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Impact of IODM and ENSO on the East Asian Monsoon: Simulations through NCAR Community Atmospheric Model

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동아시아 몬순 지역에서 IODM과 ENSO의 영향 : NCAR Community Atmospheric Model을 이용한 모의 실험

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ABSTRACT

The normal Indian Ocean is characterized by warmer waters over the eastern region and cooler waters over the western region. Changes in sea surface temperature (SST) over the western and eastern Indian Ocean give birth to a phenomenon now referred to as the Indian Ocean Dipole Mode (IODM). The positive phase of this mode is characterized by positive SST anomalies over the western Indian Ocean and negative anomalies over the southeastern Indian Ocean, while the negative phase is characterized by a reversed SST anomaly pattern. On the other hand, the normal Pacific Ocean has warm (cool) waters over the western (eastern) parts. Positive (negative) SST anomalies over the central/eastern (western) Pacific Ocean characterize the El Nino phenomenon. The reverse situation leads to the La Nina phenomenon. The coupled ocean-atmosphere phenomenon over the Pacific is referred to as the El Nino Southern Oscillation (ENSO) phenomenon. In this study the impact of IODM and ENSO on the East Asian monsoon variability has been studied using observational data and using the Community Atmospheric Model (CAM) of the National Center for Atmospheric Research (NCAR). Five sets of model experiments were performed with anomalous SST patterns associated with IODM/ENSO superimposed on the climatological SSTs. The empirical and dynamic approaches reveal that it takes about 3-4 seasons for the peak IODM mode to influence the summer monsoon activity over East Asia. On the other hand, the impact of ENSO on the East Asian monsoon could occur simultaneously. Further, the negative (positive) phase of IODM and El Nino (La Nina) over the Pacific enhances (suppresses) monsoon activity over the Korea-Japan Sector. Alternatively, IODM appears to have no significant impact on monsoon variability over China. However, El Nino (La Nina) suppresses (enhances) monsoon activity over China. While the IODM appears to influence the North Pacific subtropical high, ENSO appears to influence the Aleutian low over the northwest Pacific. Thus, the moisture supply towards East Asia from the Pacific is determined by the strengthening/weakening of the subtropical high and the Aleutian low.

Key words **: IODM, ENSO, East Asian monsoon, NCAR CAM**

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I. INTRODUCTION

The normal Indian Ocean is characterized by warmer waters in the east and cooler waters on the west. The Indian Ocean Dipole Mode (IODM) refers to the episodic occurrence of an anomalous zonal gradient in sea surface temperature (SST) across the equatorial Indian Ocean (Saji *et al.,* 1999; Webster *et al.,* 1999; Behara *et al.,* 1999). The IODM is characterized by anomalous cooling of SST in the south eastern equatorial Indian Ocean off Sumatra and an anomalous warming in the western equatorial Indian Ocean. Cooler waters in the eastern Indian Ocean gives rise to easterly winds in the vicinity of the equator. This state of the Indian Ocean is identified as a positive IODM event, which develops rapidly in boreal summer and peaks in boreal autumn. The reverse situation viz. warm (cool) SST anomalies over the southeast (western) equatorial Indian Ocean is termed as the negative IODM event. This mode has been associated with the climate and monsoon variability over India (e.g. Ashok *et al.,* 2004; Kripalani and Kumar, 2004), Sri Lanka (Zubair *et al.,* 2003), East Africa (e.g. Clark *et al.,* 2003; Black *et al.,* 2003), Australia (Ashok *et al.,* 2003), East Asia (Guan and Yamagata, 2003; Kripalani *et al.,* 2005; Chaudhari *et al.,* 2005) and other parts of the globe (Saji and Yamagata, 2003).

On the other hand the normal Pacific Ocean is characterized by warm water towards the west and cool water towards the east. The migration of warm waters towards the central/east Pacific gives birth to El Nino with anomalous westerly flow over the equatorial Pacific. The anomalous warming (cooling) over the western (eastern) Pacific Ocean is termed as the La Nina. This coupled atmosphere-ocean phenomenon is termed as the El Nino Southern Oscillation (ENSO) phenomenon. The impact of this mode over the globe has been well documented since the time of Sir Gilbert Walker, more than a century ago. Some studies to investigate the impact of this mode on East Asia monsoon have been done (e.g. Tao and Chen, 1987; Ho and Kang, 1988; Huang and Sun, 1992; Oh *et al.,* 1997; more references in Ding and Chan, 2005).

