Impact of El Niño on the East Asian Monsoon:
A Diagnostic Study of the '86/87 and '91/92 Events

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Abstract

The East Asian monsoon circulation during the El Niño episodes of '86/87 and '91/92 is studied diagnostically. It is found that a southerly wind anomaly appeared in the lower troposphere along the coast of the East Asia during the mature phases of these two El Niño events. In the case of '86/87, the mature phase covered the boreal summer and the East Asian summer monsoon was intensified. On the other hand, in the case of '91/92, the northern winter was within the mature phase and the East Asian winter monsoon was weakened.

Examination of the circulation features suggests that the effects of the El Niño events on the East Asian monsoon are felt through the variation of convective activities over the western equatorial Pacific. Convections in this area are strongly influenced by the evolution of sea surface temperature anomalies in the equatorial Pacific and are strongly suppressed during the mature phase, which exerts significant influences on the direct monsoonal circulation over the western tropical Pacific and the East Asia.

The relationship between the East Asian monsoon and El Niño in its mature phase is also confirmed by a historical 850 hPa wind dataset that covers 6 events prior to the '86/87 event. The dataset also suggests that an inverse relationship does not hold during the La Niña periods.

1. Introduction

The El Niño/Southern Oscillation (ENSO) is one of the most striking phenomena in the tropics. It is regarded as an interannual oscillation of the air-sea coupled system in the tropical Pacific, an idea which has been substantiated by numerous studies using air-sea coupled models (e.g., Philander et al., 1984; Zebiak and Cane, 1987; Zhang and Chao, 1993; Neelin et al., 1994). A number of studies has also shown that the variations in the thermal states of the tropical Pacific Ocean influence not only the circulation and weather in the tropics, but also those over the globe (e.g., Rowntree, 1979; Horel and Wallace, 1981; Wallace and Gutzler, 1981).

Previous studies have shown that the monsoon should not be regarded as a regional phenomenon, but a phenomenon connected with global-scale circulations (e.g., Kutzbach, 1987; Yasunari, 1990, 1991; Webster and Yang, 1992). South-East Asia is a well-known monsoon region in the world. Some investigators have found that weak Indian summer monsoons tend to occur in El Niño years (e.g., Mooley and Parthasarathy, 1983; Rasmusson and Carpenter, 1983; Khandekar and Neralla, 1984). The East Asian monsoon is distinct from the Indian monsoon in both their large-scale structures and constituent subsystems (Lau and Li, 1984; Tao and Chen, 1987). For example, during the northern winter East Asia is under the influence of surface northerlies coming from the Siberian High, and in summer it is influenced not only by the Indian monsoon crossing the Bay of Bengal but also by the western Pacific subtropical high and the cross-equatorial low-level flow from the anticyclonic outflow over Australia. Several investigators have studied the relationship between ENSO and the East Asian monsoon. Nitta (1987) proposed that the summer climate over East Asia is largely affected by the sea surface temperature (SST) and convective activities near the Philippine Islands. In most of the El Niño years, colder SST appeared in this region and the convection was inactive over the Philippine Sea and thus mid-latitude East Asia experienced relatively cool summers. Studies by Fu and Teng (1988) and by Huang and Wu (1989) have shown that anomalies in summer precipitation in China may depend on the stage of the El Niño development. From these studies we can see that the

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weather and short-term climate variation in the East Asian region are related to the El Niño event and the stage of the evolution of the El Niño event seems to be important.

Bjerknes (1966, 1969) was the first to recognize the importance of the teleconnection between sea surface temperature anomalies (SSTA) in the equatorial Pacific and the circulation in the extratropics. He pointed out that the teleconnection was through the changes in the Hadley circulation and associated energy and momentum transportation. Horel and Wallace (1981) related an anomalous circulation pattern called the Pacific-North American (PNA) pattern to the stationary Rossby wave-train theory of Hoskins and Karoly (1981). This is one of the mechanisms by which El Niño events affect the North Pacific and North America. However, it is not yet clarified how atmospheric circulations are affected by El Niño events in the subtropics of the western Pacific and East Asian regions. It is important to investigate the relationship between the El Niño events and the East Asian monsoon in order to understand the weather and short-term climate variabilities in the East Asian region.

