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TECHNICAL REPORT

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PREFACE

It is our pleasure to present to you the APEC Climate Center (APCC)'s Technical Report 2011, which reports the core outcomes of our research activities from the past year.

Since 2005, APCC, as a hub of climate information in the Asia-Pacific region, has strived to share our analysis and prediction of abnormal climate and to apply this information to regional development. The center has established the largest Multi-Model Ensemble (MME) system for seasonal prediction through its international science network and has provided value-added products to various stakeholders. Recently, APCC has expanded its mandate to include enhancement of the capacity of APEC member economies information to respond effectively to climate change and variability through better application of climate.

To achieve its research and social objectives, in 2011, APCC made efforts to research improvements in its climate prediction performance from various angles and towards better understanding of climate variability and the reproducibility of the climate models for the relevant application of climate information to society. The following technical report provides more information about our research outcomes from 2011.

APCC will continue to improve the quality and accuracy of climate information, recognizing that the utility of this information is only as good as its quality. We would like to make the best use of our research results for the benefit of society and academia. We also welcome any feedback on this report or on our services.

My best and warmest regards to all of you.

Dr. Chin-Seung Chung
Director/APEC Climate Center

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Typhoon Activity in the North West Pacific Region and Its Relation to Different Types of SST Warming over Indian and Pacific Oceans

Dr. Prabodha Kumar Pradhan

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Dr. Prabodha Kumar Pradhan

ABSTRACT

An interesting feature during El Niño Modoki summers (June – August) is the occurrence of surplus rainfall anomalies over South China Sea (SCS) and off-equatorial tropical Northwest Pacific. Based on analyses of observed and reanalyzed data, it is noted that anomalous warming in central tropical Pacific during an El Niño Modoki induces a quasi-stationary Rossby wave response in the form of a low-level cyclonic flow over the northern SCS. This anomalous response favors rainfall enhancement over the SCS and also promotes the seasonal typhoon activity. We find that this scenario over SCS and sub-tropical NW Pacific is further amplified when an El Niño Modoki co-occurs with a positive IOD as in 1994. The combination is apparently more conducive for extreme convection events over the region as compared to a pure El Niño Modoki case. The respective impacts of positive IOD and El Niño, on the other hand, are opposite to one another. The modulation of the typhoon activity by IOD events, however, is prominent only since late 1970s

1. Introduction

Canonical El Niño events [*Rasmusson and Carpenter* 1982; henceforth El Niños], characterized by anomalous warming (cooling) in the eastern (western) equatorial Pacific Ocean, with their global climatic teleconnections, are a dominant feature of tropical climate variability on sub-decadal timescales. Recent studies such as *Larkin et al*. [2005]; Ashok et al. [2007a; henceforth *A*2007a] show that the El Niños have become less frequent. *A*2007a and *Ashok et al*. [2009a] show that a different kind of phenomenon, with warm sea surface temperature anomalies (SSTA) in the central Pacific flanked on the east and west by cooler SSTA has become more common after 1970s. The maximum SSTA are confined to the central tropical Pacific from boreal summer (June to August; henceforth JJA) through the following winter rather than amplifying and moving east as in case of a canonical El Niño such as 1997. This type of tropical Pacific phenomenon has been catalogued as the El Niño Modoki or pseudo-El Niño [*A*2007a]. The frequent occurrence of the El Niño Modoki events since late 1970s are apparently associated with recent background changes with global warming [*A*2007a, *Yeh et al*., 2009].

Recent studies suggest distinct and various possible mechanisms of thermocline feedback [*A*2007a], zonal advection in the ocean [*Kug et al*., 2009], local coupling in central tropical Pacific and subtropical forcing [*Kao and Yu*., 2009; *Yu et al*., 2010]. In accordance with the theories of *Matsuno* [1966] and *Gill* [1980], the teleconnection of the canonical ENSO and ENSO Modoki during boreal summer as through winter are distinctly different [*Navarra et al*., 1999; *Kumar et al*. 2006; *Trenberth and Stepaniak*, 2001; *Larkin and Harrison*, 2005; *A2007a, Ashok et al*. 2009a, 2009b; *Ashok and Yamagata*, 2009; *Weng et al*., 2007, 2009; *Wang and Hendon*, 2007; *Cai and Cowan*, 2009; *Taschetto and England*, 2009; *Taschetto et al*., 2009, 2010; *Chen and Tam*, 2010; *Ratnam et al*., 2010 etc.] in both the spatial and temporal scales.

Composites of SSTA for the El Niño Modoki summer (Figure 1a) show that the associated warm SSTA maximum in the central tropical Pacific extends more meridionally and has weaker zonal and meridional gradients of SST compared to its counterpart in the eastern tropical Pacific during a typical El Niño (Figure 1b). Importantly, while the maximum SSTA during the El Niño Modoki is confined to the central tropical Pacific, the maximum surplus rainfall associated with the event is located to its west and its northwest, and the positive rainfall anomalies over the Philippines through the Taiwan region (Figure 1c), where insignificant SSTA persist [also see *Chang et al*., 2008]; this is in contrast to the equatorially confined rainfall anomalies more tightly aligned with the warm SSTA in the tropical eastern Pacific during El Niño (Figure 1b and 1d), and seen only to the east of 150°E. The current study explores the possible reasons behind the unique extensive anomalous rainfall surplus up to the Philippines and beyond during the El Niño Modoki summers. As it is known, about 42% of the total annual number of Tropical Cyclones (TC) in the tropical western north Pacific (WNP; 120°E–180°E, 0o–30°N) form during JJA. In this context, it is interesting that during the summer of 2004, a strong El Niño Modoki event, an unusually high number of six typhoons has been recorded south of Japan [*Weng et al*., 2007, *A2007a*].

