Interdecadal change of the active-phase summer monsoon in East Asia (Meiyu) since 1979

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Abstract

The timing of active-phase East Asian summer monsoon (Meiyu) undergoes a marked shift since 1979. Diagnostic analysis indicates that active convection over Taiwan has occurred later in the season, from late May to early June, with a tendency of increasingly intense rainfall. This timing shift of convection results from a southward migration of Meiyu rainband, driven by an upper-level cyclonic anomaly over eastern China and a lower-level anticyclonic anomaly in the subtropical Western Pacific. Together, these two circulation patterns enhance both the moisture transport and baroclinic forcing. The role of Western Pacific warming and anthropogenic greenhouse gases in these changes is suggested.

Keywords: Meiyu; SST warming; East Asian monsoon; subtropical high

1. Introduction

The East Asian summer monsoon (EASM) undergoes an active–break–revival sequence and the associated migration of the rainbands makes the timing of each phase geographically unique (Chen et al., 2004). This distinct lifecycle of EASM regulates rainfall and water supply in several Asian countries, including Taiwan. Located in the central region of EASM, Taiwan covers 36,000 km² of complex terrain with a population approaching 24 millions (location shown in Figure 1(a), inset). The active phase of EASM (Meiyu) produces the first influx of substantial water for agricultural, industrial and residential uses. Wang and Chen (2008) indicated that the active-phase EASM (interchangeable with Meiyu hereafter) contributes to ~60% of Taiwan’s early-summer rainfall. The phases of EASM relative to Taiwan are displayed in Figure 1(a) by the outgoing longwave radiation (OLR) averaged within 119°–122°E, 21°–25°N; here, OLR is shown as departure from 235 W m⁻² to approximate convective rainfall regime, denoted as ΔOLR (=235 – OLR). This feature is critical because, as of April 2015, Taiwan underwent the most severe drought in its 67 years of recorded history and yet, the arrival of Meiyu mitigated the drought situation. However, predicting the timing and strength of active-phase EASM at longer range (>2 week) remains a challenge, making drought adaptation and planning difficult (M.-M. Lu, Central Weather Bureau, 2015, personal communication).

The Meiyu rainband is driven by the mid-tropospheric warm advection and transient eddies that are steered by the westerly jet, and these circulations induce instability and adiabatic ascent while the tropical warm pool supplies the moisture (Chen et al., 2004; Sampe and Xie, 2010). Previous studies have indicated that interannual variability of the EASM circulations is linked to the Tibetan Plateau thermal conditions and India Ocean sea surface temperature (SST) anomalies (Li and Yanai, 1996; Zhao et al., 2010; Liu and Wang, 2011; Hu and Duan, 2015). These processes are complicated by the varying mid-tropospheric temperature advection within the Meiyu rainband (Kosaka et al., 2011; Okada and Yamazaki, 2012). However, few studies have focused on the interdecadal variability of Meiyu. Among these, Li et al. (2010) found that EASM has shifted southward since 1958 probably due to the meridional asymmetric warming between the South China Sea (SCS) and East Asian continent. Luo and Zhang (2015) reported that peak Meiyu rainfall in southern China has tended to arrive later since 1993 due to weakened low-level southwesterly winds. Focusing on Taiwan, Huang and Chen (2014) observed a transition of Meiyu rainfall from the predominately frontal regime to an increase in the diurnal convection regime. Regardless, a mechanistic explanation of the Meiyu’s interdecadal variation is lacking; this is analyzed herein.

2. Data

The following data sets are utilized: (1) the 1.0°-resolution daily OLR Version 1.2 produced by the National Oceanic and Atmospheric Administration (NOAA) (Lee and NOAA CDR program, 2011) from 1979 to 2014 with the missing values during May–June
1985 filled by the NOAA interpolated OLR (Liebmann and Smith, 1996), (2) the monthly NOAA Extended Reconstructed SST Version 3b (Smith et al., 2008), (3) the ECMWF post-1979 reanalysis data at a 1.0° resolution (ERA-Interim) (Dee et al., 2011) and (4) the ECMWF 40-year Reanalysis (ERA-40) from 1958 to 1979 at a 2.5° resolution (Uppala et al., 2005) to merge with ERA-Interim for a longer-term analysis (i.e. for Figure 4).

