21. TROPICAL CYCLONE CHARACTERISTICS AND MONSOON CIRCULATIONS

PATRICK A. HARR

Department of Meteorology
Naval Postgraduate School, Monterey, California, USA
E-mail: paharr@nps.edu

CHUN-CHIEH WU

Department of Atmospheric Sciences
National Taiwan University, Taipei, Taiwan
E-mail: cwu@typhoon.as.ntu.edu.tw

The large-scale environmental characteristics that are favorable for tropical cyclone formation are typically found to occur over most ocean basins that contain a monsoon system. Although the favorable conditions occur consistently in the monsoon basins, tropical cyclone activity is closely tied to variability in the monsoon that provides favorable or unfavorable modifications to the basic environmental characteristics. This variability may occur on interannual, intraseasonal, and synoptic time scales. Therefore, it is important to understand the various linkages between monsoon variability and tropical cyclone activity in each monsoon basin.

Over recent years, several international field programs have been conducted to investigate various interactions among factors that link tropical cyclone activity and monsoon circulations. The primary programs have been conducted over the tropical western North Pacific. These include the special programs such as the THORPEX-Pacific Asian Regional Campaign (T-PARC) and the Tropical Cyclone Structure–2008 (TCS-08) that were conducted during August-September 2008, and the annual Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR). The anomalous monsoon environment that existed during T-PARC/TCS-08 is described. Additionally, the science objectives, observing platforms, and facilities associated with these programs are summarized with respect to observations of tropical cyclone characteristics in the monsoon environment.

1. Introduction

Gray (1968, 1975) related tropical cyclone activity to six primary environmental factors: (i) large values of low-level cyclonic relative vorticity; (ii) a location that is at least a few degrees poleward of the equator; (iii) weak vertical wind shear; (iv) large values of relative humidity in the lower and middle troposphere; (v) conditional instability throughout a deep tropospheric layer; and (vi) sea-surface temperatures above 26°C. Factors (i), (ii), and (iii) were classified as dynamic contributors to tropical cyclone formation and factors (iv), (v), and (vi) as thermodynamic factors. Furthermore, Gray (1975) demonstrated that the thermodynamic factors were often above threshold values throughout tropical cyclone seasons but the dynamic factors can undergo large changes that exhibit favorable and unfavorable conditions for tropical cyclone formation. As defined by Gray (1975) and

The Global Monsoon System: Research and Forecast (2nd Edition)
edited by Chih-Pei Chang et al.

summarized by McBride (1995) and Elsberry (2004), the favorable environmental conditions apply to the monsoon environment. Therefore, in a monsoon environment characteristics of the dynamic conditions favorable for tropical cyclone activity are often related to primary, large-scale monsoon circulations.

In addition to the impact of large-scale monsoon circulations on favorable conditions for tropical cyclone formation, the slowly-varying temporal characteristics of the monsoon circulations contribute to a variability of tropical cyclone activity. Nearly each monsoon circulation worldwide has exhibited significant variability from intraseasonal to synoptic time scales. These include the Australian summer monsoon (Hendon and Liebmann 1990b), the South China Sea monsoon (Chen and Chen 1995), the western North Pacific monsoon (Krishnamurti *et al.* 1985), the eastern North Pacific monsoon (Maloney and Hartmann 2001), and the Indian summer monsoon (Goswami and Ajayamohan 2001). In each monsoon basin, tropical cyclone characteristics are primarily tied to the monsoon trough with significant variability associated with factors that cause variability in the monsoon trough. This variability may extend over interannual time scales in relation to the El Nino–Southern Oscillation (Goldenberg and Shapiro 1996; Chan 2000; Wang and Chan 2002; Dong 1988). The Madden-Julian Oscillation (MJO, Madden and Julian 1994) impacts tropical cyclone and monsoon interactions on intraseasonal time scales (Liebmann *et al.* 1994; Hendon and Liebmann 1990a; Hall *et al.* 2001; Maloney and Hartmann 2001; Goswami *et al.* 2003; Kim *et al.* 2008; Hsu *et al.* 2008). Harr and Elsberry (1995) demonstrated that for the western North Pacific active (inactive) monsoon regimes tended to be associated with active (inactive) tropical cyclone periods. Therefore, significant intraseasonal variability in tropical cyclone characteristics may be related to large-scale monsoon circulations. Over synoptic scales, tropical cyclone and monsoon interactions may be influenced by equatorial waves (Liebmann and Hendon 1990; Lau and Lau 1990; Takayabu and Nitta 1993; Chang *et al.* 1996; Sobel and Bretherton 1999; Thorncroft and Hodges 2001; Dickenson and Molinari 2002) and general synoptic-scale influences on the monsoon trough, which include cross equatorial surges (Love 1985) and downstream development (Davidson and Hendon 1989).

During August-September 2008, several specialized field programs under The Observing Research and Predictability Experiment (THORPEX) and other international tropical meteorology programs were conducted to investigate tropical cyclone formation, structure, intensification, motion, and extratropical transition in the monsoon environment of the western North Pacific. These programs are described with reference to important characteristics related to tropical cyclone and monsoon interactions. This includes the impact of the monsoon circulations, which quite anomalous during August-September 2008, on the primary environmental factors defined to be important to tropical cyclone formation and the role of monsoon circulations in significant tropical cyclone track characteristics.

2. Tropical Cyclones in the Monsoon Environment: Observations

The THORPEX Pacific Asian Regional Campaign (T-PARC) was a multi-national field campaign and analysis period that addressed the shorter-range dynamics and forecast skill associated with high-impact weather events of one region (eastern Asian and the western North Pacific) and their downstream impacts on the medium-range dynamics and forecast skill of another region (in particular, the eastern North Pacific and North America). Although many significant weather events occur over eastern Asia and the western North Pacific, the focus of T-PARC was on various aspects of typhoon activity in the monsoon environment, which include formation, intensification, structure change, motion, and extratropical transition. Because of the significant impact of typhoon activity on the region of eastern Asia and the western North Pacific, T-PARC was comprised of several affiliated programs. These programs and their national sponsor include:

- Tropical Cyclone Structure-2008 (TCS-08) [United States];
- Typhoon Hunter-2008 (TH-08) [Japan];
- Predictability and Observation Experiment (PROBEX) [South Korea];
- Tibetan Plateau Experiment [China];
- The South China Sea Experiment [China];
- Dropsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) [Taiwan].