IODM has a life cycle that is different from ENSO. Period of IODM is short and it may develop in summer (June-July-August: JJA), peak in autumn (September-October-November: SON) and thereafter it decays (it may last for 2-3 seasons). ENSO can initiate in spring (March-April-May: MAM), peak in winter (December-January-February: DJF) and continue to be strong. It can last for 3-6 seasons. Studies on the possible impact on IODM and ENSO on East Asian monsoon have been limited. In view of the above we investigate the impact of the IODM and ENSO on East Asian Monsoon using empirical and dynamical approach. Numerical simulations are performed with the NCAR CAM (National Center for Atmospheric Research Community Atmospheric Model) version 2.0.2.

In section 2 the data used are described, while in section 3 the empirical relationships between IODM and ENSO with the East Asian summer monsoon are investigated. The design of the numerical experiments conducted is detailed in section 4. The simulated precipitation pattern and the lower troposphere circulation fields are discussed in section 5. Finally section 6 summarizes the main results of this study.

II. DATA

Following data sets have been used in this study:

(i) An index to quantify the IODM has been proposed by Saji et. al. (1999). This is the difference in SST anomaly between the tropical western Indian Ocean (50°-70°E, 10°S-10°N) and the tropical southeast Indian Ocean (90°-110°E, 10°S-equator) and is denoted as Dipole Mode Index (DMI). The standardized monthly time series of DMI for the period January 1960 through December 1999 has been derived from monthly GISST data (Rayner *et al.,* 1996).

(ii) The ENSO phenomenon is quantified by the Nino3 (4°S-4°N, 150°W-90°W) monthly SST values downloaded from ftp.ncep.noaa.gov for the period 1960-2000.

The above monthly data sets are converted to seasonal series for DJF, MAM, JJA, and SON by simple arithmetic averages for the respective months.

(iii) Seasonal summer monsoon rainfall for the following regions:

- Average rainfall of 13 stations over North China (36°-41°N, 109°-124°E) for the period 1960-1998, designated as China monsoon rainfall (CMR).
- Average rainfall for 12 stations over South Korea (34°-38°N, 126°-130°E) for the period 1961-2000, designated as Korean monsoon rainfall (KMR) is taken from Kim *et al.* (2002).
- Average rainfall of 16 stations over southern Japan (31°-36°N, 130°-141°E) for the period 1960-1999, designated as Japan monsoon rainfall (JMR).

The source of station rainfall data used to compute CMR and JMR and the justification for the regions identified for averaging are available in Kripalani and Kulkarni (2001). Seasonal rainfall over China, Korea, and Japan contribute to the intensity of the monsoon over East Asia. Thus the main focus of this study is to investigate seasonal relations of IODM and ENSO with summer monsoon rainfall over China, Korea and Japan.

III. EMPIRICAL RELATIONSHIPS

The search for a relationship usually involves the calculation of a sample cross-correlation function for pairs of time series. Hence we compute correlation coefficients (CCs) of Dipole Model Index (DMI) and Nino3 SST with the summer monsoon rainfall over China, Korea, and Japan. CCs are based on the period 1961-1998. For a sample of this size a value of ~0.3 (0.4) is significant at 5(1)% significance level. The suffix -1, 0, +1 with the seasons indicates the seasons for the preceding, concurrent and following the monsoon year, respectively. The seasons on the left (right) of JJA0 (Fig. 1, 2) indicate DMI or Nino3 SST leading (lagging) the monsoon rainfall.

Fig. 1 illustrates the relationship between DMI and monsoon rainfall over China, Korea, and Japan. The most striking features of this analysis are:

(i) The simultaneous CCs between DMI and seasonal rainfall during summer (JJA0) for China, Korea and Japan are insignificant.

(ii) Summer (JJA-1) and autumn (SON-1) indices during the preceding year show a significant negative relationship with rainfall over Korea and Japan respectively, implying that the negative (positive) phase of IODM will enhance (suppress) monsoon activity over Korea-Japan sector 3 to 4 seasons later. Interestingly the strongest relationship (CC= -0.6) is with the Korean monsoon rainfall. The mechanism for such delayed impact of IODM on the summer monsoon rainfall over Korea-Japan sector 3 seasons later has been explained through the Eurasian snow cover (Kripalani *et al.*, 2005; Chaudhari *et al.*, 2005).