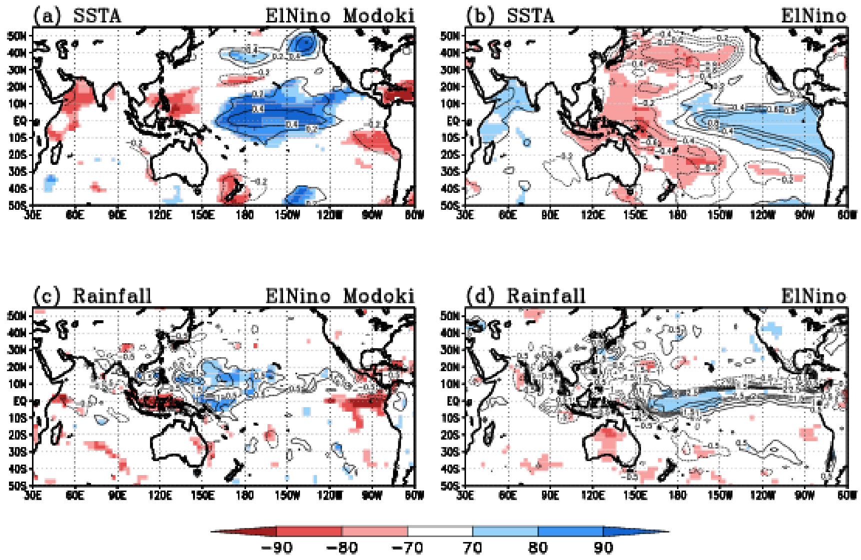

Figure 1 Composite of boreal summer (JJA) SSTA [°C; (a) and (b)] and anomalies of summer rainfall [mmday^{-1}; (c) and (d)]. (a) and (c) for El Niño Modoki years (1986, 1990, 1991, 1992, 1994, 2002 and 2004); (b) and (d) for Canonical El Niño years (1982, 1983, 1987 and 1997). Significant values at 70, 80 and 90 % confidence level are shown in shadings.

A recent study by *Chen and Tam* [2010] also argues that the typhoons in the western tropical Pacific get affected differently by the two tropical Pacific phenomena. However, it is well known that the Indian Ocean Dipole (IOD; *Saji et al.*, 1999) events are seasonally phase locked to the June-November period [*Saji et al.*, 1999; *Yamagata et al.*, 2002; *Yamagata et al.*, 2004]. Also, the tropical Indo-Pacific basins are connected through the atmosphere, leading to the inter-smearing of the individual impacts of the three tropical Indo-Pacific phenomena, namely, ENSO, ENSO Modoki and IOD, when the individual events are strong [*Ueda and Matsumoto*, 2000; Saji and Yamagata, 2003; *Yamagata et al.*, 2002; *Yamagata et al.*, 2004; *A*2007a; *Ashok et al.*, 2009a,b]. From all these considerations, in this study apart from looking into the potential links between the typhoon activity in the WNP with the El Niño and El Niño Modoki associated anomalous rainfall distributions, through modulation of the large scale circulation for the period 1979-2010, we also examine the potential role of the IOD events in modulating the rainfall and typhoon activity over the off equatorial tropical northwest Pacific, including the South China Sea region (together referred to as the

SCS henceforth), and whether they modulate the typhoon frequency during the co-occurring ENSO or ENSO Modokis. We also briefly evaluate the potential role of the IOD events in modulating the Modoki-associated extreme activity in the western tropical Pacific.

2. Data and Methodology

The datasets used in the present study for the main study period from 1979 through 2010 are, the extended reconstructed monthly sea surface temperature (ERSST) from National Ocean Atmosphere Administration (NOAA) at a resolution of 2° × 2° [*Smith et al.*, 2007], the gridded rainfall data from the Global Precipitation Climatology Project (GPCP) Version 2 Combination data [*Adler et al.*, 2003; only available from 1979 to 2009], the National Center for Environmental Prediction /National Center for Atmospheric Research (NCEP/NCAR) reanalysis circulation datasets [*Kalnay et al.*, 1996], observed outgoing long wave radiation (OLR) data from NOAA satellites [www.cdc.noaa.gov] and observed 'best cyclone track' data from the Joint Typhoon Warning Center, USA [www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.html]. In addition, the ERSST and observed 'best cyclone track' data for the period from 1945 to 2010 have also been used to verify the association between typhoon activity in the tropical WNP the various tropical Indo-Pacific drivers.

All the tropical cyclones (TCs) with maximum surface wind > 17m/sec are considered in this study. Further, we have followed the method of *Mujumdar et al.*, [2007] to realize the TC tracks and frequency in the tropical WNP. For identification of the El Niño Modoki (El Niño) events, two criteria used, broadly following *A2007a* are (i) a minimum amplitude of 0.7σ of the ENSO Modoki index (Nino3 index) during boreal summer (JJA), and (ii) that the maximum SSTA by the following DJF are in the central (eastern) tropical Pacific. Based on this categorization, the El Niño Modoki (El Niño) years we identified are 1986, 1990, 1991, 1992, 1994, 2002 and 2004 (1982, 1983, 1987 and 1997), respectively.

Table 1 Definitions of different regions/SSTA-based indices used in this study

Index Name	Definition
NINO3	The region is bounded by (5ºN-5ºS, 150ºW-90ºW). The area-averaged sea surface temperature anomaly over this region is known as NINO3 index, which is a well-known ENSO index.
El Niño Modoki index	Following, Ashok et al. (2007a), the El Niño Modoki index (EMI) is defined as $EMI = [SSTA]C-0.5[SSTA]E-0.5[SSTA]W$ where the square bracket with a subscript represents the area-mean SSTA, averaged over one of the three regions specified as the central (C: 165°E-140°W, 10°S-10°N), eastern (E110°-70°W, 15°S-5°N), and western (W: 125°-145°E, 10°S-20°N).
Indian Ocean Dipole Mode Index	The Indian Ocean Dipole Mode Index (IODMI) is defined as the SSTA difference between the western (50°E-70°E, 10°S-10°N) and southeastern (90°E-110°E, 10°S-equator) regions of the tropical Indian Ocean (Saji et al., 1999).

Composite of any parameter for El Niño Modoki (El Niño) summers is an average of the same over the afore-cited seven (four) events. During the boreal summer of 2009, a unique basin wide warming was observed in the tropical Pacific Ocean and that is different from the two flavors of El Niño, and ocean-atmosphere interaction is very distinct (*Ashok et al*. 2012). Hence we have decided to not catalogue this particular summer. In this study, we use the NINO3 index, ENSO Modoki index, and the Indian Ocean Dipole Mode index (see Table 1 for definitions) to represent the ENSO, ENSO Modoki, and IOD events respectively.