In addition to the field campaigns listed above, a significant international component existed via contribution of specific observation platforms. A high-altitude jet aircraft (FALCON) was operated by the Deutches Zentrum für Luft- und Raumfahrt (DLR). Driftsonde balloon operations were conducted by the Centre National d'Etudes Spatiales (CNES) of France. Although the western North Pacific plays a unique role in defining many characteristics of the midlatitude circulation of the Northern Hemisphere, the near-global participation in T-PARC is an indication that the scientific principles being examined with respect to the impacts on downstream weather by significant events upstream in a monsoon environment are applicable to many regions.

The combination of observational platforms and collaborative experiments has been defined such that the experimental design for T-PARC and affiliated programs addressed three primary components: (1) A tropical measurement strategy was designed to examine circulations of the tropical western North Pacific monsoon environment as they relate to enhanced and reduced periods of wide-spread deep convection, tropical cyclone formation, tropical cyclone intensification, and tropical cyclone structure change. (2) The measurement strategy for the extratropical transition (ET) and downstream impacts was based on the poleward movement of a decaying tropical cyclone and the resulting intense cyclogenesis that results from its interaction with the midlatitude circulation. The ET process illustrates clearly the need for tropical-to-extratropical measurement strategies as the predictability of an ET event depends on the intensity and structure of the tropical cyclone, where and when the tropical cyclone arrives in the midlatitude westerlies, the characteristics of the middle latitude wave guide that impact the ET cyclogenesis, and the downstream propagation and evolution of the wave packets. (3) The third measurement strategy focused on identification of regions in which extra observations may reduce numerical forecast error growth. In T-PARC, the targeted observations were aimed primarily at reducing errors and uncertainty associated with forecasts of tropical cyclone track over the western North Pacific. In particular, this includes whether a tropical cyclone will recurve, the longitude of recurvature, and the orientation and speed along the track following recurvature.

The observations collected during the field phase are being used in concert with an unprecedented variety of numerical models, which includes research modeling and assimilation systems together with access to the members of the ensemble forecasts of ten operational weather centers through the THORPEX Interactive Global Grand Ensemble (TIGGE). Thus, unlike past weather experiments, T-PARC was able to readily include the probabilistic nature of the forecast problem, rather than examination of a few deterministic forecasts from research and operational models. An augmented satellite-based observing strategy was also implemented during T-PARC. For example, observations from the Japanese MTSAT geostationary satellite were collected in rapid-scan mode. From this rapid-refresh imagery, high-resolution wind fields are being derived from state-of-the-art automated feature-tracking methods during T-PARC intensive observing periods.

During T-PARC and its collaborative programs, several aircraft were used to obtain measurements in and around western North Pacific tropical cyclones during formation, intensification, and extratropical transition. In addition to the FALCON aircraft mentioned above, a United States Air Force (USAF) WC-130J from the 53rd Weather Reconnaissance Squadron and a Navy Research Laboratory (NRL) P-3 participated. Each of these aircraft was used to obtain observations with specialized instruments designed to address specific science objectives, which are defined below.

With the exception of the DOTSTAR program, all the programs affiliated with T-PARC listed above were specially designed for the T-PARC observation period of August-September 2008. The DOTSTAR program (Wu *et al.* 2005; Wu *et al.* 2007a, b; Chou and Wu 2008; Yamaguchi *et al.* 2009) has been operational for several years since 2003 to gather observations in the environment of tropical cyclones that may threaten Taiwan. A high-flying commercial jet (ASTRA) with dropwindsonde capability was adopted to conduct the surveillance observations as part of the DOTSTAR program.

2.1. Science Objectives

In general, the science objectives of T-PARC were associated with increasing predictability of high-impact weather events (i.e., tropical cyclone formation, intensification, motion, and extratropical transition) in the monsoon environment and the forcing of one region on the weather of a downstream region. As such, the specific objectives are divided into three categories.

2.1.1. Tropical Cyclone Formation, Intensification, Structure Change, and Satellite Validation

The key objectives associated with the tropical cyclone component contained in the affiliated TCS-08 program address understanding and predictability of tropical cyclone formation, intensification, and structure change. In particular, outer structure change is a special focus as changes at outer radii impact interactions between the tropical cyclone and its environment that will affect recurvature. Specific objectives were:

- Define the factors that impact the large-scale atmospheric and oceanic control on tropical cyclone formation;
- Define the relative roles of mesoscale processes during tropical cyclone formation. Specifically, identify contributions from the organization of low-level vorticity in deep convective towers versus mid-level circulations embedded in stratiform regions of mature mesoscale convective systems. This objective addresses the predictability associated with the location, timing, and rate of tropical cyclone formation over the western North Pacific;
- Define the relative role of environmentally-induced, vortex-generated mechanisms versus cyclogenesis determined initial conditions in determining the outer wind structure of a mature tropical cyclone;
- Define the key structural characteristics that limit the predictability of recurvature and the start of extratropical transition over the western North Pacific;
- Define representative wind distributions and maximum intensities of tropical cyclones from in situ data obtained at times coincident with satellite overpasses. The purpose of this objective is to provide baseline measurements and validation of satellite-based estimates of tropical cyclone intensity and structure.

2.1.2. Data Targeting

To advance forecast skill of high-impact weather events such as tropical cyclones over the western North Pacific and their downstream impacts, it is necessary to address issues associated with such factors as reducing analysis and forecast errors, observational network design, data calibration, and data assimilation. The use and evaluation of a variety of adaptive sampling strategies (Wu *et al.* 2006; Wu *et al.* 2009) for reducing errors in numerical forecasts was an integral part of the T-PARC field program design. The adaptive sampling strategies included in situ data as well as remotely-sensed observations. Specific objectives included:

- Define the influence of adaptive sampling based on dropwindsonde measurements from aircraft in the synoptic environment of tropical cyclones over the western North Pacific on the forecast skill of the tropical cyclone track;
- Increase understanding of the significant differences in the prediction of targeting locations produced by different targeting techniques;
- Identify the impact of assimilating additional observations from a variety of platforms, which includes in situ aircraft observations and satellite remote sensing;
- Identify the impact of data on multiple spatial and temporal scales using a variety of data assimilation methods.