Fig. 2 illustrates the relationship between Nino3 SST and monsoon rainfall over China, Korea, and Japan. The most striking features of this analysis are:

(i) The simultaneous relationship between Nino3 SST and rainfall over China, Korea and Japan are significant. The positive relationship with monsoon rainfall over Korea and Japan indicates that El Nino is conductive for good monsoon activity over Korea-Japan sector, while the negative relationship with monsoon rainfall over China indicates that it will inhibit monsoon activity over China. These significant CCs are also evident one season prior (MAM0) for China, Korea and following the monsoon season for China.

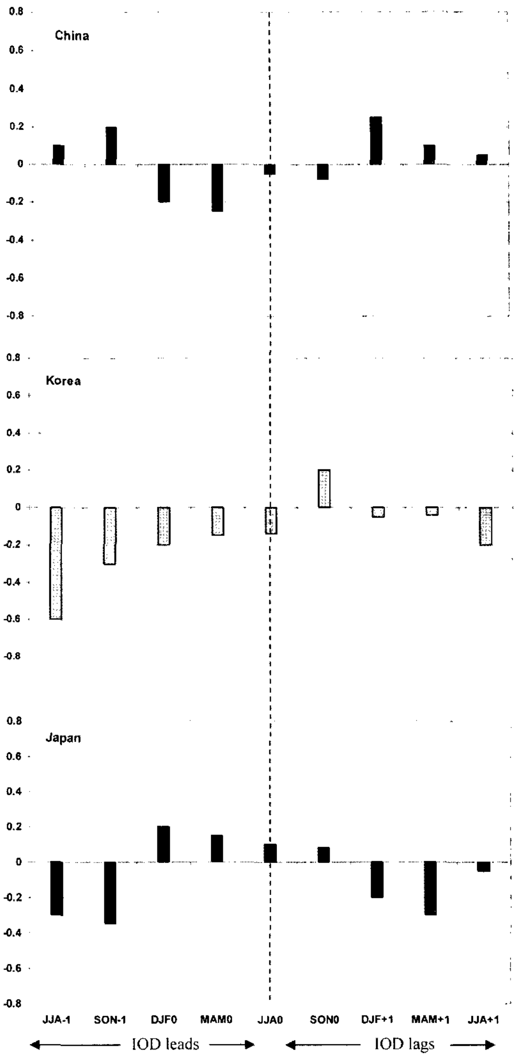


Fig. 1. Correlation coefficient between seasonal DMI and summer monsoon rainfall over China, Korea and Japan. The JJA0 season marked by vertical dashed line denotes the concurrent season. The seasons on the left (right) of JJA0 indicate DMI leading (lagging) monsoon rainfall.

An overall summary of the above statistical analysis is as follows:

(i) While the impact of IODM on East Asia monsoon, in particular over Korea-Japan sector may take about 3-

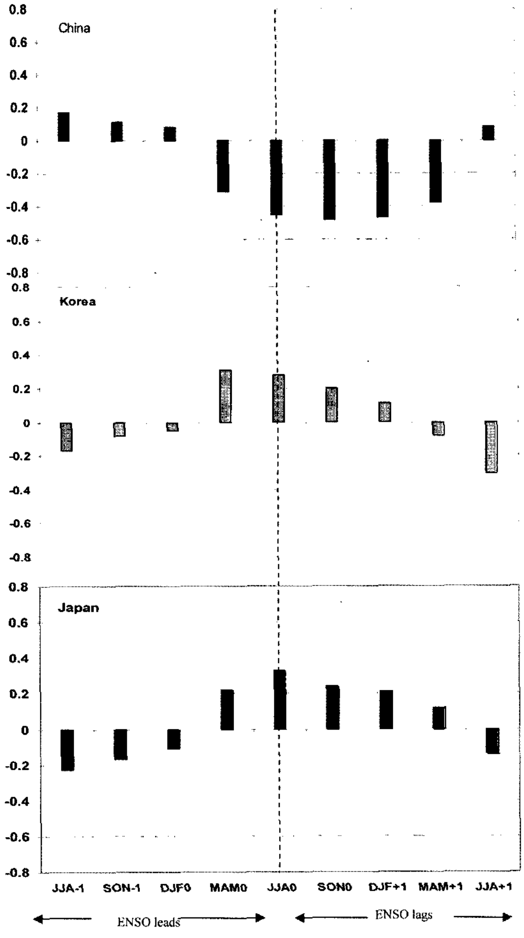


Fig. 2. Same as Fig. 1 but for Nino 3 SST.