3. The Modoki rainfall and Typhoon interaction in the WNP

3.1 Anomalous seasonal conditions in the South China Sea region during El Niño Modoki summers

Composited boreal summer circulation anomalies of the El Niños and El Niño Modokis (Figure 2) are examined in order to distinguish the distinct atmospheric signatures in the tropical western north Pacific (WNP). During El Niño Modoki summer, lower level westerly anomalies over the tropical WNP meridionally extend to 15°N (Figure 2a) and are associated with anomalously reduced convection (Figure 3a).

Anomalously suppressed convection is also seen in the central to western maritime continent. Further north, we see a well-organized large-scale anomalous cyclonic circulation over south China Sea, Taiwan and Philippines region followed by an anomalous anticyclone further north over Japan (Figure 2a), in agreement with earlier studies [*Weng et al*. 2009; *Chen and Tam*, 2010]. We also find (Figure 3a) anomalously enhanced convection over broad regions of the SCS region and suppressed convection in eastern China, Korea and Japan regions. The alternating anomalous cyclonic and anti-cyclonic circulation over the SCS and its north, associated with an anomalous low and an anomalous high respectively as seen from the distribution of 850 hPa geopotential anomaly (Figure 2a). The findings are in general agreement with earlier studies [*Weng et al*., 2007; *Mujumdar et al*., 2007; *Chen and Tam*, 2010]. It is noticeable that the aforementioned low level cyclonic circulation anomaly to the south of Japan is not associated with any SSTA of significant magnitude. These anomalous low level circulation and convection features can be interpreted as meridional dispersion of Rossby waves associated with the warmer SSTA in the central tropical Pacific [*Li and Wang*, 2005; *Lau and Wang*, 2006] as per the Matsuno-Gill (*Matsuno*, 1966; *Gill*, 1980) theory.

During El Niño years, anomalously strong convection (Figure 3b) is noticed over the central Pacific region, with the maximum near the dateline, and mainly confined to within 10° on each side of the equator. Positive OLR anomalies are noticed over north of 10°N, which clearly indicates that suppressed convection prevails over that region.

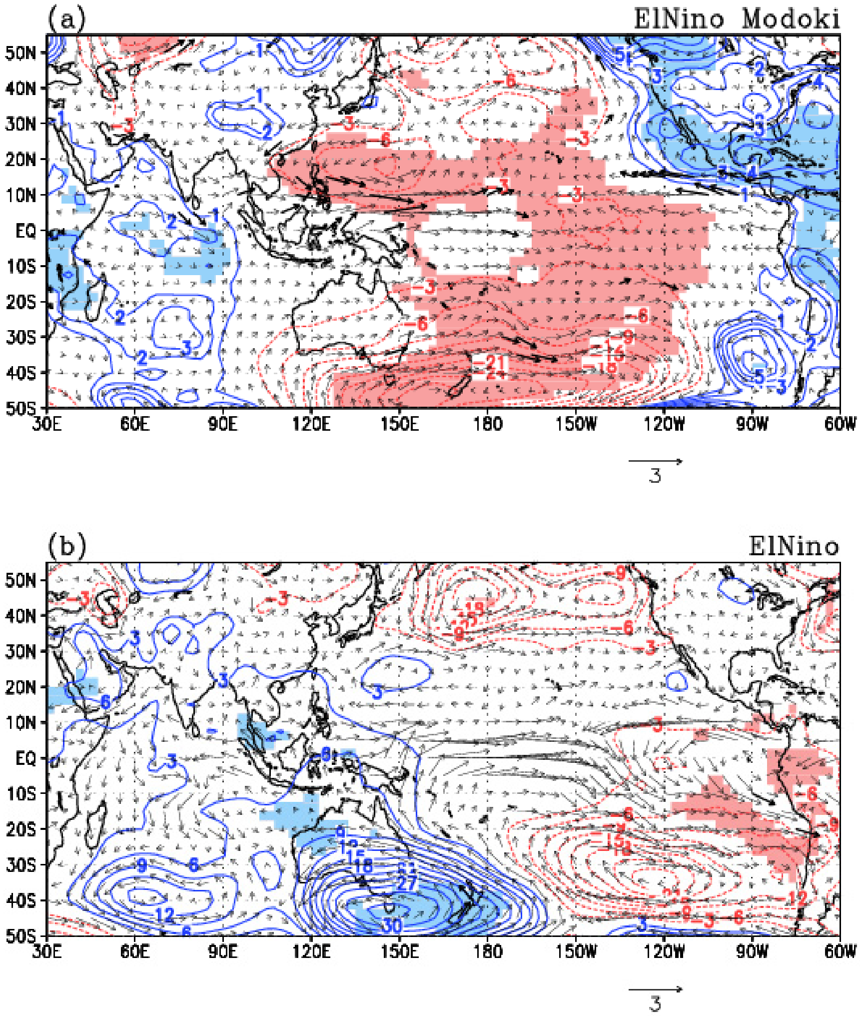

Figure 2 Composite of geopotential height anomalies (m) at 850hPa (blue/red contours indicating positive and negative values; significant values at 80% confidence level are shown in shadings) and wind anomalies (m sec^{-1}) at 850hPa level during boreal summer (JJA) for (a) El Niño Modoki (1986, 1990, 1991, 1992, 1994, 2002 and 2004) (b) Canonical El Niño years (1982, 1983, 1987 and 1997) respectively.