2.1.3. Extratropical Transition of Tropical Cyclones and Downstream Impacts

The extratropical transition of a tropical cyclone often has far-reaching effects on the midlatitude circulation. Furthermore, there is a large amount of variability in the occurrence and amplitude of the downstream impacts. Forecasts of the downstream circulations tend to have reduced skill, and the variability among ensemble members during extratropical transition events suggests that the predictability associated with these cases is low.

Combinations of aircraft, radar, dropwindsonde, and satellite observations are used in conjunction with model simulations and data assimilation to define the interactions between a decaying tropical cyclone and the midlatitude circulation into which it is moving that affect the downstream impact. Specific objectives were:

- Document the contributions from various physical processes that impact the development of the deep tropospheric anticyclone immediately downstream of an ET event. Physical mechanisms associated with such features as the poleward movement of heat and moisture along the eastern side of the decaying tropical cyclone, warm frontogenesis, and the interaction of the tropical cyclone outflow and the midlatitude jet stream will be examined;
- Examine the temporal evolution of the processes by which the decaying tropical cyclone impacts the midlatitude circulation;
- Define the relative roles of a variety of tropical cyclone and midlatitude circulation characteristics as they influence the variability of downstream impacts during ET;
- Examine the utility of satellite data in defining the important physical characteristics of an ET event;
- Examine the importance of the re-intensification of the decaying tropical cyclone as an extratropical cyclone on maintaining the downstream transport of energy;
- Examine the impact on forecast accuracy due to improved analysis of key structural characteristics during the ET of a decaying tropical cyclone.

2.2. Domain of Interest

The field phase of T-PARC and affiliated programs was conducted over the western North Pacific (Fig. 1). The WC-130J and the NRL P-3 primarily operated from Guam with periods of deployment to Okinawa and Japan. The FALCON operated primarily from Japan with periods of deployment to Okinawa. The DOTSTAR aircraft operated from Taiwan.

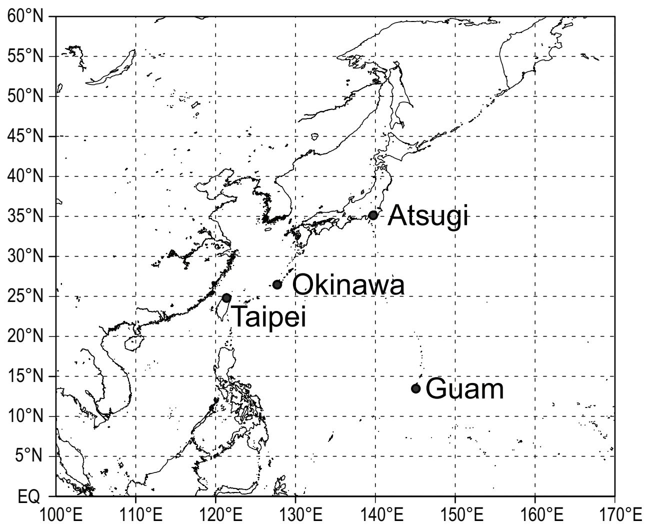

Figure 1. T-PARC and collaborative programs domain of interest.

2.3. T-PARC Resources

Observational facilities for T-PARC involved the NCAR ELDORA dual-Doppler radar system onboard the NRL P-3. The NRL P-3 also deployed GPS dropwindsondes. Also, the Twin Otter Doppler Wind Lidar (TODWL) operated on the NRL P-3. To provide a capability to obtain measurements in the inner core of a developing and mature tropical cyclone, the WC-130J deployed GPS dropwindsondes and utilized a stepped frequency microwave radiometer (SFMR) to obtain estimates of the surface wind speed.

While the WC-130J and the NRL P-3 with ELDORA and GPS dropwindsonde capabilities provided detailed views of the physical characteristics associated with the tropical cyclone lifecycle, the interaction of the upper-level outflow and midlatitude jet was observed by the DLR Falcon aircraft outfitted with an airborne Doppler wind lidar and a water vapor differential absorption lidar (DIAL). This 2 μm Doppler lidar had been used in the Atlantic THORPEX Regional Campaign (A-TReC) in autumn 2003. The wind lidar provided profiles between 0.5 and 12 km altitude with accuracy better than 1 m s^{-1}. The horizontal resolution is up to 5 km and the vertical resolution is up to 100 m. The T-PARC program provided an opportunity for the initial use of the combined Doppler wind lidar and DIAL. The DLR Falcon also deployed GPS dropsondes.

To support the collection of observations at upper levels for data targeting, the DOTSTAR project ASTRA jet was used in cases when a tropical cyclone entered the region of the northern Philippine Sea and uncertainty existed in the track of the storm as it neared Taiwan. The ASTRA aircraft had the Airborne Vertical Atmospheric Profiling System (AVAPS) and deployed GPS dropwindsondes. Data from the dropwindsondes were relayed to the Central Weather Bureau in Taiwan and placed on the GTS weather data network where they were used in operational numerical weather prediction systems.

The driftsonde is a zero-pressure high-altitude balloon system that includes a gondola that carries approximately 40 miniature dropsondes (MIST). During the T-PARC period, 16 balloon systems were launched from Hawaii. Communication with the balloon through a satellite link allowed coordination of the release of the MIST sondes.

In addition to the in situ observation systems described above, substantive use was made of satellite data from geostationary and polar-orbiting platforms. Various tropical cyclone-related products were generated to aid in the decision-making procedure. Through coordination with the Japan Meteorological Agency, rapid-scan operations from the MTSAT-2 geostationary satellite were implemented over several special observing periods (Table 1) when tropical cyclones are forecasted to approach Japan.

Finally, through special programs such as the Predictability and Observation Experiment (PROBEX) in Korea and Typhoon Hunter-2008 (TH-08) in Japan, certain radiosonde sites were operated to collect special observations during the T-PARC period. In addition, the Japan Meteorological Agency (JMA) deployed four observation ships at various locations in the East China Sea to obtain special radiosonde data. During aircraft operations, special radiosonde launches were made from U.S. National Weather Service sites on several islands in the tropical western North Pacific.

Table 1. Periods of rapid-scan operation of the MTSAT-2 geostationary satellite by the Japan Meteorological Agency. The targeted typhoon is listed in the right-most column.