4 seasons, the impact of ENSO could take only 1 season or could be simultaneous.

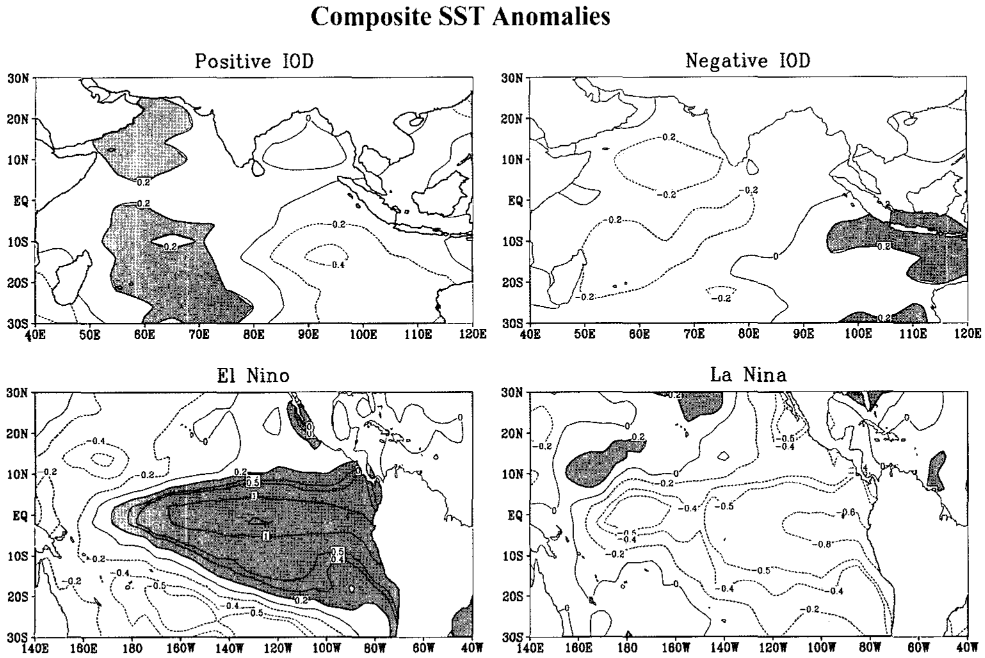
(ii) The negative phase of the IODM and the occurrence of El Nino over the Pacific will enhance monsoon activity over Korea-Japan sector, while the positive phase of IODM and occurrence of La Nina over Pacific will suppress the monsoon activity.

(iii) IODM appears to have no significant impact on monsoon rainfall over China, but the occurrence of El Nino (La Nina) over the Pacific will suppress (enhance) monsoon activity over China.

IV. DESIGN OF NUMERICAL EXPERIMENTS

The Community Atmospheric Model version 2.0.2 (CAM2) of the National Center for Atmospheric Research (NCAR) has been used to understand the impact of the IODM and ENSO on the summer monsoon variability over East Asia. This model has a standard T42 spectral resolution (about 2.8° latitude/ longitude) and 26 vertical levels. A detailed description of the governing equations and physical parameterizations of this model is given by Collins *et al.* (2003). In brief CAM2 includes prognostic cloud water, long wave radiation transfer improvements, generalized cloud overlap, improved treatment of sea ice, enhanced evaporation of convective precipitation, improved vertical diffusion of dry static energy. The CAM2 consists of Zhang and McFarlane (1995) parameterization for deep moist convection, while shallow dry convection is treated using the Hack scheme (Hack, 1994). The parameterization of non-convective cloud processes in CAM2 is described in Rasch and Kristjansson (1998) and Zhang *et al.* (2003). The surface exchange of heat, moisture and momentum between the atmosphere and land, ocean or ice surfaces are treated with a bulk exchange formulation. The sea ice formulations in CAM2 uses parameterizations from NCAR Community sea ice model (Briegleb *et al.*, 2002) for predicting snow depth, brine pockets, internal shortwave radiation transfer, surface albedo, ice-atmosphere drag and surface exchange fluxes. This model can simulate reasonably well many characteristics of the South and East Asian summer monsoon (Tzeng and Lee, 2001). Numerical experiments conducted by Community Atmospheric Model uses PCMDI (Program for Climate Model Diagnosis and Inter-comparison) AMIP (Atmospheric Model Inter-comparison Project) observed and boundary condition data (Taylor *et al.*, 2000) of SST and sea ice concentration (1960-1999).