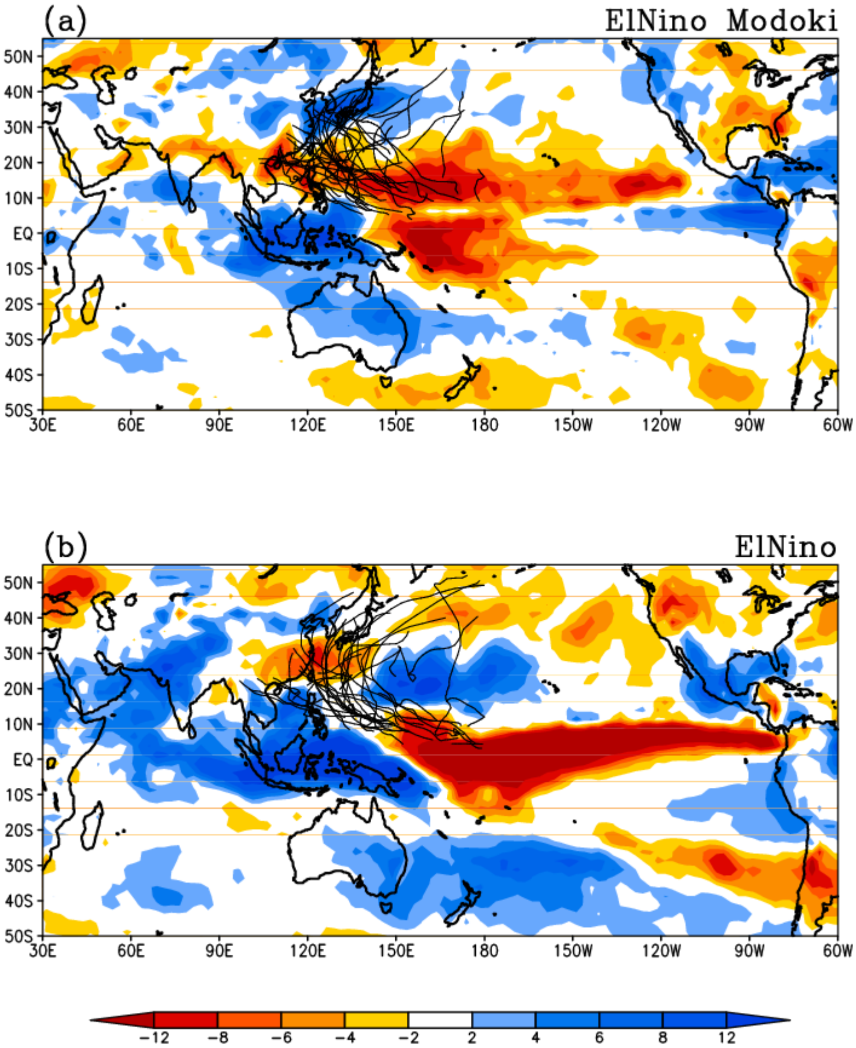

Figure 3 Composite of observed tropical storm tracks over the North Western Pacific and averaged OLR anomalies (Wm^{-2}) [shading] during boreal summer (JJA) for (a) El Niño Modoki years (1994, 2002 and 2004 (b) Canonical El Niño Years (1982, 1987 and 1997) respectively.

3.2 Tropical cyclones during El Niño and El Niño Modoki summers: Year to Year differences

Figure 4 shows the interannual variability of the TC frequency in the tropical NWP. It is seen that out of the 7 El Niño Modoki events, 4 are associated with near or above 30% anomalous surplus of TCs. Noticeably, the strongest Modoki events (1994, 2002 and 2004) are associated with the highest 1, 2 and 4 above average TC frequencies. The 1990 and 1991 events do not show significant TC activity while 1986 summer witnessed a lower than normal TC activity. Nonetheless, the EMI and TC frequency in SCS during JJA (1979-2010) are significantly correlated at 0.39 (significant at 99% confidence level from a 2-tailed Student's t-test), in agreement with the findings (correlations of 0.36) *of Chen and Tam* [2010] for a longer period. Based on these statistics, we can make a statement that the El Niño Modokis have a strong propensity to be associated with above average TC frequency during boreal summer. The presence of the anomalous cyclonic (anticyclonic) circulation in the SCS (south of Japan), shown in Figure 2a, apparently favors the TCs to northward and re-curve around 25°N between Taiwan and Japan (see Figure 3).

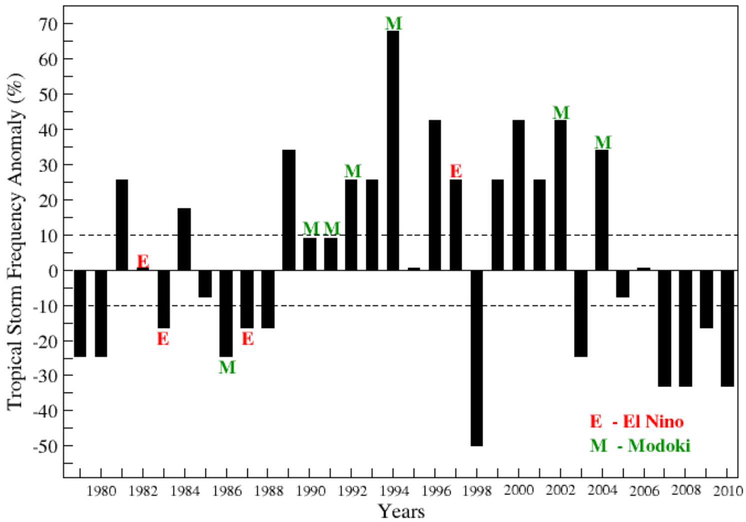

Figure 4 Year-to-year variation of tropical storm frequency anomaly over the western north Pacific region (120°E–180°E, 0°–30°N) for the period 1979 to 2010.

On the other hand, Figure 4 shows that the El Niño events are associated with lesser than normal TC activity, is apparently due to the broad low level anticyclonic circulation in the western north Pacific between 10°N-30°N (Figure 2b). To further understand the seasonal anomalous features that enhance the TC activity in the WNP during the El Niño Modoki, we present the anomalous 850 hPa vorticity (Figure 5a) and also the anomalous magnitude of the vertical wind shear of zonal flow (Figure 5c), obtained as the difference between 200 and 850 hPa levels. These two are important dynamical factors related to TCs development [*Gray*, 1979; *Kurihara and Tuleya*, 1981].