Start Time	End Time	Typhoon
1200 UTC 10 September	1200 UTC 13 September	TY Sinlaku
1200 UTC 17 September	1200 UTC 1800 September	TY Sinlaku
1200 UTC 27 September	1200 UTC 28 September	TY Jangmi

2.4. Western North Pacific Monsoon Environment during T-PARC and TCS-08

Typically, the western North Pacific monsoon trough is oriented from the South China Sea southeastward across the Philippine Sea to the south of Guam (Fig. 2a). Lander (1996) defined the anomalous condition of a reverse-oriented monsoon trough as one in which the trough becomes oriented from the South China Sea northeastward toward the subtropical western North Pacific (Fig. 2b). During the August-September 2008 period, the monsoon trough environment was in a reverse-oriented structure such that anomalous easterly zonal winds (Fig. 3a) existed over tropical latitudes south and east of Guam and westerly anomalies occurred over the subtropical western North Pacific. Accordingly, the pattern of outgoing longwave radiation (OLR) anomalies (Fig. 3b) defined a region of above normal convection that extended northeastward from the South China Sea to the subtropical western North Pacific.

As defined by the Accumulated Cyclone Energy (ACE) index for the western North Pacific (Bell *et al.* 2000), tropical cyclone activity during the early portion of the Northern Hemisphere summer western North Pacific monsoon season was nearly normal (Fig. 4). However, during the latter portion of the monsoon season in August-October, tropical cyclone activity was extremely below normal. While ACE values in September were near normal, the values in August and October were very much below normal. Therefore, the anomalous reverse-oriented monsoon trough that contributed to easterly anomalies across much of the tropical western North Pacific and reduced convection was related to much below normal tropical cyclone activity. During La Niña conditions, ACE values tend to be lower than normal (Wang and Chan, 2002; Camargo and Sobel 2005). While the 2007/2008 La Niña event dissipated during the summer of 2008, the sea-surface temperatures anomalies remained negative over the west-central tropical Pacific. These anomalous ocean conditions contributed with the anomalous low-level easterlies to define conditions that were not favorable for tropical cyclone development in the monsoon region of the western North Pacific during the late summer of 2008.

2.5. Field Program Highlights

As defined above, each observation platform was chosen to address specific objectives associated with many facets of tropical cyclones in the monsoon environment. The allocation of aircraft missions dedicated to each objective is defined for the NRL P-3, WC-130J, and DLR Falcon in Fig. 5. All DOTSTAR missions were mainly dedicated to tropical cyclone targeting. Two highlights from the field program are introduced below.

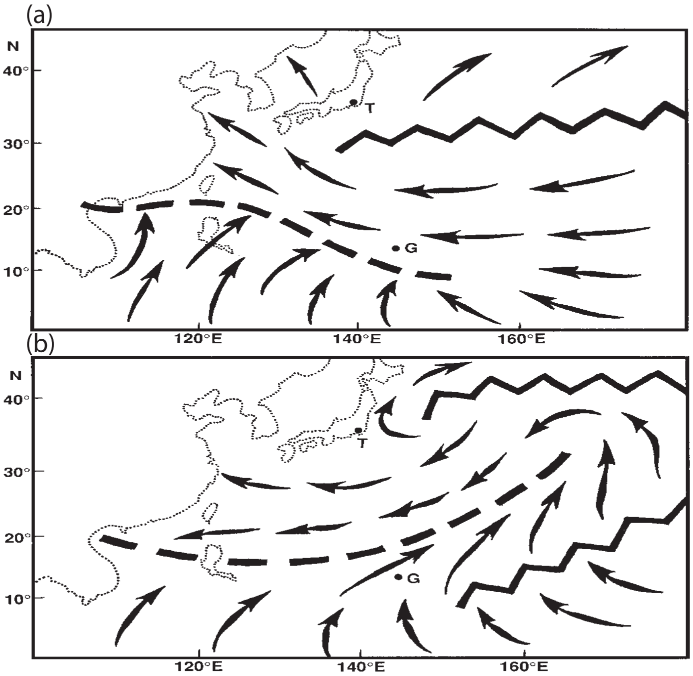

Figure 2. Schematic of the low-level winds over the western North Pacific during the Northern Hemisphere summer: (a) long-term average; and (b) example of a reverse-oriented monsoon trough. (after Lander 1996)

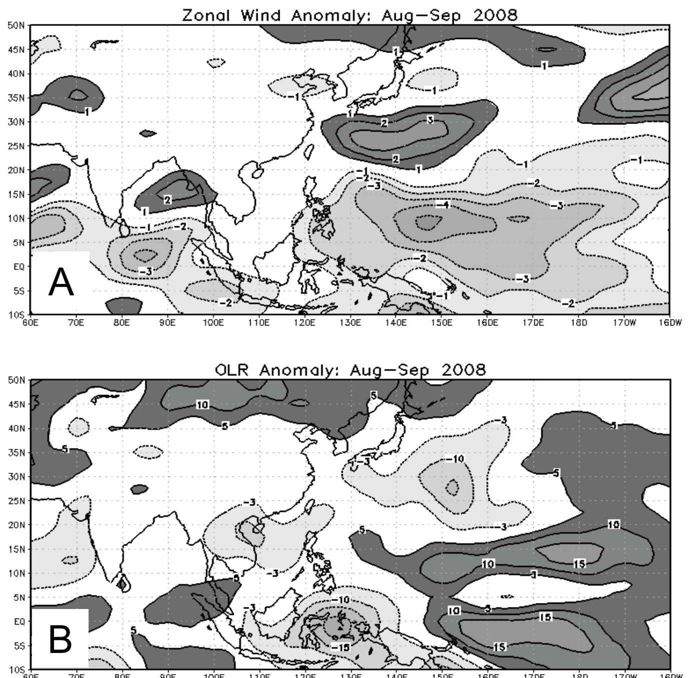

Figure 3. (a) Zonal wind anomalies (m s^{-1}) at 850 hPa for the period of August-September 2008. The anomalies are computed as a difference from the 1968-1996 average. (b) As in (a) except for outgoing longwave radiation anomalies (W m^{-2}).