This paper investigates circulation anomalies in the East Asian monsoon as observed during two recent El Niño events, '86/87 and '91/92. We describe the data and analysis procedure in Section 2. Sections 3 and 4 describe SSTA in the equatorial Pacific and the outgoing longwave radiation anomalies in the tropics during the two El Niño episodes, respectively. The circulation features in the lower and upper troposphere over the East Asian monsoon region are examined in Section 5. Although these two El Niño episodes matured in the northern winter and summer respectively, similar features in the lower tropospheric anomalies are found; that is, anomalous southerlies appeared along the coast of East Asia during the mature phase of these two El Niño events. In this section we also investigate anomalies in divergent circulations over the western Pacific. In order to check the generality of the findings, we examine statistically the covariability of ENSO and lower tropospheric winds over the last 30 years in Section 6. Concluding remarks follow in Section 7.

2. Data

The datasets used to study circulation anomalies are initialized, gridded analyses from the European Centre for Medium Range Weather Forecasts (ECMWF) from January 1986 to February 1993, available twice daily (00 and 12 UTCs) at 500 and 200 hPa levels on a 2.5° × 2.5° grid. Monthly climatology is computed over the above 7 years. Outgoing longwave radiation (OLR) data from NOAA are available twice daily on a 2.5° × 2.5° grid. Monthly anomalies and climatology are calculated over the same period as the ECMWF data. The monthly SSTA data on a 2° × 2° grid are provided by the Japan Meteorological Agency (JMA).

Through a detailed intercomparison of the National Meteorological Center (NMC) and ECMWF datasets, Trenberth and Olson (1988) indicated fairly extensive agreement between the analyses from these two centers over the Northern Hemisphere extratropics. Major disagreements between them in the tropics seen in the early 1980s were largely eliminated by 1986. We use the ECMWF data only after 1986 when they are more reliable.

In order to establish a statistical relation between the East Asian monsoon and El Niño events, 850 hPa daily wind data in the Northern Hemisphere (north of 20°N) from January 1963 to December 1985 analyzed by the NMC are utilized in Section 6. The monthly climatology is computed over this period.

3. The evolution of sea surface temperature anomalies in the equatorial Pacific during the '86/87 and '91/92 El Niño episodes

Figure 1 shows a longitude-time section of SSTA averaged between 5°S and 5°N. One of the characteristic features of two El Niño events in '86/87 and '91/92 is that the warming first appeared in the central equatorial Pacific rather than in the eastern equatorial Pacific (Fig. 1). Subsequently, SSTA migrated eastward rather than westward, in contrast to most of the previous events (Rasmusson and Carpenter, 1982). The El Niño event of '86/87 began in around July 1986 and peaked in 1987. The SSTA decreased rapidly in early 1988 and the El Niño event ended around February 1988. During the warming over the central-eastern equatorial Pacific, the SST in the western Pacific warm pool remained slightly below normal. For the El Niño event of '91/92, there were warm waters in the central equatorial Pacific in the second half of 1990. In March 1991, the central and eastern equatorial Pacific SST started to warm and peaked between the fall of 1991 and the spring of 1992, when the SST in the western equatorial Pacific remained below normal. The SSTA decreased rapidly in the summer of 1992 except near the dateline where it persisted up to the end of our dataset.

In the present study, we refer to the phase of the El Niño events defined in terms of SSTA averaged over an area in the eastern equatorial Pacific called NINO3 (5°S–5°N; 90°W–150°W) (Fig. 2). It is probably the best single indicator of an El Niño event likely to affect global climate (Rasmusson and Wallace, 1983; Cane et al., 1986). The El Niño episode and its mature phase are defined as periods when the NINO3 SSTA exceeds 0.5°C and 1.0°C, respectively. With such definitions, we can see in Fig. 2 that the '86/87 El Niño event began in September 1986 and ended in Febru-
ary 1988 and that the mature phase was from March to May 1987. The '91/92 El Niño event began in May 1991 and ended in June 1992. Although the SSTA exceeded 1.0°C in June and July 1991, it dropped sharply in the following three months and the value was less than 0.5°C in the September 1991. So we define the mature phase of this El Niño event from November 1991 to May 1992.