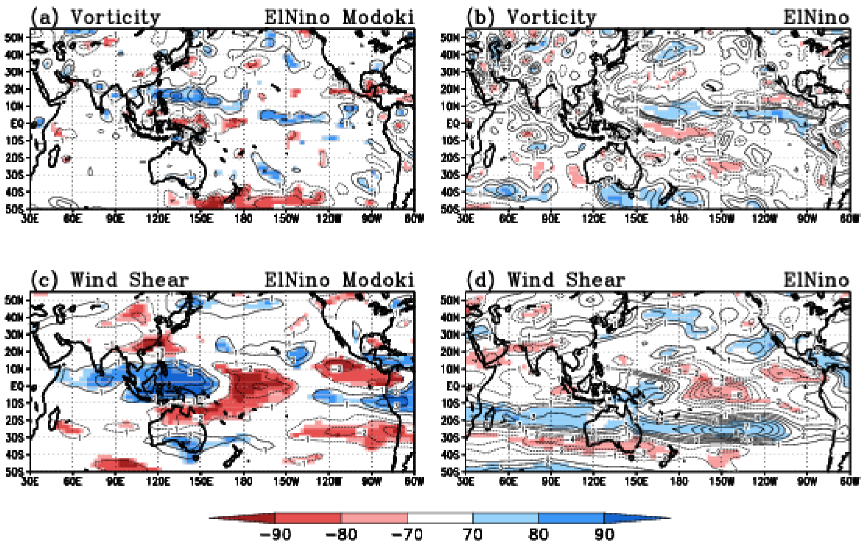

Figure 5 Composites of anomalies of relative vorticity (10^{6} sec^{-1}) at 850 hPa and magnitude of vertical shear of horizontal wind anomalies (m sec^{-1}) during boreal summer (JJA) for (a) El Niño Modoki (1986, 1990, 1991, 1992, 1994, 2002 and 2004 (b) Canonical El Niño years (1982, 1983, 1987 and 1997) respectively. Significant values at 70, 80 and 90 % confidence level are shown in shadings.

A broad swath of positive vorticity anomalies from the SCS extends southeast into the central tropical Pacific, in agreement with the circulation anomalies (Figure 2a), favoring TCs formation and development. Figure 5c shows a small wind shear anomaly over the area where the anomalous cyclonic vorticity is maximum. Thus anomalous decrease in the vertical wind shear and increase in vorticity are contiguous in northwestward of the WNP, therefore, the TCs that develop and move northwestward, will continue to be under these favorable conditions. On the other hand, during El Niños, though the positive vorticity anomalies are seen (Figure 5b) to the region of 0-10°N, 130°E-150°W, the magnitude of vertical wind shear has, however, changed appreciably with in the box 5°N-25°N, 110oE-180oE (Figure 5d); the second condition is at least not favorable for TCs activities. Another important environmental condition for tropical cyclone activity is SSTA. As discussed in previous section, the broader warmer SST in the central tropical Pacific during El Niño Modoki summers tends to create a favorable thermodynamic condition for tropical cyclones through the air–sea heat flux exchange [*Emanuel*, 1999] than El Niño years (Figure not shown). Earlier data analysis and GCM experiment studies by *Kumar and Krishnan* [2005], *and Mujumdar et al* [2007] also indicate that the central tropical Pacific warming in years such as 2002 increases the typhoon activity in northwest Pacific. Accordingly, the warm SST anomalies in the equatorial western-central and central Pacific are also postulated as a possible cause for inducing the favorable conditions for the northward shift of the typhoon track.

3.3 IOD and Tropical cyclones during El Niño Modoki summers

Guan et al., [2003], show, by diagnostic analysis, that during a positive IOD such as that occurred during the boreal summer of 1994 (see Figure 9 for the time series of the IOD mode index; IODMI) a Rossby wave train is excited in the upper troposphere by the IOD-induced vorticity source (the divergent flow) over India, the Bay of Bengal, and the southern China. This response results in a net diabatic surplus in a region extending from Bay of Bengal through SCS (see Figure 3c of *Guan and Yamagata*, [2003]). Subsequently, *Fu et al*., [2008] through a composite analysis of multiple IOD summers confirm the finding. Further, recent studies by *Ashok et al*., [2007b] and *Cai et al*., [2011] demonstrate that the diabatic (convective) heating anomalies induced by ENSO and IOD excite Rossby wave trains and these wave trains induce changes to the midlatitude westerlies across southern Australia and affects the rainfall over the region, including transient activity. These studies, along with the AGCM results of *Guan et al*., [2003], *Mujumdar et al*., [2007], form a basis to suggest that positive IODs can influence the ENSO or ENSO Modoki-induced circulation, and associated typhoons activity there in.

During 1994 boreal summer, when a positive IOD event co-occurred with the El Niño Modoki, 20 typhoons were recorded in the SCS (Table 2; also see Figure 4), the highest for the summer season during the study period. Considering that the amplitude of the EMI during 1994 summer was more or less of similar to that of the corresponding of 2004 and 2002 (see Figure 9), the TC increase for that season (Figure 4) is disproportionately high to be attributed to the El Niño Modoki only.

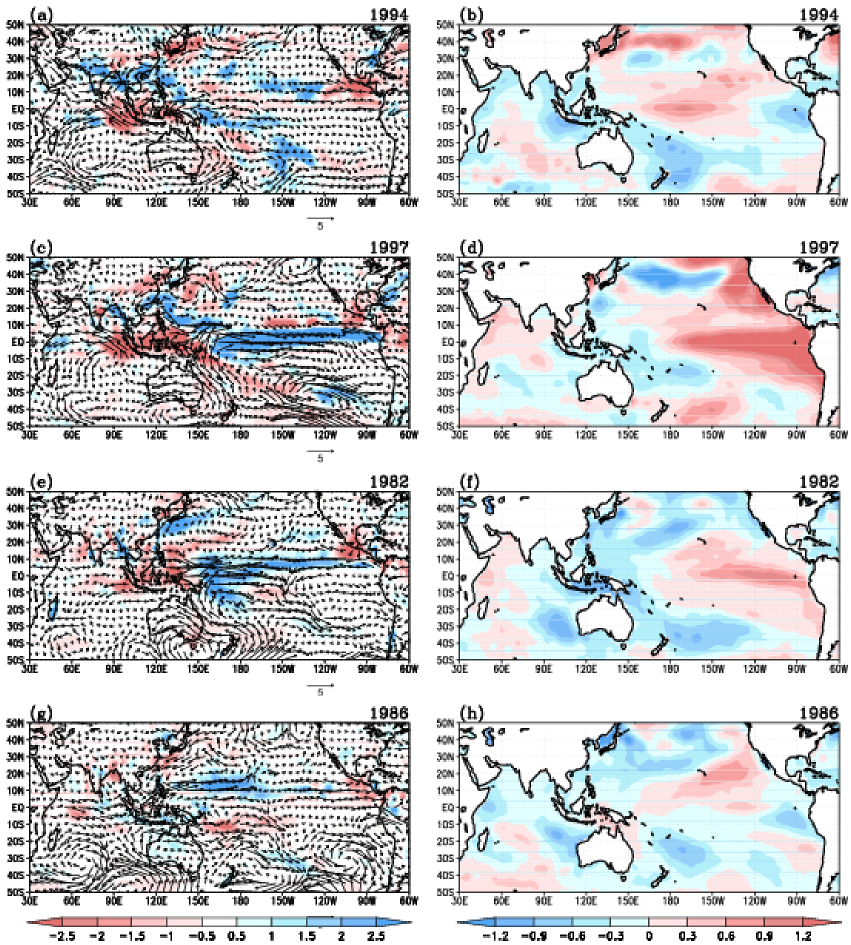

Figure 6 Rainfall and 850hPa circulation anomalies during boreal summer (JJA) of (a) 1994, (c) 1997, (g) 1982 and (g) 1986 and the corresponding SST anomalies (b), (d), (f) and (h) respectively.