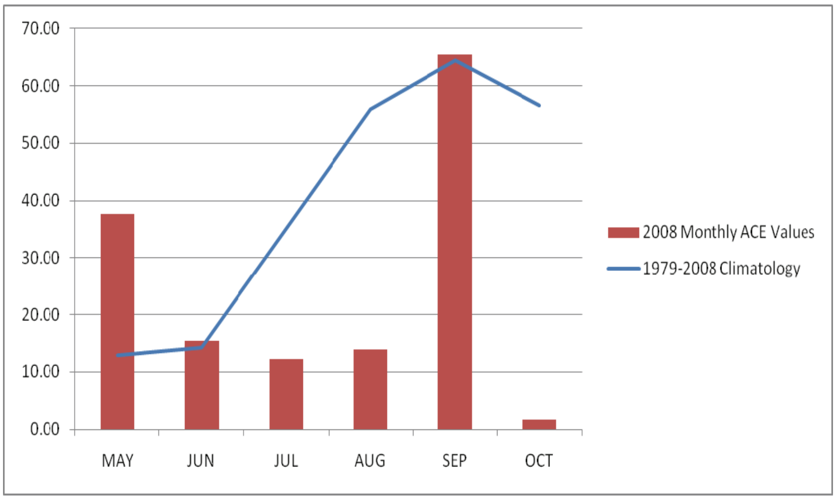

Figure 4. Monthly ACE values (bars) and the 1979-2008 average ACE values for May-October 2008.

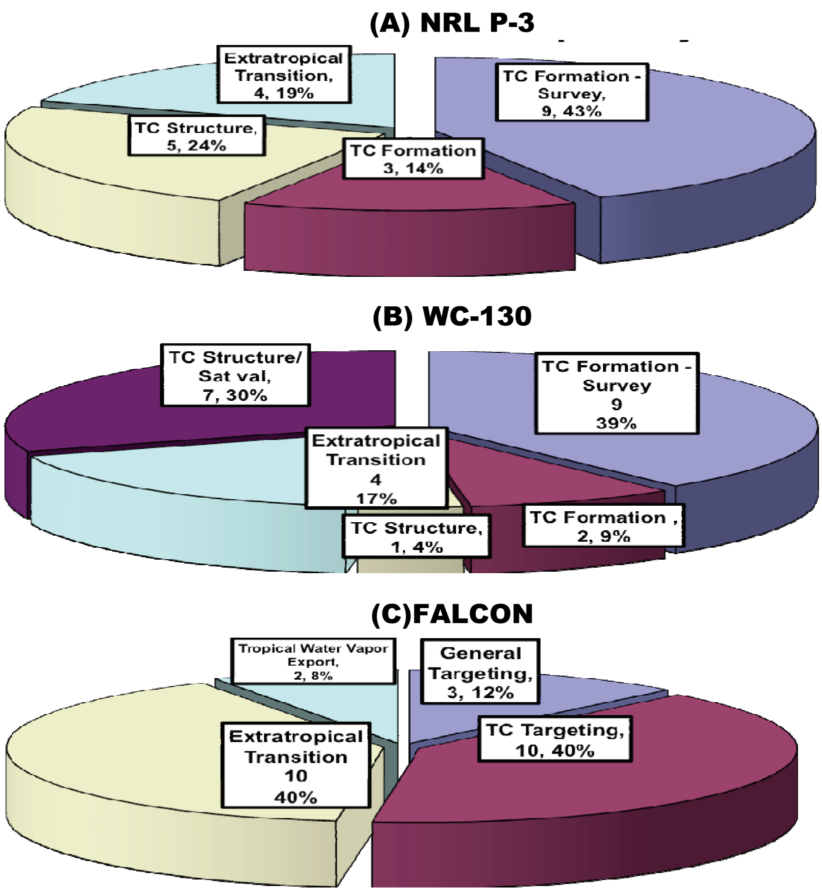

Figure 5. Distribution of objectives addressed by each aircraft. Each box identifies the objective along with the number of flights and the percentage of flight hours.

2.5.1. *Tropical Cyclone Structure Change*

As stated above, a primary objective of T-PARC was to observe the entire lifecycle of a tropical cyclone in the monsoon environment of the western North Pacific. Typhoon (TY) Sinlaku (Fig. 6) provided this opportunity as 28 missions were flown in the typhoon and in the environment surrounding the typhoon. Following recurvature near Taiwan, large vertical wind shear existed over TY Sinlaku, which contributed to considerable weakening and the exposure of the low-level circulation center. During, the period of a combined WC-130J, NRL P-3, and DLR Falcon mission between 2100 UTC 16 September and 0500 UTC 17 September, deep convection increased to the east of the exposed low-level center (Fig. 7). This development coincided with a 24-h period in which the typhoon rapidly re-intensified and formed a clear eye as it skirted the southern islands of Japan. During this time, the three aircraft again flew in and around the typhoon to collect detailed observations (Fig. 8) as it was undergoing rapid re-intensification near 30°N over the coastal waters of Japan. The re-intensification of TY Sinlaku represents an example of severe tropical cyclone structure change over the western North Pacific. Investigations are focusing on whether a reduction in vertical wind shear was sufficient to allow the vortex to re-organize or whether the deep convective burst was able to fight off the strong shear and form a new vortex.

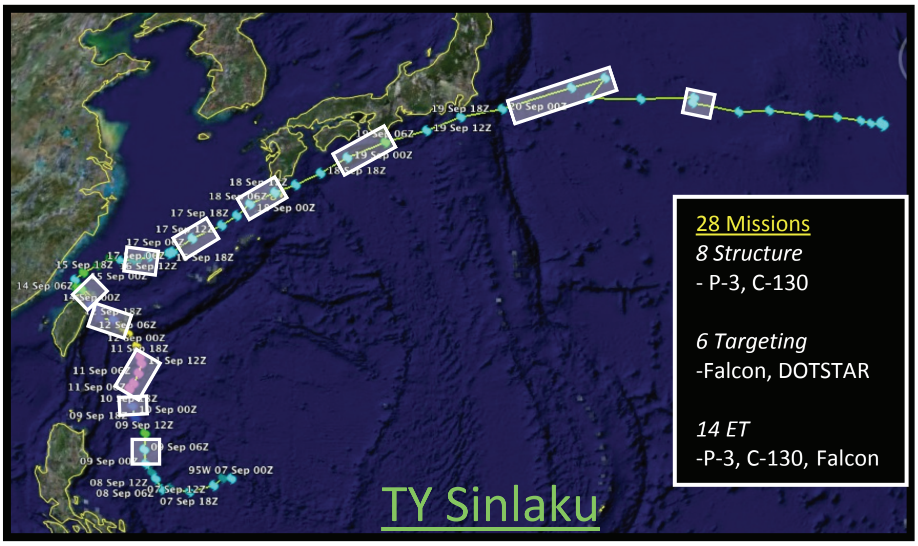

Figure 6. Track of TY Sinlaku. The shaded boxes along the track define the time periods in which aircraft were flying in and around TY Sinlaku.