Five sets of model experiments are performed in this study: the control run with climatological SSTs, runs with SSTs associated with only the positive and only negative phase of the dipole mode (not in concurrence with El Nino/La Nina), runs with SSTs associated with only El Nino or La Nina (not in concurrence with IODM). To determine the SST anomaly patterns associated with the positive and negative phases of the dipole mode, time series of monthly DMI index is examined. Months are identified with DMI larger than or equal to one standard deviation in magnitude. For these identified months the respective Nino3 index should be within one standard deviation for the consideration of pure positive and negative phases, in other words only those months are identified with extreme DMI values excluding the extreme ENSO related values. Composite SST anomaly patterns are computed by averaging cases for the months


Composite SST Anomalies

Positive IOD

Negative IOD

El Nino

La Nina

Fig. 3. Composite SST anomalies associated with the positive (upper panel, left), negative (upper panel, right) phases of the Indian Ocean Dipole mode, and SST anomalies associated El Nino (lower panel, left) and La Nina (lower panel, right) phenomenon.

with DMI greater than (less than) or equal to + (–) one standard deviation and Nino3 index less than one standard deviation for the pure positive (negative) phase of the dipole mode using AMIP SST data. A similar procedure is adopted to determine anomalous SST patterns associated with El Nino/La Nina phenomenon. These anomalous SST patterns are shown in Fig. 3.

The SST anomaly pattern (Fig. 3 upper panel, left) shows positive anomalies west of 80°E and negative anomalies east of this meridian for the positive phase of the dipole mode in the equatorial Indian Ocean. A reverse anomaly pattern is clearly visible for the negative phase of the dipole phenomenon (Fig. 3 upper panel, right). Fig. 3 (lower panel, left) represents El Nino. Significant positive Nino3 SST anomalies are visible in Pacific Ocean. Significant negative Nino3 SST anomalies are visible in Pacific Ocean indicating La Nina (Fig. 3 lower panel right). These SST patterns (Fig. 3 lower panels) associated with the El Nino and La Nina are independent of IODM. These anomalies have been super-imposed on the climatological SST patterns for the four perturbed runs. Thus the model control run is performed with AMIP SST climatology, and the perturbed simulations are carried out with additional forcing from the composite anomalies associated with only the dipole phases, and only the ENSO phases. Model simulation for each experiment is performed from September through to August for one year since the IODM peaks in SON and ENSO peaks in DJF.

V. ANALYSIS OF SIMULATED RESULTS

In this section we examine the summer precipitation distribution over East Asia and the circulation features during summer as simulated by the perturbed runs. The features over the China-Korea-Japan region are only discussed.

5.1. Precipitation distribution over East Asia

Fig. 4 (upper panel, left) depicts the anomalous (perturbed minus control) precipitation distribution for the positive dipole phase during JJA. Figure reveals that the positive phase of the dipole mode can induce negative anomalies over the Korea-Japan peninsula during the following summer, with positive anomalies north and south of this region. For the negative dipole phase (Fig. 4 upper panel, right), the negative anomalies