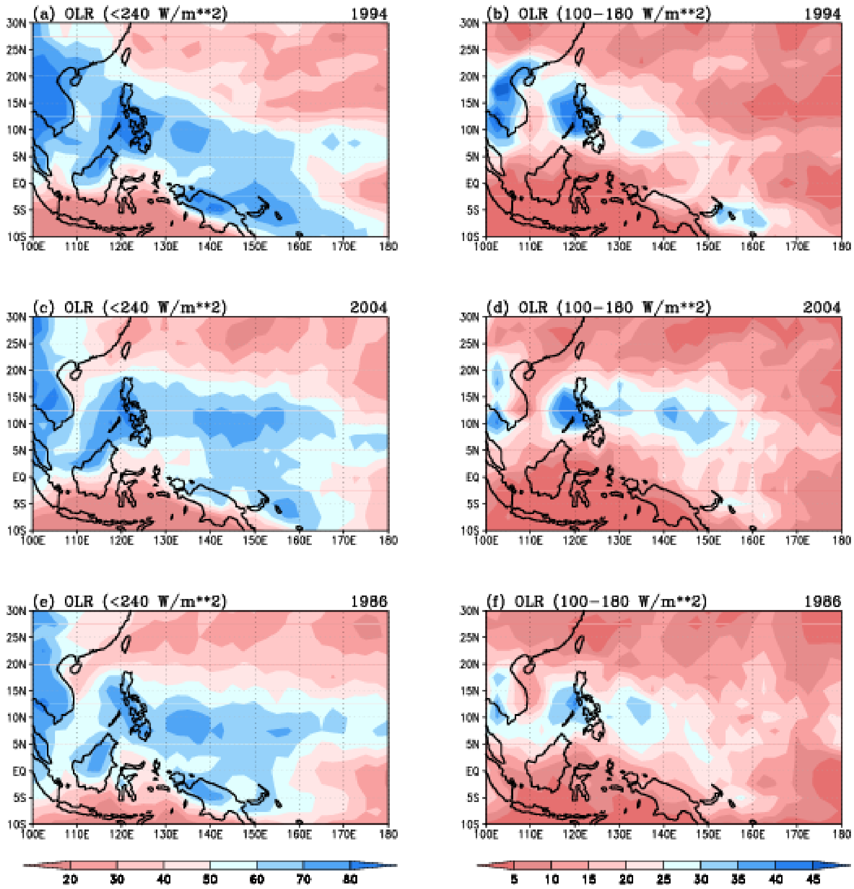

Figure 7 Boreal summer (JJA) frequency distribution of the number of days when the mean daily OLR is (a, c, e) less than 240 W.m^{-2} during 1994, 2004, and 1986 respectively and (b, d, f) between 100-180 W.m^{-2}.

On a similar note, during all the El Niño years the TC activity was below normal except during the boreal summer of 1997. In fact, the 1997 boreal summer witnessed 15% above normal typhoons; the negative anomaly of the typhoon frequency during 1982 was also rather small. It is worth noting, again, that both 1982 and 1997 are positive IOD years (Figure 9). Figure 6 shows the circulation conditions during the summers of 1994 and 1997. During the 1994 summer, westerly anomalies have been observed over Bay of Bengal, extending up to western Pacific region (Figure 6a).

Table 2 Frequency of typhoons formed over the western North Pacific Ocean during boreal summer (JJA) period of 1979 to 2010.

Years	Frequency
1979	9
1980	9
1981	15
1982	12
1983	10
1984	14
1985	11
1986	9
1987	10
1988	10
1989	16
1990	13
1991	13
1992	15
1993	15
1994	20
1995	12
1996	17
1997	15
1998	6
1999	15
2000	17
2001	15
2002	17
2003	9
2004	16
2005	11
2006	12
2007	8
2008	8
2009	10
2010	8

The anomalous low level convergence induced by the positive IOD and positive SSTA over the region (Figure 6b) might have enhanced the cyclonic anomalies induced by the El Niño Modokis and resulted in more number of TC being formed in/moved into the SCS. On the other hand, the co-occurring positive IOD apparently reduced the favorable conditions for a strong anticyclonic circulation at lower levels associated with the El Niño of 1997 (Figure 6c and 6d), and also during 1982 (Figure 6e and 6f). However, all these arguments are based on linear assumptions, and also implicitly take into account that all through the season, the strengths of the respective tropical Indo-Pacific events are significant. The findings do not explain why the 1986 summer witnessed such a strong negative anomaly of typhoons, despite being an El Niño Modoki We shall try to speculate what may have happened in light of the above arguments. An examination of the monthly ENSO Modoki index (Figure not shown) reveals that the 1986 El Niño Modoki has evolved slightly late as compared to stronger events such as 1994, 2004, etc. Further, we also witnessed the occurrence of weak negative IOD-like conditions during the JJA of 1986, particularly during June-July. These two factors jointly may have resulted unfavorable conditions for the formation of TCs during the summer of 1986 (Figure 6g and 6h).