3. Results

The long-term change in the active-phase EASM is examined by analyzing the daily $\Delta$OLR in Taiwan from mid-May to mid-July (x-axis) for each year from 1979 to 2014 (y-axis); this is plotted in Figure 1(b). The use of $\Delta$OLR compensates for the lack of long, stable record of daily precipitation. Here, $\Delta$OLR is subject to a 5-day and 5-year running mean to focus on the

Figure 1. (a) Long-term 15-day evolution of $\Delta$OLR (235 W m$^{-2}$-OLR) averaged in Taiwan ($119^\circ$–$122^\circ$E, $21^\circ$–$25^\circ$N) from 1980 to 2010, following Wang and Chen (2008). The inset map depicts the geographical location of Taiwan (red). (b) Yearly distribution of daily $\Delta$OLR applied with a 5-day moving average (shadings) overlaid with the linear trend contours from 1979 to 2014. A white and two yellow dashed lines indicate the period difference of the Meiyu as referred in the text.
Figure 2. Differences of $\Delta$OLR (shadings) and (a) 250- and (b) 850-mb winds vectors between 1991–2002 and 1979–1990 for the 7 June–20 June period. (c–d) Same as (a–b) except for the differences between 2003–2014 and 1999–2002. (e) $\Delta$OLR latitude (y-axis) and year (x-axis) distribution across the vicinity of Taiwan (white box in (b) and (d)) during the 7 June–20 June periods overlaid with the linear trend contours from 1979 to 2014. The latitudinal extent of Taiwan is shown by the green dashed lines.

predominant intraseasonal variability that drives the EASM lifecycle (Chen et al., 2004). The peak of $\Delta$OLR has undergone a timing shift from mostly late May before the 1990s to predominantly early June. There is also a tendency for $\Delta$OLR to become stronger and more concentrated in mid-June (10th–15th) after 2003. To illustrate this change, we compute the linear trend of $\Delta$OLR for each day from 1979 to 2014 and superimpose it on Figure 1(b) as contours. Apparently, $\Delta$OLR has decreased by 20 W m$^{-2}$ in late May accompanied by an increase of 30 W m$^{-2}$ in mid-June, estimated from the linear trend. Noteworthy is the change in the convective time span that has reduced from 3 weeks before 2003 to less than 2 weeks afterwards, suggesting more intense rainfall occurring within a shorter period of time. This feature echoes the finding of Huang and Chen (2014) that the upper-level westerly winds enhance slightly, while a low-level cyclonic circulation appears in the vicinity of Taiwan (Figure 2(d), ‘L’). Combined, these circulation changes delineate a meridional migration of Meiyu in the context of interdecadal variation. The change in $\Delta$OLR is also substantial as it is shifted further south adjacent of the Philippines covering only the southern part of Taiwan. To clarify this implication, we plot in Figure 2(e) the latitude-time section of $\Delta$OLR across Taiwan during 7th–20th June. Apparently, positive $\Delta$OLR north of Taiwan has migrated southward from 26° to 20°N. Consequently, what used to be a relatively dry spell in Taiwan (i.e. between 18° and 24°N) has become increasingly convective in recent years. As is shown in Figure S1, Supporting Information, the earlier period of 24 May–6 June undergoes a decrease in convective activity as a result of this $\Delta$OLR migration. These results provide a geographical reference for the timing change of Meiyu.

In order to connect the reported timing shift with the large-scale circulation change, we adopt a method designed to delineate the yearly evolution of a daily variable, following Wang et al. (2014). This method uses the empirical orthogonal function (EOF) of the covariance matrix of $\Delta$OLR over Taiwan, by treating $\Delta$OLR’s daily interval as eigenvalue and its yearly interval as eigencoefficient. After applying a 5-day moving average (to capture the predominant intraseasonal variability of EASM), we obtain a set of EOFs representing the daily variation of $\Delta$OLR and a set of principal
The EOF analysis of daily $\Delta$OLR from 1979 to 2014 for (a) EOFs 1, (b) PCs 1, (c) EOFs 2, (d) PCs 2, (e) reconstructed EOFs 1 + 2 and (f) reconstructed PCs 1 + 2. A 5-day moving average is applied prior to the EOF analysis.

The first two EOFs are shown in Figure 3(a)–(d) representing the amplification of the temporally displaced $\Delta$OLR, constituting collectively 32.7% of the total variance. The EOF 1 (Figure 3(a)) and EOF 2 (Figure 3(c)) show positive values in mid-June with an increasing trend of the PCs (Figure 3(b) and (d)), suggesting a tendency for enhanced convective activity and its timing shift in Taiwan. Next, we combine these two leading modes to reconstruct the $\Delta$OLR changes in Taiwan while filtering out less relevant signals (Van den Dool, 2007). The combinations of EOFs/PCs 1 + 2 are shown in Figure 3(e) and (f). The distribution of EOFs 1 + 2 indicates maximum $\Delta$OLR in mid-June and minimum $\Delta$OLR in late May, and this feature has intensified as shown by the increasing trend in PCs 1 + 2 (significant at $p < 0.05$). Consequently, PCs 1 + 2 form an index enabling us to compare the change in subseasonal variability against interannual variations of any given variable.