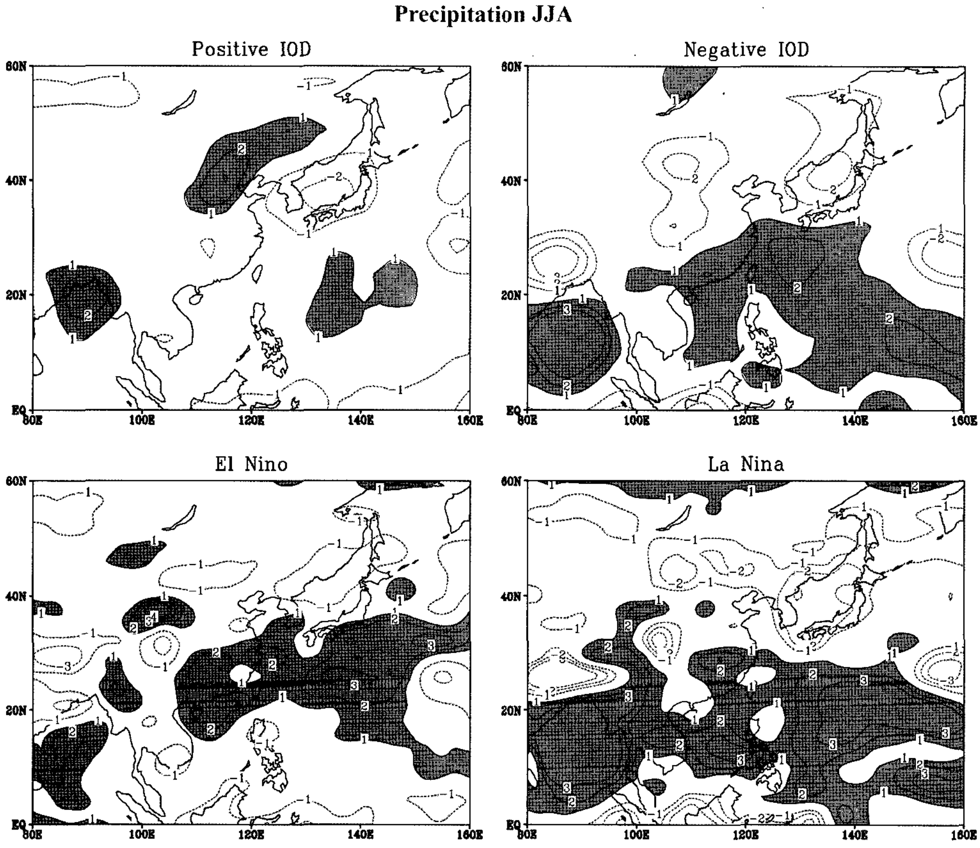


Fig. 4. Same as Fig. 3 but for precipitation anomalies in mm/day during the summer simulated by NCAR CAM.

over Korea-Japan and the positive anomalies over western Pacific have shifted northwards. Although there is some indication of positive anomalies over Korea-Japan sector, model suggests that the negative phase of the dipole has no appreciable impact on the precipitation distribution over Korea-Japan. However this phase may induce negative anomalies over north China and positive anomalies from south China through to the west Pacific. In case of El Nino (Fig. 4 lower panel, left), there is an indication of positive anomalies over Korea-Japan sector while for the La Nina case (Fig. 4 lower panel, right) negative anomalies over entire Korea-Japan sector are evident. These model simulated results are consistent with the empirical results (section 3). The precipitation patterns over China appear to be complex. Thus the model is able to capture, reasonably well the precipitation patterns, as indicated by the empirical relationships.

5.2. 850 hPa vector wind fields

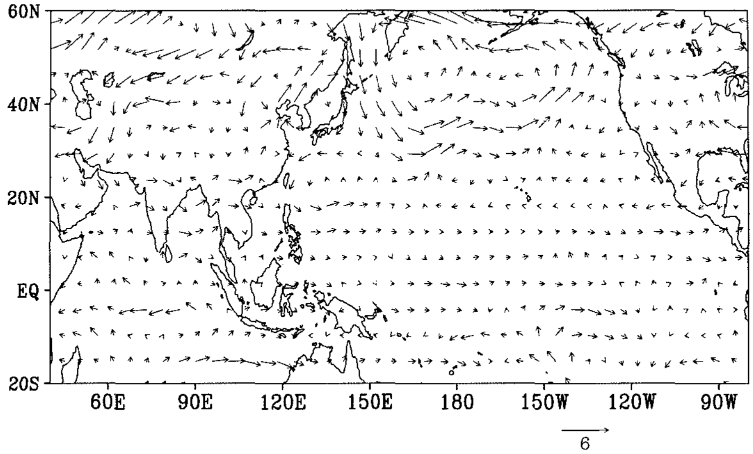
The simulated 850 hPa vector wind fields during summer for the IODM phases is depicted in Fig. 5, while for the ENSO phases is depicted in Fig. 6.

A weakening (strengthening) of the North Pacific Subtropical high is evident (region Equator-30°N, 130°E-160W) for the positive (negative) phase of the IODM (Fig. 5). While the weakening of subtropical high during the positive phase will inhibit moisture supply towards the Korea-Japan sector, the strengthening of the subtropical high during the negative phase will transport moisture from the Pacific (southwesterly flow over the region 15°-35°N, 120°-150°E) towards the Korea-Japan sector. The cyclonic circulation over north Pacific (30-60°N, 140°E-130°W) may be related with the Aleutian low. This may transport cold dry air from its western edge (150°E) during the positive phase.