4. Convective activities in the tropics

In order to study changes in convective activities associated with El Niño events, we examine the OLR data. In the tropics, it can serve as a proxy index of the amount of convection (Morrissey, 1986). The decreased OLR corresponds to the increased coverage of cold (high) cloud tops and increased convection.

The OLR anomalies during the '86/87 and '91/92 El Niño episodes are shown in Figs. 3 and 4, respectively. It can be seen that these two El Niño episodes were marked by strong convections (negative OLR anomalies) in the central and/or eastern equatorial Pacific. In the western tropical Pacific, the pattern of large-scale OLR anomalies appears to depend on the stages of the evolution of the El Niño events. The convective activities present a striking contrast between the El Niño mature phases and others. During the mature phases (Figs. 3c, 3d, 3e and Figs. 4c, 4d), the strongest positive OLR anomalies appeared over the western equatorial Pacific around the maritime continent of Borneo and Indonesia.

In the previous section we have defined the mature phase of the '86/87 or '91/92 El Niño event as the peak period of the NINO3 SSTA. Here we can see that in the mature phase the strongest positive OLR anomalies appeared around the maritime continent and that a notable east-west dipole of the convection anomalies was formed. Such a dipolar distribution indicates that there existed anomalous heating to the atmosphere over the central and eastern equatorial Pacific and anomalous cooling over the western Pacific. Because of the notable cooling and associated subsidence, the effects of the El Niño events on the atmosphere in the western Pacific should be the largest during the mature phase.
5. Circulation features over the East Asian monsoon region

As described by Lau and Li (1984), Tao and Chen (1987), the atmospheric circulation over the East Asian area changes completely from summer to winter. In order to study the variations of the monsoonal flow in the '86/87 and '91/92 El Niño episodes, the anomalies of monsoonal circulation over the East Asian area during these two El Niño episodes are analyzed in this section.

Fig. 3. Seasonal mean OLR anomalies during the '86/87 El Niño episode. The contour interval is 10 W/m². Heavy shadings indicate OLR anomalies greater than 10 W/m². Light shadings indicate values less than −10 W/m².
5.1 Flow patterns in the lower troposphere (850 hPa)

Figures 5 and 6 show the seasonal mean patterns of 850 hPa wind anomalies for the '86/87 and '91/92 El Nino episodes, respectively. During the '86/87 El Nino episode (Fig. 5), we can see that the patterns over the East Asian region and the western tropical Pacific in the mature phase of this El Nino episode (Figs. 5c, 5d and 5e) were distinct from those in the other phases. Common features during this period were southwesterly anomalies along the coast of East Asia and easterlies over the western equatorial Pacific. The southwesterly anomalies over East Asia were in the same direction as the climatological monsoonal flow in northern summer (see Lau and Li, 1984) and thus strengthened the East Asian summer monsoon.

During the '91/92 El Nino episode (Fig. 6), similar anomaly patterns appeared along the coast of East Asia and over the western tropical Pacific during the mature phase (Figs. 6c and 6d). Because the anomalous flow along the coast of East Asia was opposite to the climatological monsoonal flow in the northern winter, the winter monsoon was weak.

It appears that the southwesterlies along the coast of East Asia and the easterlies over the western equatorial Pacific in the mature phases of these two El Nino episodes were parts of the anomalous anticyclone over the area to the north of maritime continent around Borneo and Indonesia. In the previous section, we have seen that the convections were strongly weakened over the maritime continent during the mature phase of these two El Nino episodes. It is tempting to interpret this anticyclone as the equatorial Rossby wave response in the lower troposphere to the anomalous cooling near the equator. The southwesterlies along the northwestern side of the anomalous anticyclone are favorable for intensifying the East Asian monsoon in the northern summer and weakening it in winter.