2.5.2. *Tropical Cyclone Motion*

As TY Sinlaku approached Taiwan, there was a large amount of uncertainty (such as the ensemble spread) in forecast track guidance (Fig. 9). The uncertainty was measured by spread among ensemble members from ensemble prediction systems (Figs. 9a, b) of the European Center for Medium-range Weather Forecasts (ECMWF) and the Japan Meteorological Agency (JMA) and from the spread among operational deterministic model products (Fig. 9c).

Because of the uncertainty in the track forecasts, several aircraft missions were conducted in regions of initial condition sensitivity. Several operational products, which were based on a variety of principles, were utilized to identify the regions to be targeted for aircraft observations. Experiments are being conducted to assess the relative merit of aircraft and satellite-derived atmospheric motion vectors in the sensitive regions for improving numerical track prediction guidance products.

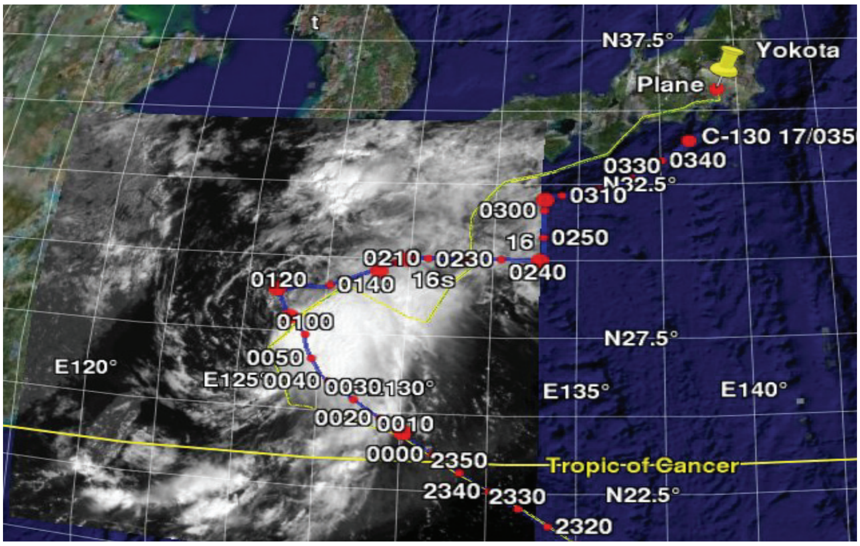

Figure 7. Visible MTSAT imagery of TY Sinlaku at 0015 UTC 17 September. The blue line defines the flight track of the WC-130J and the red dots define locations at which dropsondes were released. The yellow line defines the flight track of the NRL P-3.

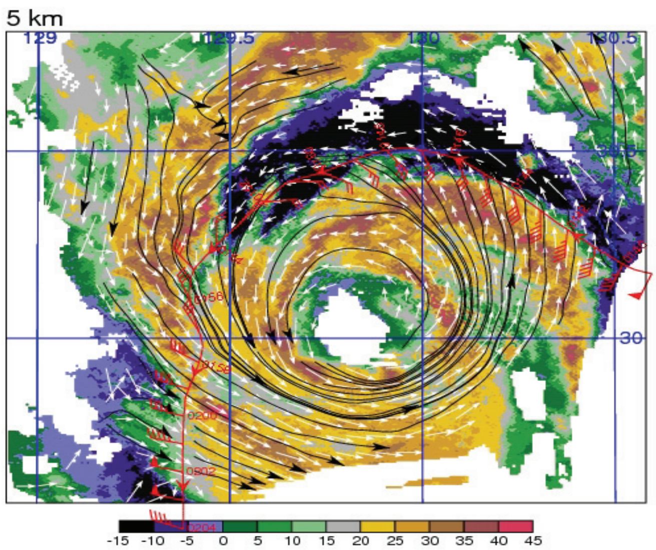

Figure 8. Dual-Doppler quick look analysis at 5 km from the ELDORA radar aboard the NRL P-3 during the period 0130-0202 UTC 18 September 2008. The red line defines the aircraft flight track with flight-level winds (kt). Shading is reflectivity (dBZ).

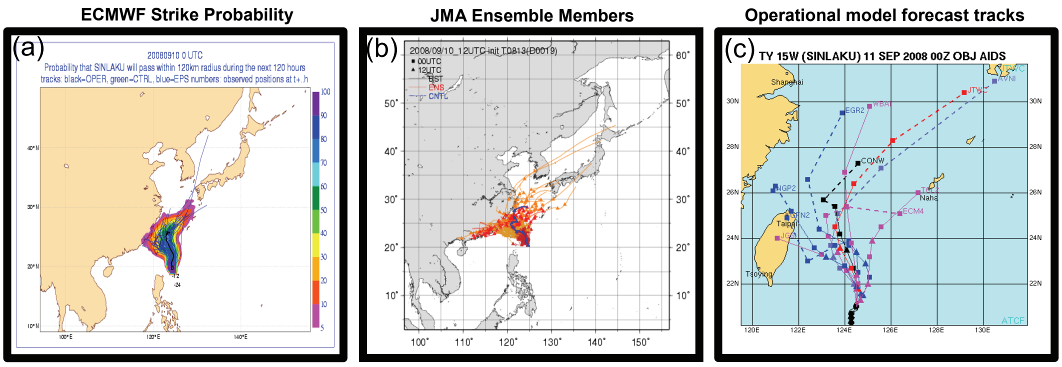

Figure 9. Forecast tracks of TY Sinlaku generated by the ensemble prediction systems of the (a) ECMWF at 0000 UTC 10 September 2008, (b) JMA at 1200 UTC 10 September 2008, and (c) several operational deterministic numerical forecast models at 0000 UTC 11 September 2008.