On the other hand cyclonic circulation just east of Japan (30-45°N, 130°E-160°W) will transport moisture towards Japan-Korea from the northwestern part of the Pacific during El Nino (Fig.6 upper panel). By the time this northwesterly flow reaches north China, these winds

850 hPa Vector Winds (JJA)

Positive IOD



Negative IOD

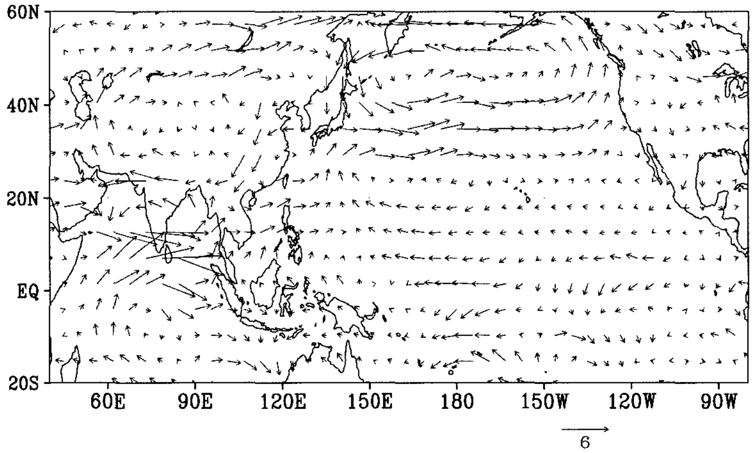


Fig. 5. Summer patterns of 850 hPa vector wind (perturbed minus control) in m/sec simulated by the model for positive dipole (upper panel) and negative dipole (lower panel) phase.

will be devoid of moisture. Thus the northwesterly flow and northerly flow (20-50°N, 100-130°E) will bring dry air over north China. The northerly winds just north of Korea-Japan will supply dry air from north inhibiting rainfall activity during the La Nina case (Fig. 6 lower panel). However the easterlies (30°N, 100-140°E) will inject moisture towards China.

VI. SUMMARY

This study has identified possible impact of the IODM and ENSO on the summer monsoon variability over East Asia. The NCAR CAM2 model was used to investigate this mechanism. Five sets of model experiments were performed: the control run with climatological SSTs and the transient runs with SSTs associated with the positive/negative phases of the dipole mode and El Nino/ La Nina super-imposed on the climatology. Each model experiment was run for one year from September through to August. Results reveal that the dipole mode influences the summer monsoon activity over East Asia, in particular the Korea-Japan peninsula three seasons later and ENSO affects monsoon variability over China simultaneous.

The positive phase of the dipole mode weakens the North Pacific Subtropical High and the cross-equatorial flow. This inhibits the moisture supply from the Pacific towards the Korea-Japan peninsula. Thus the moisture