In order to clarify the above-mentioned features, we prepared Fig. 7, which gives the time evolutions of NINO3 SSTA, OLR anomalies averaged over the western equatorial Pacific (100°E–150°E, 10°S–10°N), OLR anomalies averaged over the central and eastern equatorial Pacific (170°E–120°W, 10°S–10°N) and meridional wind anomalies at 850 hPa averaged over the East Asian area (110°E–140°E).
20°N–40°N) during the two events. It is seen clearly that when NINO3 SSTA reached their peaks, convection over the western equatorial Pacific (WEP) was weakened significantly (positive OLR anomalies). In the central and eastern equatorial Pacific (CEEP), convection was very strong. The east-west contrast was largest during the mature phases. Over the East Asian area (EA), the notable southerly anomalies prevailed in the lower troposphere in the mature phases and they were obviously distinct from

Fig. 5. Seasonal mean wind vector anomalies at 850 hPa during the '86/87 El Niño episode.
those in the other phases.

5.2 Flow patterns in the upper troposphere (200 hPa)

Figure 8 shows the seasonal mean anomalies of 200 hPa winds for the northern summer of 1987 and winter of 1991/92, respectively. As we have seen before, these two seasons were in the mature phases of the two El Niño episodes. Although both maps show similar westerly anomalies near the equator, flow patterns in sub- and extratropics differ considerably. In the northern summer, the climatological subtropical high is located in the middle latitudes of East Asia and an intense anticyclone is centered over the Tibetan Plateau (Lau and Li, 1984). For the northern summer of 1987 (Fig. 8a), we can see that an anticyclonic anomaly was located over the East Asian continent where the climatological anticyclone appears. This anticyclonic anomaly strengthened the northerlies along the coast of East Asia and the monsoon circulation became stronger. To the west of the Philippines, a cyclonic anomaly appeared, which was just over the anticyclonic anomaly in the lower troposphere.

In the northern winter, the climatological westerlies prevail over East Asia and a strong jetstream exists in the middle latitudes with the jet core stretching from East China, across Japan, to the central North Pacific (Lau and Li, 1984). For the northern winter of the 1991/92 (Fig. 8b), a strong cyclonic anomaly appeared over the East Asian area. Anomalous easterlies prevailed in the middle latitudes and westerlies in the subtropics and tropics. The anomalous easterlies in the middle latitudes reduced the intensity of the climatological jetstream in the middle latitudes. As proposed by Chang and Lau (1982), the weakening of the westerly jetstream over East Asia was accompanied by an inactive winter monsoon.

In both of these two seasons, the westerly anomalies prevailed over the equatorial western Pacific. Comparison with the corresponding flow patterns in
the lower troposphere (Figs. 5d and 6c) shows that the flow anomalies at the two levels were out of phase over the equatorial western Pacific. As inferred form the OLR anomalies, this baroclinic vertical structure is consistent with the interpretation as a response of the tropical atmosphere to the anomalous cooling.

The wind response in the western tropical Pacific is a reversal of that in the central and eastern tropical Pacific (Rasmusson, 1991).

Figure 8 also shows that the anomalies at 200 hPa exhibit larger seasonality in the subtropics and in the extratropics. In the tropics and at 850 hPa,
however, the seasonality appears smaller. In particular, the flow anomalies in the lower troposphere (Figs. 5d and 6c) show more similar patterns along the coast of East Asia between the two events. Despite the large difference in the basic states (see Lau and Li, 1984), the mature-phase convective forcing is so strong that an apparently linear response-like feature can be seen, which has great influence on the variations of the monsoonal flow in the summer and in the winter.

5.3 Divergent circulations

An important aspect of the planetary scale circulation is the divergent circulations (Krishnamurti, 1971). Usually, this field is presented by velocity potential at 200 hPa, a level which reflects the upper branches of the direct thermal circulation in the tropics. The meridional and zonal components of the divergent flow reflect the upper branches of the Hadley and Walker circulations, respectively.

Figures 9 and 10 show the velocity potential anomalies at 200 hPa and corresponding divergent wind anomalies during the ’86/87 and ’91/92 El Niño episodes, respectively. It can be clearly seen that there exists a striking contrast between the El Niño mature phases and others. Common features in the mature phase of these two episodes (Figs. 9c, 9d, 9e and Figs. 10c, 10d) were the inflow anomaly in the western tropical Pacific and the outflow in the eastern tropical Pacific, which corresponded well to the tropical convection anomalies detected by the OLR data (Figs. 3c, 3d, 3e and Figs. 4c, 4d); that is, the areas of anomalous convergence and divergence corresponded to the regions of the anomalous cooling and the anomalous heating, respectively. Like OLR, the dipolar distributions of the divergent wind anomalies were pronounced only in the mature phase of these two El Niño events. In the tropical Pacific, the zonal component of the divergent circulation anomalies had its updraft centered over the tropical eastern Pacific and downdraft over the tropical western Pacific, in the reverse direction to the climatological Walker circulation. Concurrently, the direction of the meridional component of the divergent circulation anomalies over the western Pacific was opposite to that in the eastern Pacific; that is, in the western Pacific the anomalous circulation had a reverse direction from the Hadley circulation (reverse-Hadley anomaly, hereafter) with sinking motion near the equator and rising in the subtropics, while in the eastern Pacific it was in the same direction as the Hadley circulation.