3.4 Long term links of the frequency of typhoons with ENSO, Modoki and IOD

Occurrence of Modoki events became more frequent only since late 1970s and hence in this paper the analysis has been carried out in detail for the recent period 1979 to 2010. However, the limited data period is subject to sampling issue. Therefore, the analysis has been extended for a longer period (1945-2010) to understand the association of the frequency of typhoons in the tropical NWP region with the tropical Indo-Pacific drivers. The results are presented in Table 3. It is to be noted that any Modoki-like signal during pre-1970 summers is just a transnino [*Trenberth and Stepaniak.*, 2001], i.e. transitory signal associated with the evolution of a canonical El Niño, rather than a real Modoki event with maximum anomalous warming in the central tropical Pacific from boreal summer through winter [*A*2007a, *Yeh et al.*, 2009]. Out of the 13 El Niño Modoki like summers that occurred during the extended period, 9 are associated with an enhancement in typhoon activity over the region, while 4 experienced a reduction in typhoon activity. Further, the boreal summer EMI and the NWP typhoon are correlated by 0.25 (0.36) for the period 1945-2010 (1960-2010), significant at 98% (99%) confidence level from a 2-tailed Student's t-test. This confirms the predisposition of the El Niño Modoki events to increase the typhoons in the off-equatorial northwestern Pacific during the boreal summer.

The recent paper by *Chen and Tam* [2010] also arrived at a similar conclusion based on a different SST dataset. However, as seen from the Table 3, for the extended period, equal number of positive and negative IOD events co-occurred during the El Niño Modoki summers with above and below normal typhoon activity. On a longer period basis, the IOD events appear to be not significantly associated with modulation of the Modoki-associated typhoon activity. This is in conformation with earlier studies [*Ashok et al*., 2001, *Ihara et al*., 2008] which indicate that the IOD impact on the Indian summer monsoon and Bay of Bengal convection only since late 1970s, and it is subject to the frequency, phase, and intensity of the IOD events. Decadal variability of the tropical Indo-Pacific drivers, including the regime shift in late 1970s [*Ummenhofer et al*., 2008, A2007a] may be an important factor in deciding the large scale background for typhoon activity in the off equatorial NWP during boreal summer. Nonetheless, the conclusions based on the analysis of the longer period data are subject to quality issues of the SST and typhoon frequency datasets.

Table 3 Frequency of El Niño and El Niño Modoki events associated with above and below normal typhoon activities in the tropical WNP region along with the phase of IOD for boreal summer (JJA) period of 1945 to 2010.

Frequency of Events (years)	Typhoon Activity in tropical WNP region					
	Above Normal Years			Below Normal Years		
	Total	IOD Phase		Total	IOD Phase	
		Positive	Negative		Positive	Negative
El Niño (11)	6	3	0	5	2	0
El Niño Modoki (13)	9	2	2	4	1	1

4. Summary and discussion

In this study, an effort has been made to understand the distinct rainfall surplus in the northern portions of the South China Sea associated with the El Niño Modoki events during the boreal summer, using the observed datasets such as the GPCP rainfall, ERSST, NOAA OLR and NCEP/NCAR reanalysis products mainly for the period 1979-2010. Composite analyses of SSTA, rainfall, circulation, etc. for the El Niño Modoki events indicate that the positive rainfall anomalies in the SCS are associated with an anomalous low level cyclonic circulation in the SCS, induced as a Rossby response to the anomalous central Pacific warming. This anomalous response apparently facilitates amplification of the seasonally phaselocked typhoon activity in this region, and results in anomalously surplus rainfall that forms a continuum all the way to the central tropical Pacific. On the other hand, the unfavorable conditions induced by El Niños in the SCS during JJA [*Chen and Tam*, 2010] are unfavorable for cyclonic activity.

Interestingly, since late 1970s, the positive IOD events play a major role by inducing anomalous low level cyclonic circulation as well as above normal convection all the way from Bay of Bengal through the SCS. The result is that the anomalous increase (decrease) in typhoon frequency during the El Niño Modoki (El Niño) is further amplified (weakened). This means that it is likely that strong IOD events can also modulate the anomalous extreme event activity induced by the El Niño Modokis. To verify this, we have binned the frequencies of the area-averaged daily mean OLR values over the tropical Western pacific (120°E-150°E,5°N-30°N) during boreal summers of three El Niño Modoki years in to various categories depending on the OLR value at each grid point in the selected region. These years are (i) 1994, with a co-occurring positive IOD event (ii) 1986, with a co-occurring negative IOD event, and (iii) 2004, when there was no co-occurring IOD event.

An examination of the distribution of frequency of number of days the OLR falls in the range of 100-180 W/m^{-2} (Figure 7b, 7d, 7f), i.e. those days when extreme convection prevailed, shows that the region, particularly from the Philippines through to Taiwan experienced extremely low OLR values during 1994 in comparison with the other two summers. This conclusion in general also holds for the frequency distribution of those days when the OLR fell below 240 W/m^{-2}. This analysis indicates that strong positive IOD events can enhance the extreme convection activity in the tropical western Pacific induced by the co-occurring El Niño Modokis. One possible implication of increase in extreme convection activity is a positive feedback from these extreme convection events on the Modoki-induced large scale cyclonic circulation itself. However, we cannot make any strong conclusion at this stage given that the sample we have used in this exercise is rather small, and that the low OLR values are always not necessarily due to high convection. Further, the IOD impact seems to be prominent only since late 1970s. The changing impact, and the possible association with background changes, is beyond the scope of the current study.

The major objective of this study is the identification of the Rossby response in association with convective activities and their intensity due to the individual and combined influence of canonical El Niño, El Niño Modoki and IODs. These convective activities and their source regions are depicted in Figure 8, shows the source regions of enhanced convection and non-convection activity over the tropical region during warm phase of ENSO. The active (non-active) convection over NWP is particularly associated with Rossby waves during El Nino Modoki (El Niño) years. Similar studies also discussed in Cai et al. (2011).