2.5.3. Air-sea Interaction

Following TY Sinlaku, Super-typhoon (STY) Jangmi formed in the Philippine Sea. As STY Jangmi rapidly intensified, several aircraft missions were flown to investigate the formation of outer rainbands and the wind distribution associated with possible initiation of a concentric eyewall. To examine the role of air-sea interaction in the environment of a super-typhoon, a second set of drifting buoys was deployed directly in the path of Super-Typhoon Jangmi (Fig. 10). The buoy data are being analyzed to identify critical thermodynamic and dynamic factors at the air-sea interface under a typhoon with maximum sustained winds exceeding 130 kt.

The monsoon environment of the western North Pacific contains the necessary thermodynamic and dynamic conditions that favor tropical cyclone formation. Additionally, the monsoon plays important roles in the determination of the structure and motion of tropical cyclones across the western North Pacific. Recent international field programs have been conducted in the monsoon region of the western North Pacific to study tropical cyclone formation, intensification, structure change, and extratropical transition. These programs were organized under the World Weather Research Program/THORPEX of the World Meteorological Organization to increase predictability associated with high-impact weather events related to tropical cyclones over the western North Pacific and downstream across the North Pacific.

Several significant first-time achievements were accomplished during the recent programs. These include:

- First simultaneous operation of four aircrafts in a tropical cyclone in the western North Pacific.
- First systematic data targeting operation in the western North Pacific, which included examination of a variety of targeting products.
- First deployment of drifting buoys in the path of a tropical cyclone in the western North Pacific and in front of a category five storm in any basin.
- First systematic observations of the full extratropical transition process.
- First operation of the driftsonde in the North Pacific.

- First use of the ELDORA radar, Doppler wind lidars, and DIAL in tropical cyclones of the monsoon environment of the western North Pacific.

Analysis of the variety of data collected during the recent programs is expected to significantly improve the understanding of tropical cyclone characteristics, their variability, predictability, and downstream impacts.

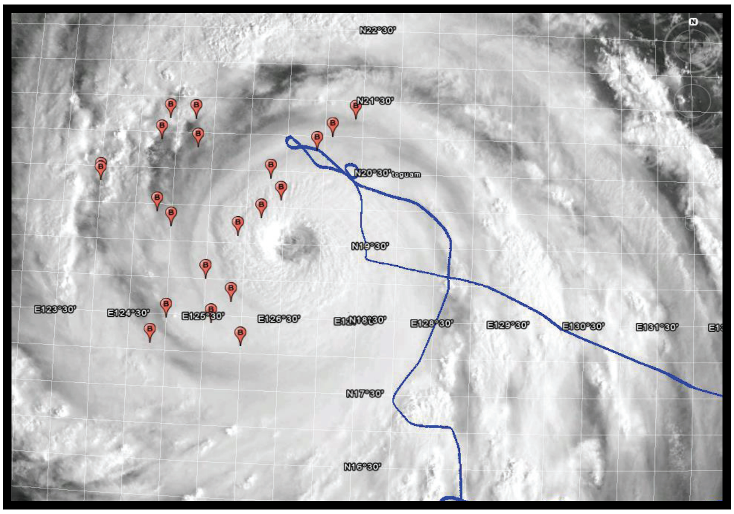

Figure 10. Visible MTSAT imagery of STY Jangmi at 0230 UTC 27 September 2008. The blue line defines the flight track of the NRL P-3 and the tabs define the locations of drifting buoys deployed in the path of STY Jangmi by the WC-130J.

Acknowledgments

DOTSTAR is supported by the National Science Council of Taiwan through Grant NSC97-2111-M-002-016-MY3, the Office of Naval Research Grants N00014-05-1-0672 and N00173-08-1-G007, National Taiwan University Grant 97R0302, and the Central Weather Bureau Grant MOTC-CWB-97-6M-01. The first author was supported by the U.S. National Science Foundation grant ATM-0736003 and the Office of Naval Research, Marine Meteorology Grant N00014-08-WR20101. Many agencies and individuals contributed to the success of T-PARC and affiliated programs. In particular, the ground support and air crews associated with all the aircraft are acknowledged. Support from several U.S. Navy and Air Force bases across the western North Pacific was critical to the success of the aircraft operations.

References

Bell, G. D., M. S. Halpert, R. C. Schnell, R. W. Higgins, J. Lawrimore, V. E. Kousky, R. Tinker, W. Thiaw, M. Chelliah, and A. Artusa, 2000: Climate Assessment for 1999. *Bull. Amer. Meteor. Soc.*, **81**, s1-s50.

Camargo, S. J. and A. H. Sobel, 2005: Western North Pacific tropical cyclone intensity and ENSO. *J.*

Climate, **18**, 2996-3006.

Chan, J. C. L, 2000: Tropical cyclone activity over the western North Pacific associated with El Nino and La Nina events. *J. Climate*, **16**, 2960-2972.

Chang, C.-P., J. M. Chen, P. A. Harr, and L. E. Carr, 1996: Northwestward-propagating wave patterns over the tropical western North Pacific during summer. *Mon. Wea. Rev*., **124**, 2245-2266.

Chen, T.-C. and J.-M. Chen, 1995: An observational study of the South China Sea monsoon during the 1979 summer: Onset and life cycle. *Mon. Wea. Rev*., **123**, 2295-2318.

Chou, K.-H. and C.-C. Wu, 2008: Development of the typhoon initialization in a mesoscale model – Combination of the bogused vortex with the dropwindsonde data in DOTSTAR. *Mon. Wea. Rev*., **136**, 865-879.

Davidson, N. E. and H. H. Hendon, 1989: Downstream development in the southern hemisphere monsoon during FGGE/WMONEX. *Mon. Wea. Rev*., **117**, 1458-1470.

Dickinson, M. and J. Molinari, 2002: Mixed Rossby-gravity waves and western Pacific tropical cyclogenesis. Part I: Synoptic evolution. *J. Atmos. Sci*., **59**, 2183-2196.

Dong, K., 1988: El Niño and tropical cyclone frequency in the Australian region and Northwest Pacific. *Aust. Meteor. Mag*., **36**, 219-225.

Elsberry, R. L., 2004: Monsoon-related tropical cyclones in East Asia. *East Asian Monsoon*, Chap. 13. World Scientific Series on Meteorology of East Asia, 2. World Scientific, (Ed.) C.-P. Chang, 463-498.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev*., **96**, 669-700.

Gray, W. M., 1975: *Tropical cyclone genesis*. Dept. of Atmos. Sci. Pap. 232, Colorado State Univ., 121 pp.