In the mature phase of the ’86/87 event (Figs. 9c, 9d and 9e), northerlies in the divergent wind anomaly prevailed over the western Pacific and East Asian region. The strengthening of the summer monsoon in this period appears to be related to this reverse-Hadley anomaly over the western Pacific and East Asia, which intensified the climatological East Asian monsoonal circulation in the northern summer.

In the mature phase of the ’91/92 event (Figs. 10c and 10d), the same features were observed. In the northern winter, over the western tropical Pacific and East Asian region the climatological (local) Hadley circulation is pronounced with the divergent flow from the region of active convection in the west Pacific and Indonesia toward the subsiding airmass over the cold Asian continent at the upper troposphere (Lau and Li, 1984). In the winter of ’91/92 (Fig. 10c), the reverse-Hadley anomaly over the western Pacific was in the opposite direction to the climatological Hadley circulation, which acted to weaken the climatological East Asian monsoonal circulation in the northern winter.
6. Meridional wind anomalies over the East Asian region during historical El Niño events since 1963

We have shown that during the mature phases of the '86/87 and '91/92 El Niño events, the southerlies became stronger in the lower troposphere along the coast of the East Asia. They should have significant influences on the variation of the East Asian monsoon. However, we also noted in Section 3 that

Fig. 9. Seasonal mean velocity potential anomalies at 200 hPa during the '86/87 El Niño episode. The contour interval is $1 \times 10^6 \text{ m}^2/\text{s}$. Arrows indicate anomalous divergent wind vectors.
during these two El Niño events the warming first appeared in the central Pacific and then propagated eastward unlike most of the previous ones. In order to check if similar features can also be found over East Asia in the previous El Niño episodes, wind and SST data for the historical El Niño events since 1963 are analyzed in this section.

Figure 11 shows the time evolutions of monthly NINO3 SSTA and a three-month running mean of meridional velocity anomalies at 850 hPa averaged over the East Asian region in an area 110°E–130°E, 20°N–30°N. The monthly wind anomalies from January 1963 to December 1985 are calculated by the NMC data while those from January 1986 to February 1993 are from the ECMWF dataset as used in the previous sections. It can be seen in Fig. 11 that from January 1963 to February 1993 there were 8 El Niño events which occurred in 1963, 1965/66, 1968/69, 1972/73, 1976/77, 1982/83, 1986/87 and 1991/92, respectively. Since the SSTA at NINO3 were less than 1.0°C for the weak El Niño events in 1963, 1968/69 and 1976/77, we defined the mature phase of these El Niño events to be the period when NINO3 SSTA exceeded 0.5°C. It is seen in Fig. 11 that the southerly anomalies prevailed in the lower troposphere of East Asia during the mature phase of all these El Niño events (shaded areas in the figure). The averages of these meridional velocity anomalies during the mature phase for each of these El Niño events are also shown in Fig. 11 (figures in the shaded areas). It is clear that for all these El Niño events, the mature phase is characterized by the mean anomalous southerlies in the lower troposphere over East Asian region, which is in good agreement with the results of the two recent cases in the previous sections.

The statistical significance of the above relation is checked by a t-test which compares the average over all the 8 El Niño mature phases against that over the rest of the period by using the three-month running mean of the meridional wind anomalies in the lower troposphere over the East Asian region, as shown in
The former value is 0.46 m/s and the latter -0.11 m/s with standard deviations being 0.55 m/s and 0.59 m/s, respectively. With a conservative estimate for the numbers of degrees of freedom, 8 and 22 for each subperiod (8 El Niños in 30 years), the difference in the two time averages is statistically significant at a 95% level. It should be noted that significance is not verified when the monthly means are used. The month-to-month variation of the East Asian monsoonal flow is complicated, so that this kind of relationship is buried in the noise. Our findings may not hold on subseasonal time scales.