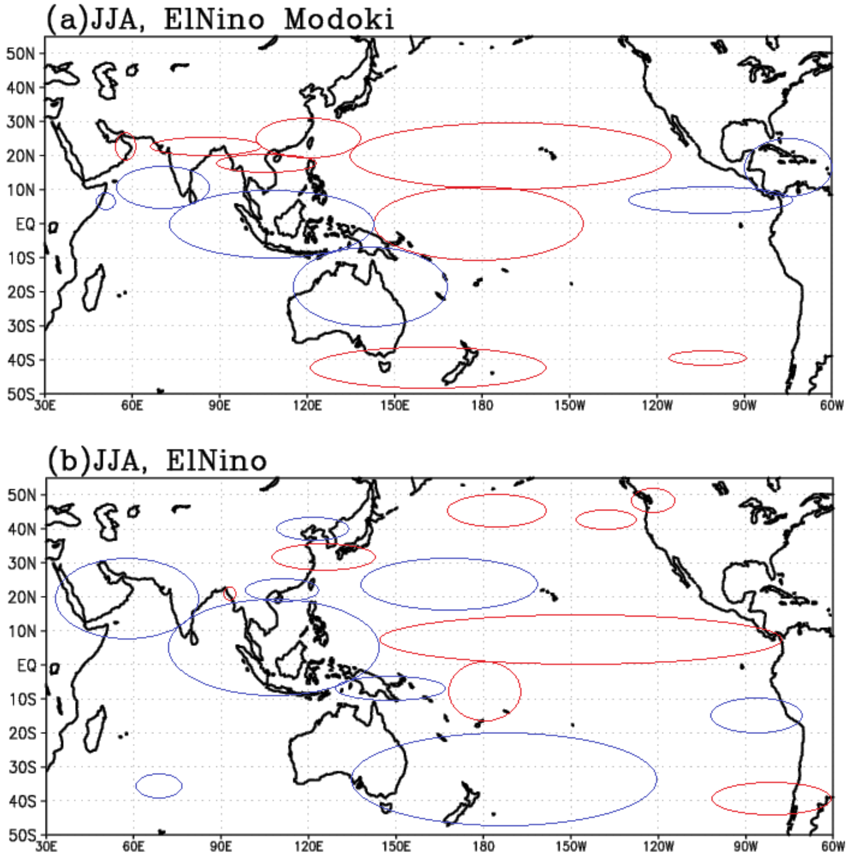

Figure 8 Schematic illustration shows the boreal summer rainfall (JJA) period associated with convective activity over tropical region (a) El Nino Modoki (b) El Nino years [red (blue) areas indicate regions of enhanced convection (non-convection)] respectively.

It is also interesting to note that during the boreal winter (December-February), the anomalous circulation and rainfall responses over the SCS during the El Niño Modoki as well as El Niño are similar (See Figure not shown; see *Weng et al*., 2009), while the corresponding responses over Australia as well as regions east of the eastern Pacific, the circulation and precipitation responses are distinctly different. In a recent study, *Taschetto et al*. [2010] show that during those Februarys associated with an El Niño Modoki, the Modoki-induced Walker circulation over Australia is overwhelmed by and the Matsuno-Gill response associated with the anomalous convection in the central tropical Pacific.

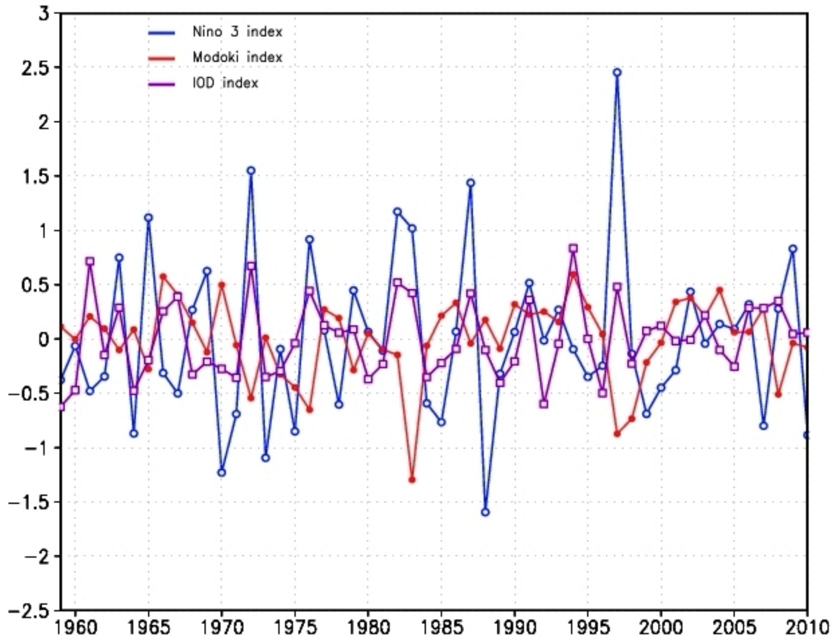

Figure 9 SSTA based indices for boreal summer (JJA) period 1959 to 2010. for three climate indices such as Nino 3 index (blue line), El Niño Modoki Index (red line) and Indian Ocean Dipole Mode Index (purple line) respectively.

Briefly, based on data analysis and model experimentations, they explain out that apart from the seasonally phaselocked southward shift of the inter-tropical convergence zone and strengthening of the South Pacific convergence zone that play an important role in enhancing the diabatic heating in the central tropical Pacific, the seasonal monsoon background conditions over Australia also facilitate generation of a cyclonic response over Northwest Australia, akin to a Rossby wave response. This gives us a clue that absence of seasonal rain bearing processes during the boreal winter in the SCS region, such as monsoons or typhoons, apart from the inter-seasonal structural differences of SSTA and Walker circulation associated with the Modoki and ENSOs, may be a reason why such prominent response such as during boreal summer is not seen. Secondly, the boreal winter season is also associated with strong MJO activity in the tropical Indo-Pacific region, which may play an important role in smearing out the remote Matsuno-Gill signatures of the ENSO as well as ENSO Modoki in the SCS. These issues need further attention.

A limitation of this study is that this is based on an analysis of observed and reanalyzed datasets that is subject to data sampling. We plan to carry out appropriate sensitivity experiments using general circulation models to confirm the respective roles of the three tropical Indo-Pacific drivers, and also the potential importance of seasonal cycle and seasonal features such as the propensity of the typhoons that occur during boreal summer in causing the positive rainfall anomalies in the SCS during the El Niño Modoki events.

5. Acknowledgments

The author is sincerely thankful to the director general of APEC Climate Center (APCC), Busan, Republic of Korea, for giving an opportunity and providing the necessary facilities to carry out this work. The author also acknowledges JTWC, NOAA and NCEP/NCAR, USA for providing best tropical storm track datasets, OLR and reanalysis fields. I acknowledged to the COLA/GrADs, USA for their software support, in which figures prepared and used in the report.

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ISBN 978-89-97333-16-5
ISBN 978-89-97333-15-8 (세트)