Goldenberg, S. B. and L. J. Shapiro, 1996: Physical mechanisms for the association of El Nino and West African rainfall with Atlantic major hurricane activity. *J. Climate*, **9**, 1169-1187.

Goswami, B. N. and R. S. Ajayamohan, 2001: Intraseasonal oscillations and interannual variability of the Indian summer monsoon. *J. Climate*, **14**, 1180-1198.

Goswami, B. N., R. S. Ajayamohan, P. K. Xavier, and D. Sengupta, 2003: Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. *Geophys. Res. Lett.*, **30**, 1431-1434.

Hall, J. D., A. J. Matthews, and D. J. Karoly, 2001: The modulation of tropical cyclone activity in the Australian region by the Madden-Julian Oscillation. *Mon. Wea. Rev*., **129**, 2970-2982.

Harr, P. A. and R. L. Elsberry, 1995: Large-scale circulation variability over the tropical western North Pacific. Part I: Spatial patterns and tropical cyclone characteristics. *Mon. Wea. Rev.*, **123**, 1225-1246.

Hendon, H. H. and B. Liebmann, 1990a: A composite study of onset of the Australian summer monsoon. *J. Atmos. Sci*., **47**, 2227-2240.

Hendon, H. H. and B. Liebmann, 1990b: The intraseasonal (30-50 day) oscillation of the Australian summer monsoon. *J. Atmos. Sci*., **47**, 2909-2923.

Hsu, H.-H., C.-H. Hung, A.-K. Lo, C.-C. Wu, and C.-W. Hung, 2008: Influence of tropical cyclone on the estimation of climate variability in the tropical western North Pacific. *J. Climate*, **21**, 2960-2975.

Kim, J.-H., C.-H. Ho, H.-S. Kim, C.-H. Sui, and S.-K. Park, 2008: Systematic variation of summertime tropical cyclone activity in the western North Pacific in relation to the Madden-Julian Oscillation. *J. Climate*, **21**, 1171- 1191.

Krishnamurti, T.-N., P. K. Jayakumar, J. Sheng, N. Surgi, and A. Kuma, 1985: Divergent circulations on the 30 to 50 day timescale. *J. Atmos. Sci.*, **42**, 364-375.

Lander, M. A., 1996: Specific tropical cyclone track types and unusual tropical cyclone motions associated with a reverse-oriented monsoon trough in the western North Pacific. *Wea. Forecast.*, **11**, 170-186.

Lau, K. H. and N. G. Lau, 1990: Observed structure and propagation characteristics of tropical summertime synoptic-scale disturbances. *Mon. Wea. Rev*., **118**, 1888-1913.

Liebmann, B. and H. H. Hendon, 1990: Synoptic-scale disturbances near the equator. *J. Atmos. Sci.*, **47**, 1463-1479.

Liebmann, B., H. H. Hendon, and J. D. Glick, 1994: The relationship between tropical cyclones of the western Pacific and Indian Oceans and the Madden-Julian oscillation. *J. Meteor. Soc. Japan*, **72**, 401-411.

Love, G., 1985: Cross-equatorial influences of winter hemisphere subtropical cold surges. *Mon. Wea. Rev.*, **113**, 1487-1498.

Madden, R. A. and P. R. Julian, 1994: Observations of the 40-50 day tropical oscillation – A review. *Mon. Wea. Rev*., **122**, 814-837.

Maloney, E. D. and D. L. Hartmann, 2001: The Madden-Julian oscillation, barotropic dynamics, and North Pacific tropical cyclone formation. Part I: Observations. *J. Atmos. Sci*., **58**, 2845-2558.

McBride, J. L., 1995: Tropical cyclone formation. *Global Perspectives on Tropical Cyclones*, Chap. 3. WMO/TD No. 693, (Ed.) R. L. Elsberry, 63-105.

Sobel A. and C. Bretherton, 1999: Development of synoptic-scale disturbances over the summertime tropical Northwest Pacific. *J. Atmos. Sci.*, **56**, 3106-3127.

Takayabu, Y. N. and T. Nitta, 1993: 3-5 day period disturbances coupled with convection over the tropical Pacific Ocean. *J. Meteor. Soc. Japan*, **71**, 221-245.

Thorncroft, C. D. and K. I. Hodges, 2001: African easterly wave variability and its relationship to Atlantic tropical cyclone activity. *J. Climate*, **14**, 1166-1179.

Wang, B. and J. C. L. Chan, 2002: How strong ENSO events affect tropical storm activity over the western North Pacific. *J. Climate*, **15**, 1643-1657.

Wu, C.-C., P.-H. Lin, S. D. Aberson, T.-C. Yeh, W.-P. Huang, J.-S. Hong, G.-C. Lu, K.-C. Hsu, I-I Lin, K.-H. Chou, P.-L. Lin, and C.-H. Liu, 2005: Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR): An overview. *Bull. Amer. Meteor. Soc.*, **86**, 787-790.

Wu, C.-C. and coauthors, 2006: Targeted observation and data assimilation for tropical cyclone track prediction. *Proc. 6th Int'l Workshop Tropical Cyclones, WMO/CAS//WWW*, San Jose, Costa Rica, 21-28 November, 409-423.

Wu, C.-C., J.-H. Chen, P.-H. Lin, and K.-H. Chou, 2007a: Targeted observations of tropical cyclone movement based on the adjoint-derived sensitivity steering vector. *J. Atmos. Sci*., **64**, 2611-2626.

Wu, C.-C., K.-H. Chou, P.-H. Lin, S. D. Aberson, M. S. Peng, and T. Nakazawa, 2007b: The impact of dropwindsonde data on typhoon track forecasts in DOTSTAR. *Wea. Forecast.*, **22**, 1157-1176.

Wu, C.-C., J.-H. Chen, S. J. Majumdar, M. S. Peng, C. A. Reynolds, S. D. Aberson, R. Buizza, M. Yamaguchi, S.-G. Chen, T. Nakazawa, and K.-H. Chou, 2009: Intercomparison of targeted observation guidance for tropical cyclones in the Northwestern Pacific. *Mon. Wea. Rev*., **137**, 2471-2492.

Yamaguchi, M., T. Iriguchi, T. Nakazawa, and C.-C. Wu, 2009: An observing system experiment for Typhoon Conson (2004) using a singular vector method and DOTSTAR data. *Mon. Wea. Rev.*, **137**, 2801-2816.