In Fig. 11, we can also see that the La Niña events occurred in 1964, 1967/68, 1970/71, 1973/74, 1975/76 and 1988/89. Repeating the t-test, we cannot verify the significant difference between the meridional wind anomalies in the La Niña periods and those in all the other periods; the opposite relationship does not hold for the La Niña episodes. The correlation coefficient between the two time se-

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**Fig. 11.** Time evolutions of monthly NINO3 SSTA (circles; unit: °C) and 3-month running mean of meridional velocity anomalies at 850 hPa averaged over East Asia region in the area 110°E–130°E, 20°N–30°N (crosses; unit: m/s). Shaded areas indicate the mature phase for each El Niño event and the values in the shaded areas are the meridional velocity anomalies averaged over the mature phases.
ties shown in Fig. 11 is 0.37 and is significant at a 99% level. The contribution from the El Niño mature phases accounts more than 2/3 of this correlation.

7. Concluding remarks

An analysis of the circulation anomalies in the upper and lower troposphere during the '86/87 and '91/92 El Niño episodes has revealed that a southerly anomaly prevailed in the lower troposphere along the coast of East Asia during the mature phase of these El Niño events. In the case of '86/87, the mature phase was in the northern summer and the East Asian summer monsoon was intensified. On the other hand, the winter monsoon was weakened in the case of '91/92, when the mature phase was in winter.

Prevalence of the southerly anomalies during the mature phase has also been verified with statistical significance for the historical El Niño events since 1963. It has also been demonstrated that the opposite relationship did not hold for the La Niña episodes.

The effect of the El Niño on the variations of the East Asian monsoon seems to be through the changes in convective activities over the western Pacific and in associated Hadley circulation. The mature phase of the El Niño events is characterized by an anomalous subsidence over the maritime continent and by a divergent circulation anomaly over the western Pacific, with the direction reverse to the Hadley circulation. The existence of the southerly anomalies in the lower troposphere along the coast of East Asia, on the one hand, appears to be related to the anticyclonic anomaly to the north of the maritime continent, which may be interpreted as a form of the equatorial Rossby wave response to the anomalous cooling near the equator. On the other hand, the reverse-Hadley component over the western Pacific seems to exert a direct effect on the East Asian monsoonal circulation.

The present study has focused mainly on lower-tropospheric circulation anomalies during El Niño. The impacts on other constituents of the East Asian monsoon, moist circulations in particular, have to be studied with more extensive datasets. Although the low-level wind anomalies along the East Asia coast discussed in this paper did not exhibit significant seasonality, a more careful study is necessary to understand fully the possible seasonality of El Niño influence over the whole East Asian monsoon system. Impacts on subseasonal variabilities is another important subject for future investigation.

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References


東アジアモンスーンに対するエルニーニョの影響：
'86/87, '91/92イベントについての診断的研究

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1986/87年及び1991/92年に起きたエルニーニョ期間中の東アジアモンスーン循環場を解析した。これら2つのエルニーニョの成熟期には東アジア東岸に沿って対流圈下層に南風偏差が現れた。'86/87年のケースでは成熟期は北半球の夏にあたり、東アジアの夏のモンスーンは強化された。一方、'91/92年のケースでは成熟期は冬に起こり、モンスーンは弱まっていった。

偏差場を調べると、エルニーニョは赤道西太平洋の対流活動の変化させることによって東アジアモンスーンに対して影響を与えていることが示唆される。この領域の対流活動は赤道太平洋の海面水温変動に強く影響され、エルニーニョ成熟期には活動が著しく抑制される。この対流活動の変化に伴う循環偏差が熱帯西太平洋から東アジアに向けてのモンスーン直接循環に影響を及ぼしていると考えられる。

東アジアモンスーンとエルニーニョ成熟期の関係は'86/87年以前の6イベントを含むより長期間の850 hPa風データセットでも確認された。ラニーニャ期に逆の関係は確認されなかった。