By regressing PCs 1 + 2 upon the eddy streamfunction field (i.e. removing the zonal mean) for the month of June, the resultant regression coefficients depict the anomalous circulations accompanying the increased $\Delta$OLR in Taiwan during mid-June. Figure 4(a) and (b) show such circulation patterns at 250 and 850 hPa, depicting westerly (southwesterly) anomalies that prevail over Taiwan at the upper (lower) level. By comparison with Figure 2, these circulation features correspond well with the upper trough in eastern China and the Western Pacific anticyclone. The similarity of circulation patterns between Figure 4(a) and (b) and Figure 2 also suggests that the anomalous circulations leading $\Delta$OLR to become more active in mid-June resulted from two sources: deepening of the upper-level trough northwest of Taiwan and strengthening of the anticyclone in the subtropical western Pacific. In Figure S2, we show the individual regressions of PCs 1 and 2 and their resultant circulation pattern, which reveal similar synoptic processes.
We next compare the interannual variations of the June stream function between the upper-level cyclone and the lower-level anticyclone, using values averaged from their center areas (domain outlined in Figure 4(a) and (b)). The variations of these two circulation features are not correlated ($r < 0.16$), as illustrated by the scatter plot of Figure 4(c). In other words, the circulation patterns in response to PCs 1 + 2 (i.e. increased $\Delta$OLR) could only appear in the second quadrant of the scatter diagram, i.e. when negative 250 hPa values (trough) and positive 850 hPa values (ridge) coexisted. However, by adding the years onto the scatters, there is a discernible change in that the concurrence of the strengthened Western Pacific anticyclone with the deepened eastern China cyclone has increased after 1997 (indicated as red). This result is intriguing in that, although these two levels of circulation do not correlate, in the long run they have become increasingly cohesive in producing precipitation along the SCS-Taiwan corridor in the month of June.

4. Discussions and conclusion

A tendency has been observed in June for the low-level anticyclonic anomaly in subtropical Western Pacific and upper-level cyclonic anomaly in eastern China to occur together more frequently. This feature promotes frontal instability and subsequent convection in early June over Taiwan, delaying its Mei-yu season. For the upper level, previous studies analyzing the change in mid-latitude stationary waves have noted an amplified short-wave regime and associated increases in weather extremes (Screen and Simmonds, 2013; Teng et al., 2013; Wang et al., 2013b; Screen and Simmonds, 2014). Other research (Wang et al., 2013b; Cho et al., 2015) has indicated an intensification of the Eurasia-South Asia short-wave train in the month of June (Yasunari et al., 1991; Ding and Wang, 2005). This reported wave pattern consists of (from west to east) a deepened trough in western Nepal, a strengthened ridge over Bhutan and an enhanced trough over eastern China – these are shown in Figure 5. The cause of this changing wave-train pattern is under debate, and our testing of SST regression with PCs 1 + 2 (not shown) does not reveal any robust linkage with any known climate mode. However, the SST in subtropical Western Pacific has tended to warm by 40% associated with the 30-W m$^{-2}$ increase of $\Delta$OLR in June, based on linear regression. This increase in local SST coincides with the ongoing warming trend in the Western Pacific.

The variation of lower-level circulations in the Western Pacific has been widely documented. Yet, most studies only focused on the typical summer season of June–August, rather than the seasonal transition of May or June. Nevertheless, those studies have uniformly found a link between the strengthened North Pacific subtropical anticyclone and the increased SST under the anthropogenic global warming. The strengthened subtropical anticyclone adds thermal contrast between land
and ocean (Li et al., 2012) and further warms the northern Indian Ocean (He and Zhou, 2015) while enhancing thermal contrast in the subtropical Western Pacific (Wang et al., 2013a). These reported changes in oceanic thermal property and land-sea contrast have a detectable anthropogenic footprint and could be linked to the finding of this study.

To reconcile with the previous findings, we did conduct a preliminary analysis using the historical single-forcing experiment of the Community Climate System Model Version 4 (CCSM4) derived from the CMIP5 archive (Taylor et al., 2009). By reproducing Figure 1 using daily precipitation output of CCSM4, which is shown in Figure S3, it is observed that only the anthropogenic greenhouse gases (GHG) forcing simulates the timing shift of the active-phase EASM in a way similar to the observation. Neither the natural forcing nor the aerosol forcing generated any persistent change in the occurrence of peak rainfall. The preliminary result of Figure S3 suggests a possibility that anthropogenic GHG can influence the timing change of Meiyy rainfall in Taiwan. Subsequent analysis using the full archive of CMIP5 outputs will be the focus of future study.

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Supporting information

The following supporting information is available:

Figure S1. Same as Figure 2(e) but for 24 May–6 June period ΔOLR latitude (y-axis) and year (x-axis) distribution (shadings) overlaid with the linear trend contours from 1979 to 2014. The green lines show latitude range of Taiwan.

Figure S2. Same as Figure 4(a) and (b) but regressed with PCs 1 for (a) 250 and (b) 850 mb; PCs 2 for (c) 250 and (d) 850 mb.

Figure S3. Same as Figure 1, but for CCSM4 historical simulation precipitation in recent 36 years with different forcing: (a,b) anthropogenic greenhouse gases (GHG), (c,d) natural including solar and volcanic forcing (Nat), and (e,f) anthropogenic aerosol (Aero). The yearly distribution of daily precipitation is the departure from seasonal means. Notice the rather weak Meiyy phase of rainfall than the observation, as well as the peak rainfall shift in (b) that is coincident with Figure 1(b).

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