session on panel on tropical cyclone and typhoon committee Report. Bangkok, Thailand, 9-13 February.

ESCAP/WMO TC, 2016: The 48th ESCAP/WMO Typhoon Committee Session Report, Hawaii, USA, 22-15 February.

ESCAP/WMO TC, 2017: The 49th ESCAP/WMO Typhoon Committee Session Report, Yakohama, Japan, 21-24 February.

JWGFVR, 2013: Verification methods for tropical cyclone forecasts, WWRP 2013-7 (http://www.wmo.int/pages/prog/arep/wwrp/new/documents/WWRP2009-1_web_CD.pdf)).

Lee T.C, Knutson T.R., Kamahori H., Ying M., 2012: Impacts of climate change on tropical cyclones in the western North Pacific basin. Part I: Past observations. *Tropical Cyclone Research and Review*, **1(2)**, 213-230.

Lei X.T. Lei M. Zhao B.K. etc., 2017: New technology and experiment of rocket dropsondes for typhoon observation. *Chinese Science Bulletin* (in Chinese), **62(32)**, 3789-3796.

Lei X.T., Wong W.K., and Fong C., 2017: A challenge of the experiment on typhoon intensity change in coastal area. *Tropical Cyclone Research and Review*, **6(3-4)**, 94-97.

Lei X.T., Zhou X., 2012: Summary of retired typhoon within the western North Pacific Ocean. *Tropical Cyclone Research and Review*, **1(1)**, 23-32**.**

Ying M., Knutson T.R., Kamahori H., Lee T.C., 2012: Impacts of climate change on tropical cyclones in the western North Pacific basin. Part II: Late twenty-first century projections. *Tropical Cyclone Research and Review*, **1(2)**, 231-241.