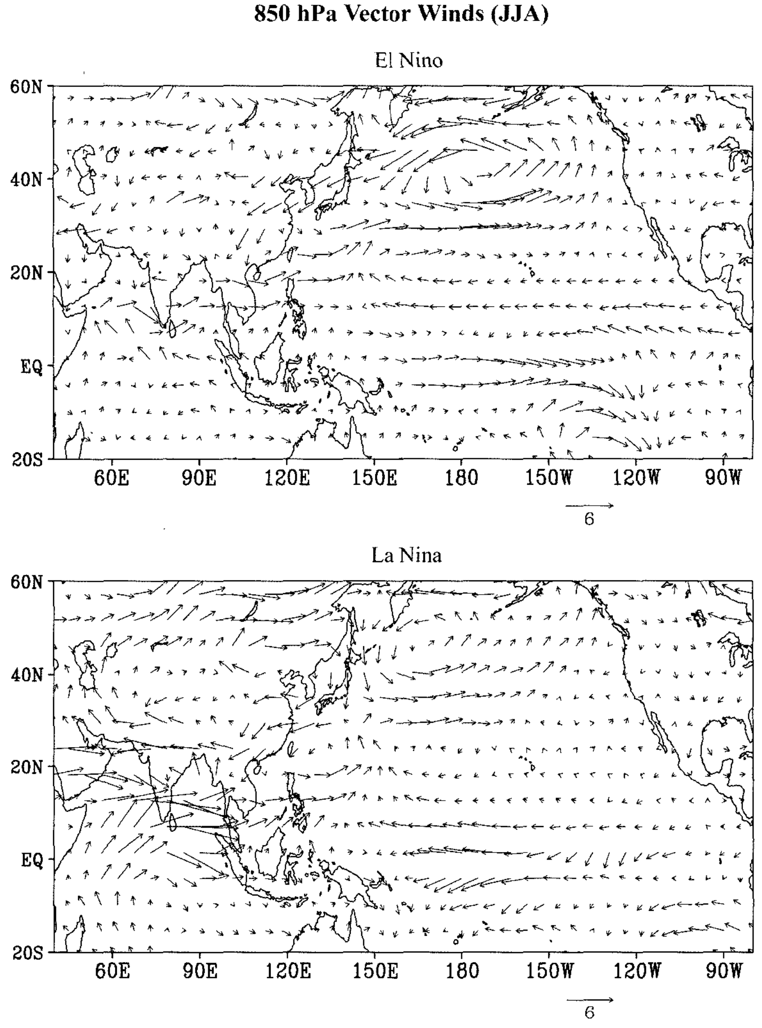


Fig. 6. Same as Fig. 5 but for El Nino (upper panel) and La Nina (lower panel) phases.

supply from the southern route is cut off. The cyclonic circulation (Aleutian low) transports cold and dry air from the north towards the Korea-Japan region from its western edge. In this way, the northern route injects dry air. Thus the net result of the above physical processes is less precipitation over Korea-Japan during summer. During the El Nino/La Nina cases the transport of moisture supply is determined by the anomalous cyclonic circulation over north Pacific. The precipitation distribution over China is also determined by these atmospheric patterns. Thus while the IODM appears to modulate the intensity of the subtropical high and determine the moisture supply from the Pacific towards East Asia; ENSO appears to modulate the Aleutian low and determine the flow of moisture. In summary the impact of IODM is stronger over Korea-Japan sector than over China, on the other hand the impact of ENSO is stronger over China than over Korea-Japan.

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적 요

일반적으로 인도양 동쪽 해수면 온도는 따뜻하고, 서쪽 해수면 온도는 차갑다. 이러한 인도양 동/서쪽의 해수면 온도 변화는 인도 해양 다이폴 현상(Indian Ocean Dipole Mode, IODM)이 그 원인이다. 다이폴의 양의 위상은 서쪽 인도양에 양의 SST 아노말리가 나타나고, 남동 인도양에는 음의 SST 아노말리가 나타나고 음의 위상은 이와 반대의 SST 아노말리가 나타난다. 반면 태평양의 경우, 일반적으로 서쪽 해수면 온도는 따뜻하고, 동쪽 해수면 온도는 차갑다. 중앙/동(서) 태평양 해양의 양(음)의 SST 아노말리가 현상이 나타날 때는 엘니뇨 시기이다. 이와 반대의 SST 아노말리 현상은 라니냐 시기이다. 이러한 태평양의 대기-해양 간의 상호작용으로 나타나는 현상을 엘니뇨 난방진동(El Nino Southern Oscillation, ENSO) 이라 한다.

본 연구에서는 IODM과 ENSO 현상에 따른 동아시아 몬순 변동성을 분석하기 위해 관측자료와 NCAR MCA 모델 자료를 사용하였다. IODM과 ENSO 현상과 관련된 SST 아노말리 5가지 실험을 수행하였다. IDO 모드는 최고의 값이 나타난 이후 약 3~4계절의 시간 지연을 가지고 동아시아의 여름 몬순 활동에 영향을 주는 반면, ENSO는 동아시아 여름 몬순과 같은 계절에 영향을 준다. IODM 음(양의)위상과 태평양에서의 엘니뇨(라니냐) 현상은 한국과 일본지역에서 몬순 활동을 강화(억제)하는 역할을 한다. 반면 중국 지역에서는 IDOM과 몬순 변동성과는 별다른 연관성이 없는 것으로 나타났다. 그러나 엘니뇨(라니냐)일 때, 중국 지역에서 몬순 활동은 억제(강화)되는 경향을 보였다. IODM은 북태평양 아열대 고기압이 강화 할 때 나타나고, ENSO는 북서 태평양 알류산 저기압의 영향으로 나타난다. 따라서 태평양으로부터 동아시아 쪽으로의 수분 공급은 아열대 고기압과 알류산 저기압의 강화/약화에 의해 결정된다.

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